PHYSICAL PROPERTIES OF FERTILIZER IN RELATION TO HANDLING AND SPREADING

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ABSTRACT

The influence of physical properties of fertilizer on the handling and spreading is studied. The reviewed properties are particle size and particle size distribution, coefficient of friction, coefficient of restitution, particle strength and aerodynamic resistance. Further a measuring procedure based on the ultrasonic Doppler effect has been developed. The procedure is used for measuring the influence of physical properties and adjustment parameters on the motion of particles. Both a reciprocating spout type and a spinning disc type fertilizer spreader have been analyzed.

STELLINGEN

I

De variatiecoëfficiënt van een strooibeeld moet gebaseerd zijn op een samengesteld strooibeeld met een breedte precies gelijk aan twee keer de effectieve werkbreedte of op een samengesteld strooibeeld met een breedte precies gelijk aan één keer de effectieve werkbreedte en waarvan het midden precies samenvalt met het midden van een rijspoor.

II

Om bij lokatie specifieke bemesting met een centrifugaalstrooier de hoeveelheid per oppervlakteeenheid te variëren moet niet de dosering maar de rijsnelheid aangepast worden.

Dit proefschrift

III

The better the job you do, the simpler the end results, and the less people will be impressed with the effort you put into it.

(Derek J. Hatley and Imtiaz A. Pirbhai in *Strategies for Real-Time System Specification*)

IV

De diametercoëfficiënt q is een betere parameter om de luchtweerstand van een kunstmestsoort te karakteriseren dan de luchtweerstandscoëfficiënt K zelf. De diametercoëfficiënt is korrelgrootte onafhankelijk en de luchtweerstandscoëfficiënt is dat niet.

Dit proefschrift

V

De eisen die, met betrekking tot de fysische eigenschappen, aan de gemengde meststoffen (de zogenaamde 'bulk blends') gesteld zouden moeten worden, teneinde een goed verdeelbaar produkt te krijgen, zijn zodanig dat de gebruiker sterk moet overwegen helemaal geen gemengde meststoffen toe te dienen.

VI

De duur van het beslissingsproces ten behoeve van particuliere investeringen is omgekeerd evenredig met de hoogte van de investering.

VII

De grote chaos die in de praktijk van de deeltjesbeweging in de strooipijp van een pendelstrooier plaats vindt, zorgt ervoor dat dit type strooier tamelijk ongevoelig is voor de invloed van fysische eigenschappen op de beweging van de korrels in de strooipijp. Voor de praktijk is dit een groot voordeel; voor een onderzoeker die wil modelleren is het een ramp.

Dit proefschrift

VIII

Een model blijft een model.

IX

Bijlagen bij een proefschrift zijn overbodig.

X

De naam 'Landbouwuniversiteit' wil nog niet zeggen dat, bij het beoordelen van de vakgroepen ten aanzien van hun prestaties op het gebied van publiceren, appels, peren, kippen en koeien zonder meer bij elkaar opgeteld kunnen worden.

J.W. Hofstee
Physical properties of fertilizer in relation to handling and spreading
Wageningen, 10 december 1993

Voorwoord

'*Het proefschrift als levenswerk sterft uit*' was de titel van een artikel dat in mei j.l. in de Volkskrant verscheen. Een levenswerk is dit proefschrift niet, maar de afgelopen jaren is het werk wel een belangrijk deel van het leven geweest. Met de komst van het AIO/OIO stelsel zijn levenswerken vrijwel niet meer mogelijk. Ik heb dit proefschrift nog volgens de 'oude' regeling kunnen realiseren.

Een proefschrift is, en zeker één op het vlak van de technische wetenschappen, niet het produkt van de promovendus alleen. Zonder de medewerking van vele anderen is het meestal niet eens mogelijk het voor een proefschrift noodzakelijke onderzoek uit te voeren. Ook bij dit onderzoek is dat het geval geweest; zonder de bijdrage van anderen was dit proefschrift nimmer gerealiseerd. Voor deze bijdrage wil ik dan ook een ieder bedanken. Hier zou ik het bij kunnen laten maar ik denk dat ik hen daarmee tekort doe, vandaar:

In de eerste plaats wil ik mijn woord van dank richten aan de beide promotoren Prof. Dr. Ir. Bert Speelman en Dr. Ir. Wim Huisman. Bert, je warme belangstelling voor het onderwerp fysische eigenschappen van kunstmest heeft voor mij in zekere zin als een katalysator gewerkt. Wim, jou ben ik veel dank verschuldigd voor de begeleiding in het eerste uur. Je klankbordfunctie is bij het ordenen van de grote hoeveelheid informatie van grote waarde geweest. Verder ben ik jullie beiden veel dank verschuldigd voor de begeleiding van het onderzoek en het met een kritische blik lezen en becommentariëren van de vele manuscripten.

In de tweede plaats ben ik veel dank verschuldigd aan Jan van Loo en Sam Blaauw. Jullie assistentie bij de uitvoering van het onderzoek is van groot belang geweest. De grote hoeveelheid programmeerwerk die voor dit onderzoek noodzakelijk is geweest, zou zonder jullie hulp niet gerealiseerd zijn. Sam, jou ben ik verder ook veel dank verschuldigd voor het leveren van de vele hand- en spandiensten die een experimenteel onderzoek met zich meebrengen. Je brede inzetbaarheid is van zeer veel waarde gebleken.

Voor de verdere technische ondersteuning van dit onderzoek hebben een aantal mensen zorg gedragen. Michel Govers heeft voor de ondersteuning op het gebied van de elektronica gezorgd en stond verder altijd klaar voor het oplossen van problemen en storingen en het meedenken bij het vinden van oplossingen. Geurt van de Scheur, jouw contacten op werkvloerniveau bij de TFDL hebben er voor gezorgd dat een groot aantal zaken op efficiënte wijze geregeld konden worden. Ook na je pensionering heb ik daarvan nog kunnen profiteren. Verder moet ik nog Jordan Charitoglou en Evert van Donselaar noemen, die ook vele hand- en spandiensten verricht hebben en Libbe Spoelstra die geassisteerd heeft bij het uitvoeren van een serie wrijvingsmetingen.

Aan dit onderzoek is ook een bijdrage geleverd door de studenten Guido Vroombout, Jørgen Audenaert, Alf Waatjes, Eric Wolthuis, Bauke Abma, Jan Willem Arts, Pieter Everts, Tamás Kutnyánszky en de gastmedewerkers Dr. Ferenc Kasza uit Hongarije en Dr. Mazhar Kara uit Turkije. Het resultaat van hun werk is direct of indirect in dit proefschrift verwerkt. Al dit werk is in ieder geval van groot belang geweest voor het totale onderzoek.

Dit onderzoek zou in het geheel niet mogelijk geweest zijn zonder de financiering van Vicon in Nieuw Vennep gedurende de eerste twee jaar en de Stichting voor de Technische Wetenschappen (STW) in Utrecht gedurende de laatste drie jaar. In dit kader moeten ook genoemd worden de leden van de gebruikerscommissie, de heren R. Breeuwer van TNO-TPD in Delft, H.H. Vissers en later B. Mijnders van Vicon/Greenland in Nieuw Vennep, J.C.A. Steevens van DSM Chemicals & Fertilizers in Sittard, W.H. Prins van het Nederlands Meststoffen Instituut (NMI) in Wageningen, P.S.A. van Helvert namens het transferpunt van de Landbouwuniversiteit en tot slot de heer F.C.H.D. van der Beemt van de STW, die dit onderzoek gedurende de laatste drie jaar gesupport hebben. Speciaal genoemd mag worden de heer Uittenbogaart, destijds werkzaam bij Vicon. Zijn inbreng in het periodieke overleg

heeft mede geleid tot de ontwikkeling van de Dopplersnelheidsmeter en heeft de weg geopend richting de STW.

Ook een woord van dank aan de overige medewerkers en collega's van de Vakgroep Agrotechniek en -fysica is op zijn plaats. Jullie belangstelling voor dit onderzoek en de, misschien niet met name genoemde, bijdrage hieraan in de vorm van gesprekken en adviezen is door mij ten zeerste op prijs gesteld.

Aan de tot stand koming van dit proefschrift is verder meegewerkt door Paul van Espelo die enige grafische werkzaamheden heeft verricht en ook de voorkant van dit proefschrift gerealiseerd heeft. De nog niet gepubliceerde hoofdstukken van dit proefschrift zijn op het engels gecorrigeerd door mevrouw Minderhoud-Jones.

Tot slot wil ik nog mijn ouders en mijn zus Joke bedanken voor de morele ondersteuning. Pa en ma, jullie hebben mijn studie in Wageningen, die de basis is geweest voor dit proefschrift, mogelijk gemaakt. Hiervoor wil ik jullie hartelijk bedanken. Ook een woord van dank richting mijn grootouders is op zijn plaats. De vele keren in het verleden dat ik bij jullie op de boerderij gelogeerd heb, hebben er op de één of andere manier voor gezorgd dat ik veel belangstelling heb gekregen voor de landbouw, en dan met name de landbouwtechniek. Dit is voor mij destijds de reden geweest in Wageningen aan de toenmalige Landbouwhogeschool Landbouwtechniek te gaan studeren.

Contents

Summary

The physical properties of fertilizer play an important role during the transport, storage, and spreading of fertilizer. In this thesis an analysis is made of the factors that influence the realization of a spread pattern. The most attention is given to those physical properties that affect the way the fertilizer is spread. The thesis consists of a general introduction (Chapter I) followed by five chapters in which the research is discussed. These five chapters consist of articles that have already been published in or are in review by the Journal of Agricultural Engineering Research. In the final chapter the findings are interpreted and the final conclusions are given.

Chapter II-A is a literature review in which the influence of the physical properties of fertilizer on the motion of particles in the fertilizer distributor and through the air is analyzed. The particle motion in the hopper and/or metering device is excluded from the discussion. The distributors considered are a spinning disc and a reciprocating spout fertilizer distributor.

Five important properties that affect particle motion are reviewed, namely particle size and particle size distribution, coefficient of friction, coefficient of restitution, aerodynamic resistance, and particle strength. The latter is indirectly related to particle motion. The coefficient of friction, the aerodynamic resistance, and the particle size and particle size distribution are most important since they have a large influence on the spread pattern. The influence of the coefficient of restitution is, on the contrary, not very clear. The particle strength is important in relation to the quality requirements that fertilizers have to meet.

Methods for determining the properties and the results of the different tests are discussed briefly. This is further discussed in Chapter II-B. The most important values for the different properties as found in the literature on the subject are presented in tables and figures. A comparison of the different results shows that there is a large variation within the values of a property. This variation can partly be explained by the measuring methods and procedures.

Chapter II-B discusses methods for measuring the coefficient of friction, the coefficient of restitution, the aerodynamic resistance coefficient, and the breaking force (particle strength) of fertilizers. These are the methods as described by different researchers in the literature. Measuring devices for the first four properties are developed and their characteristics are described. Measurements are executed with these devices with different fertilizers.

The results of the measurements show that the coefficient of friction is, to a minor extent, influenced by velocity relative to the friction surface layer. There is almost no influence of normal load but a significant influence of fertilizer type, friction surface layer and environmental conditions.

The coefficient of restitution measurements show a large effect of the impact surface and smaller effects of particle diameter and fertilizer type.

A large difference was found between two methods (elutriator and time distance relationship) for measuring the aerodynamic resistance coefficient. These differences can partly be explained. A new shape parameter for fertilizer particles (diameter coefficient) is introduced. This parameter is a measure for deviation from the perfect sphere of a fertilizer particle. It is, contrary to the aerodynamic resistance coefficient K, independent of the diameter of the particle and typical for the fertilizer type.

The breaking force measurements showed that the relationship between strength and particle size depended on the fertilizer type. Some fertilizers become stronger when the particle size increases and some other fertilizers become weaker when the size increases.

A new measuring technique has been developed for measuring the influence of physical properties and other factors on the motion of fertilizer particles in the fertilizer spreader. This method is discussed in Chapter III. Conventional methods, based on a row of collecting trays

transversely positioned with respect to the driving direction, cannot be used. With these methods it is not possible to make a distinction between the effects occurring in the spreader itself and the effects occurring in the air. The new method is based on the Doppler frequency shift of an ultrasonic beam. This frequency shift is proportional to the velocity of a passing particle. The velocity vector can be determined when a proper configuration of the ultrasonic transducers is chosen.

The possibility of obtaining an accurate measurement of particle size from the amplitudes of the received signals, have also been investigated. The results of the measurements showed that it is not possible with the present configuration. This is due to the non-flat frequency response of the ultrasonic transducers. This makes the amplitude not only dependent on the size of the particle but also on the velocity of the particle.

The new method is used to measure the influence of fertilizer properties and some adjustment parameters on the motion of fertilizer particles in the fertilizer spreader. Measurements are executed for a reciprocating spout and a spinning disc type fertilizer spreader.

Chapter IV-A discusses the motion of fertilizer particles in the spout of a reciprocating spout type fertilizer spreader. The analyzed factors are physical properties (coefficient of friction and coefficient of restitution) and the design of the spout (spout length, bow, spout angle) and the propulsion of the spout (angular velocity driving shaft, crank - connecting rod ratio). The influences of factors which possibly have an effect are studied with simulation experiments and real experiments (Doppler velocity meter). In the simulation models the motion of particles is considered as a mass flow instead of the motion of single particles.

The results of the simulations and the measurements show that it is difficult to model this type of spreader because of the oscillatory behaviour of the spout. Resulting values for velocities and durations of stay depend heavily on whether the motion of the particles along the spout is 'in phase' with the motion of the spout. The sorting-in process (from the hopper to the bowl at the beginning of the spout) plays a very important role.

This variety of behaviour also appears from the experiments with the Doppler velocity meter. The effect of fertilizer type and mass flow on the motion of particles is small and changes. One remarkable observation was that a lower oscillation velocity of the spout did not produce lower discharge velocities. The bow at the end of the spout results in a wider pattern in both the horizontal and vertical plane. A second effect of the bow is a downwards directed velocity for a certain number of particles. This fills the gap that would occur in the centre of the spread pattern.

Chapter IV-B discusses the motion of particles as affected by the physical properties (coefficient of friction) and the design of the disc (vane type, pitch angle of the vane and surface of the vane) for the spinning disc type fertilizer spreader. The influences of possible affecting factors are analyzed with simulation experiments and real experiments (Doppler velocity meter).

Comparison of the simulation results and the Doppler velocity meter results show quite a large difference. The simulation model, in combination with friction values obtained from the friction measurements, predicts a very clear effect for the coefficient of friction (realized by different surface linings of the vane). The measurements with the Doppler velocity meter do not show this effect clearly.

The measurement results further show that the increase of mass flow results in an increase of the discharge velocity. A consequence is that the particles leave the disc earlier and the spread pattern will be more concentrated in the centre. This effect is very clearly present for calcium ammonium nitrate but is hardly present for NPK.

A series of experiments to verify the findings of the Doppler velocity meter experiments for the spinning disc type spreader have been executed in a fertilizer spreader testing facility using a row of collecting trays. These measurements show good agreement between the results of both methods. Effects present or not present in the Doppler velocity meter experiments are also present or not present in the spreader testing facility measurements.

The most important conclusions that can be drawn from the research are:
(1) physical properties:
The most important physical properties of fertilizer in relation to fertilizer spreading are the particle size and the particle size distribution, the coefficient of friction, and the aerodynamic resistance (diameter coefficient). The mass flow has an effect on the particle motion for the spinning disc type spreader and some fertilizer types. This effect can be compensated in models by making the coefficient of friction mass flow dependent. The values of the coefficient of friction obtained with the rotating plate method are not sufficiently representative to be used in combination with the models used in this research to predict the effects of a change in fertilizer type or the surface lining (coefficient of friction).
(2) new measuring method:
  (a) Calculation of real spread patterns require an improved particle size measurement; The selection of the ultrasonic transducers is very important in this;
  (b) application of the method on a large scale requires a significant acceleration of the signal processing.

Samenvatting

Fysische eigenschappen van kunstmest spelen een belangrijke rol bij de opslag, transport en het strooien van de kunstmest. In dit proefschrift wordt gekeken naar de invloed van de eigenschappen van de kunstmest op de vorming van het strooibeeld. De meeste aandacht wordt besteed aan die fysische eigenschappen die het strooien van kunstmest beïnvloeden. Dit proefschrift bestaat uit een algemene inleiding (Hoofdstuk I) gevolgd door vijf hoofdstukken waarin het onderzoek dat uitgevoerd is besproken wordt. Deze vijf hoofdstukken bestaan uit artikelen die reeds gepubliceerd zijn of ter beoordeling ingediend zijn bij Journal of Agricultural Engineering Research, een van de belangrijkste gerefereerde tijdschriften op het vakgebied van de landbouwtechniek. Het proefschrift wordt afgesloten met de interpretatie van de resultaten en de uiteindelijke conclusies van het totale onderzoek.

In Hoofdstuk II-A worden de resultaten van een literatuuronderzoek besproken. In dit onderzoek is de belangrijkste literatuur in relatie tot de eigenschappen die de beweging van de kunstmestkorrels in het verdeelorgaan en door de lucht beïnvloeden, geanalyseerd. De in beschouwing genomen kunstmeststrooiers zijn de centrifugaalstrooier en de pendelstrooier. De beweging van de kunstmestkorrels in het doseerorgaan is buiten beschouwing gelaten.

De vijf belangrijkste fysische eigenschappen die nader zijn geanalyseerd zijn de deeltjesgrootte en deeltjesgrootteverdeling, de wrijvingscoëfficiënt, de elasticiteits- of restitutiecoëfficiënt, de luchtweerstand en de deeltjessterkte. De laatste is alleen indirect gerelateerd aan de deeltjesbeweging. Van deze vijf eigenschappen blijken de wrijvingscoëfficiënt, de deeltjesgrootte- en deeltjesgrootteverdeling, en de luchtweerstand de belangrijkste te zijn omdat deze een grote invloed blijken te hebben op de vorming van het uiteindelijke strooibeeld. De invloed van de restitutiecoëfficiënt is daarentegen niet erg duidelijk. De deeltjessterkte is van belang in verband met kwaliteitscriteria waaraan kunstmestkorrels moeten voldoen.

In dit hoofdstuk worden verder een aantal methoden voor het meten van de belangrijkste eigenschappen kort besproken. In Hoofdstuk II-B wordt hier verder op ingegaan. De belangrijkste waarden voor de verschillende eigenschappen zoals deze in de literatuur zijn aangetroffen, zijn weergegeven in diverse tabellen en figuren. Uit een vergelijking van de verschillende waarden blijkt dat er een grote variatie op kan treden in de resulterende waarde van een bepaalde eigenschap. Een deel van deze variatie kan toegeschreven worden aan verschillen ten aanzien van de meetmethode en de meetprocedure.

In Hoofdstuk II-B worden methodes voor het meten van de wrijvingscoëfficiënt, de restitutiecoëfficiënt, de luchtweerstandscoëfficiënt en de breekkracht (deeltjessterkte) van kunstmestkorrels besproken. Dit zijn methodes zoals deze door diverse onderzoekers in de literatuur zijn beschreven. Voor de eerste vier eigenschappen zijn ook eigen meetmethodes ontwikkeld. De karakteristieken hiervan worden ook besproken. Met deze ontwikkelde meetmethodes zijn metingen uitgevoerd met verschillende kunstmestsoorten.

Uit de resultaten blijkt dat de wrijvingscoëfficiënt in beperkte mate beïnvloed wordt door de relatieve snelheid (ten opzichte van het wrijvingsoppervlak). Het effect van de normaalbelasting blijkt niet significant te zijn. Wel significant zijn de invloed van de kunstmestsoort, het wrijvingsoppervlak en de omgevingscondities.

Uit de metingen ter bepaling van de restitutiecoëfficiënt blijkt dat het botsingsoppervlak een grote invloed heeft terwijl de diameter van de korrels en de kunstmestsoort een kleinere invloed blijken te hebben.

Uit de vergelijking van de meetresultaten van de bepaling van de luchtweerstandscoëfficiënt is gebleken dat er grote verschillen optreden tussen de waarden verkregen met de zweefsnelheidsmeter en de waarden verkregen uit valproeven. Deze verschillen kunnen slechts voor een gedeelte verklaard worden. Verder wordt een nieuwe vormparameter voor kunstmestkorrels (de diametercoëfficiënt) geïntroduceerd. Deze vormparameter is een maat

voor de afwijking van een korrel ten opzichte van de ideale bol. Deze vormparameter is, in tegenstelling tot de luchtweerstandscoëfficiënt K, diameter onafhankelijk en karakteristiek voor de soort.
Uit de metingen ter bepaling van de breeksterkte is naar voren gekomen dat de relatie tussen sterkte en deeltjesgrootte vooral afhankelijk is van de kunstmestsoort. Bij een aantal soorten blijken de korrels sterker te worden als de grootte toeneemt terwijl bij een aantal andere soorten de korrels juist zwakker worden als de grootte toeneemt.

Om de invloed van fysische eigenschappen en eventuele andere factoren op de beweging van kunstmestkorrels in of op het verdeelorgaan van de kunstmeststrooier te meten is een nieuwe meetmethode ontwikkeld. Deze methode wordt in Hoofdstuk III besproken. Conventionele methoden, gebaseerd op een rij opvangbakken transversaal ten opzichte van de rijrichting opgesteld, kunnen hiervoor niet gebruikt worden. Bij deze methoden kan er namelijk geen onderscheid meer gemaakt worden tussen effecten die in de strooier zelf zijn opgetreden en effecten die in de lucht zijn opgetreden.
De nieuwe meetmethode is gebaseerd op de Doppler frequentieverschuiving van een ultrasoon signaal. Deze frequentieverschuiving is evenredig met de snelheid van de passerende korrel. Door het kiezen van een juiste configuratie van de zender en de ontvangers is het mogelijk om van een passerende korrel de snelheidsvector te bepalen.
Ook onderzocht is of het mogelijk is de grootte van de passerende korrels voldoende nauwkeurig te bepalen op basis van de amplitude van de gereflecteerde signalen. Gebleken is dat dit met de huidige ultrasone transducenten niet met een voldoende grote nauwkeurigheid mogelijk is. Dit wordt vooral veroorzaakt door het niet vlak zijn van de frequentieresponsie van de ultrasone transducenten waardoor de amplitude van de ontvangen reflectiesignalen niet alleen afhangt van de grootte van de korrel maar ook zeer sterk van de snelheid van de korrel.

De nieuwe meetmethode is gebruikt voor het meten van de invloed van kunstmesteigenschappen en een aantal instelparameters op de beweging van kunstmestkorrels. Hierbij is gekeken naar de beweging van korrels in de pijp van een pendelstrooier en op de strooischijf van een centrifugaalstrooier.
In Hoofdstuk IV-A wordt het gedrag van kunstmestkorrels in de pijp van een pendelstrooier nader besproken. Gekeken is naar zowel de invloed van fysische eigenschappen (wrijvingscoëfficiënt en restitutiecoëfficiënt) als ontwerpparameters van de strooipijp (lengte, beugeltje, convergentie/divergentie hoek) en aandrijving van de strooipijp (hoeksnelheid aftakas, verhouding tussen crank en verbindingstang). De invloed van mogelijke beïnvloedende factoren is bestudeerd met behulp van simulaties en experimenten (Doppler snelheidsmeter).
Uit de simulatie experimenten blijkt dat het moeilijk is om dit kunstmeststrooiertype goed te modelleren vanwege het oscillerende gedrag van de strooipijp. Uiteindelijke waarden voor afwerpsnelheid en verblijftijd in de pijp blijken zeer sterk af te hangen van of de korrelmassa 'in fase' is met de beweging van de pijp. Een kleine verandering van initiële waarden kan resulteren is een grote verandering in afwerpsnelheid en verblijftijd. Het insorteerproces vanuit de voorraadbak in de kom onder het doseerorgaan en aan het begin van de strooipijp is in deze de belangrijkste factor die de beweging in de strooipijp bepaalt.
Ook in de experimenten met de Dopplersnelheidsmeter komt dit moeilijk voorspelbare gedrag naar voren. Invloeden van kunstmestsoort en massastroom op de beweging van kunstmestkorrels in de strooipijp blijken niet erg groot en bovendien redelijk variabel te zijn. Opmerkelijk was dat een lagere oscillatiesnelheid van de pijp niet resulteerde in lagere uittredesnelheden van de korrels. Het effect van het beugeltje aan het einde van de strooipijp is dat bij aanwezigheid hiervan het strooipatroon in zowel het verticale als het horizontale vlak breder wordt. Verder zorgt het beugeltje er voor dat een aanzienlijk deel van de korrels

een naar beneden gerichte snelheid krijgt. Hierdoor wordt het strooibeeld in het centrum opgevuld.

In Hoofdstuk IV-B wordt ingegaan op de beweging van kunstmestkorrels op de strooischijf van een centrifugaalstrooier. Hierbij is gekeken naar de invloed van de wrijvingscoëfficiënt (tussen kunstmestkorrel en schoep) en naar het ontwerp van de strooischijf (type schoep, hoek van de schoep ten opzichte van de radiaal en oppervlakte materiaal van de schoep). Ook voor dit type strooier zijn simulatie en reële experimenten met de Dopplersnelheidsmeter uitgevoerd.

Uit de vergelijking van de resultaten verkregen uit beide type experimenten blijkt dat er een zekere discrepantie bestaat tussen de resultaten. Op basis van de simulatie experimenten en de wrijvingscoëfficiënt metingen werd een verschil verwacht tussen de metingen waarbij de schoepen niet en wel bekleed waren met een nylon strip. In de meetresultaten blijken deze verschillen niet of nauwelijks aanwezig te zijn.

Verder blijkt uit de metingen dat een toename van de massastroom resulteert in hogere afwerpsnelheden. Een gevolg hiervan is ook dat de korrels eerder de strooischijf verlaten en het strooibeeld meer in het centrum geconcentreerd wordt. Dit effect blijkt bij kalkammonsalpeter vrij duidelijk aanwezig te zijn terwijl dit bij NPK niet of nauwelijks waarneembaar is.

In Hoofdstuk V wordt onder andere een serie metingen besproken die uitgevoerd zijn in een strooiertesthal. Dit ter controle van de meetresultaten van de Dopplersnelheidsmeter voor de centrifugaalstrooier. Uit de metingen blijkt dat er een grote overeenkomst is tussen de resultaten van beide series experimenten. Veel effecten die bij de Dopplersnelheidsmeter niet of wel aanwezig zijn blijken ook bij de metingen in de strooiertesthal niet of wel aanwezig te zijn.

De belangrijkste conclusies die uit het totale onderzoek getrokken kunnen worden zijn:

(1) fysische eigenschappen:
De belangrijkste fysische eigenschappen van kunstmest in relatie tot het strooien van kunstmest zijn de deeltjesgrootte en de deeltjesgrootteverdeling, de wrijvingscoëfficiënt, de luchtweerstand (diametercoëfficiënt).
De grootte van de massastroom blijkt bij de centrifugaalstrooier in combinatie met bepaalde kunstmestsoorten een effect te hebben op de deeltjesbeweging. Voor dit effect kan gecompenseerd worden door de waarde van de wrijvingscoëfficiënt massastroom afhankelijk te maken.
De waarden voor de wrijvingscoëfficiënt verkregen met de roterende plaat methode zijn niet voldoende representatief om op basis hiervan en de gehanteerde modellen een voorspelling te doen voor de te verwachten effecten bij verandering van kunstmest of oppervlakte bekleding (wrijvingscoëfficiënt) te voorspellen.

(2) Dopplersnelheidsmeter als nieuwe meetmethode:
   (a) voor het berekenen van echte strooibeelden moet de bepaling van de deeltjesgrootte verbeterd worden. De keuze van de ultrasone transducenten speelt hierbij een belangrijke rol;
   (b) toepassing op grotere schaal van de methode vereist dat het signaalverwerkingsgedeelte aanzienlijk versneld wordt.

Chapter I
General introduction

Handling and Spreading of Fertilizers
General Introduction

1. Rationale, objectives, and scope of the study

The first experiments with 'fertilizer' started in the 17th century. However, it was not until the 19th century that fertilizers were used on a larger scale in agriculture. The first phosphate fertilizers were ground bones treated with sulphuric acid. The first superphosphate production was started in 1842 after it was found that treatment of phosphate rock with sulphuric acid yielded an effective phosphate fertilizer. Early sources of potash were wood ashes, sugar beet wastes, and saltpetre. In Germany salt deposits were opened in 1860 and dominated the world market for 75 years. The first nitrogen fertilizers used in agriculture were guano, Chilean nitrate of soda, and various organic wastes. At the end of the 19th century ammonia, a by-product from coke ovens, became a growing source for fertilizer nitrogen, most as ammonium sulphate. In the beginning of the 20th century processes were introduced to fix the nitrogen in the air. The first ammonia plants were quite small and the ammonia was mainly used for the production of explosives or other industrial chemicals. The demand for fertilizer remained small since it was too expensive for agricultural use. Improvements in the ammonia production lowered costs and meant that the use as a fertilizer became economically attractive.

The first fertilizer spreaders were introduced at the end of the 19th century. Most of these spreaders were plate and flicker type spreaders. Spinning disc type fertilizer spreaders are described from this time on but their share of the market remained small until about 1950. The main reasons for this small share were the unpredictable and disappointing results which were due to the unknown influences of physical properties, wind and driving speed. Improvement of techniques and the availability of adjusting data made possible the introduction of the spinning disc type spreaders on a larger scale. In The Netherlands the first spinning disc type spreaders were more widely introduced after 1957 (Ref. 1). These spinning disc type spreaders had one disc. The spinning disc type spreaders with two discs were introduced many years later during the seventies. The reciprocating spout type fertilizer spreader was patented in 1954 (Ref. 2) and introduced in The Netherlands around 1958.

In the period 1950 to 1978 production and consumption of fertilizer showed an increase of more than 600% rising from $14.1 \cdot 10^6$ and $13.6 \cdot 10^6$ tons in 1950 to $105.4 \cdot 10^6$ and $99.4 \cdot 10^6$ tons in 1978 (Ref. 3). The use of N fertilizers in the 12 EC countries, Western Europe, the USA and the USSR is shown in *Fig. 1*. For most countries, the use of N fertilizers increases until about 1983 after which it decreases. There is clearly a high level of (N) fertilizer use in The Netherlands when Dutch consumption is compared to consumption in other countries. The use of the three main nutrients (N, P, and K) in The Netherlands since 1970 is given in *Fig. 2*. The amounts of P and K have some fluctuations. However, the amount of N shows an increase till 1984-1987. This increase is then followed by a decrease of almost 20% over the next three years.

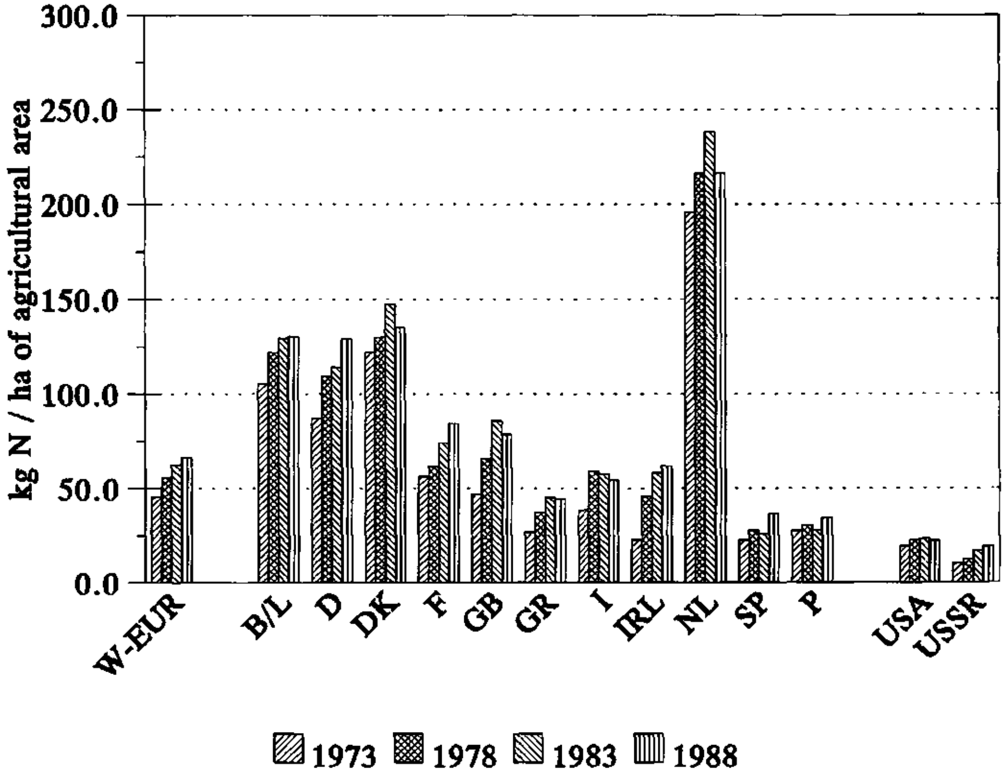

Fig. 1. The use of N fertilizer per ha of agricultural area in Western Europe, the 12 EC countries, the USA and the USSR. (Source: FAO Fertilizer Yearbook[4]).

Dutch agriculture has a surplus (the difference between input and output) of 850 million kg nitrogen or more than 400 kg per hectare agricultural land. This corresponds to 75% of the total amount of N that is supplied to agriculture by means of fertilizer, feed, and deposition[6]. For environmental reasons reduction in the use of fertilizer is required in order to prevent the leaching of nitrates in particular into the ground water. In The Netherlands the nitrate concentration of the ground water must be reduced to 50 mg/l by 1995. This requires a limitation of the amount of mineral N in the soil in the Autumn to 70 kg/ha.

The spoilage of fertilizer can also be reduced by use of special application techniques for specific situations. To prevent the spreading of fertilizer into ditches and water ways the one-side spreading technique has been developed. Advice has also been given on the introduction of fertilizer free field edges (0.5 m width) and the use of one side spreading techniques have been made obligatory. A demonstration of these techniques in The Netherlands in the summer of 1992, however, showed that the development of these techniques is not yet complete.

Another special application technique that is in development is site specific application of fertilizer. This must result in the right amount of fertilizer at the right place instead of a general mean for a whole field. The amount of fertilizer that is applied depends on the fertilizing strategy. Recent work of Finke[7] showed that site specific fertilizer level should not be based on a homogeneous nitrogen distribution for a field but on the soil specific response characteristics of a specific crop.

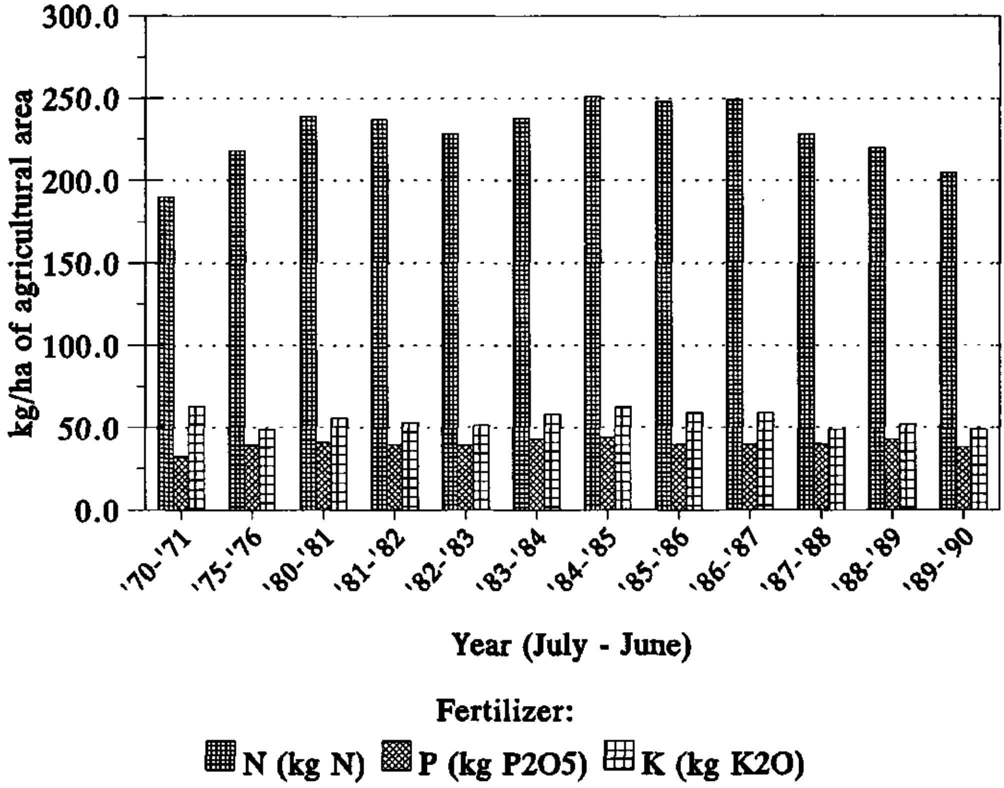

Fig. 2. Use of N, P, and K fertilizer in The Netherlands. (Source: LEI/CBS Landbouwcijfers[6]).

In the near future it will become obligatory to test the performance of fertilizer spreaders regularly. In The Netherlands operization is scheduled to come into effect in 1995 and in Sweden next year. Besides this regular test for fertilizer spreaders used by farmers, preparation is being made for a type approval for new fertilizer spreaders in The Netherlands and some other European countries.

The need for using less fertilizer means that the fertilizer must be applied in the right way and that fertilizer spoilage is brought to an absolute minimum. Optimal application of fertilizer, minimization of the spoilage of fertilizer, improvement of existing and development of possible new application techniques, all require a thorough knowledge of the processes and the factors that affect the spreading of fertilizer.

At the end of 1987, the Department of Agricultural Engineering and Physics of Wageningen Agricultural University started a research project on physical properties of fertilizer in relation to the spreading and handling of fertilizer. The main objective of the research project has been to obtain a better insight into the consecutive processes involved in fertilizer spreading. The research has been concentrated on the analysis, quantification, and modelling of the parameters that are relevant for the spreading and handling of fertilizer. The better insight should result in a better control and utilization of the factors that determine the spreading and handling properties of fertilizers. Then it should be possible to:

(a) attune fertilizer production possibilities and the demands and requirements of the user (i.e., the farmer) more finely;
(b) improve fertilizer efficiency by using smaller amounts of fertilizer but, at the same time, maintaining the financial yield because of improved application;
(c) reduce the application costs;
(d) keep losses in quality during product handling to a minimum.

Physical properties of fertilizer play an important role in this and are therefore accentuated.

The research project focuses on broadcasting fertilizer, especially on those factors that affect the motion of fertilizer particles in or on the distributor device and through the air. The production of fertilizer itself and the effects of a realized spread pattern on yield and quality of the produce are outside the scope of this study.

2. Justification for the study

Fertilizer spreading has been studied by many researchers in the past. In the sixties an important start to the analysis of the process of fertilizer spreading was made by Patterson and Reece[8], Inns and Reece[9] and Mennel and Reece[10]. Work was also carried out by Dobler and Flatow[11] and Brübach[12] in Germany at the end the sixties. At that time research was focused on the spinning disc type fertilizer spreader. A major start in analyzing of the reciprocating spout type fertilizer spreader and the influence of the physical properties of a fertilizer has been made by Speelman[2] in the 1970's.

A major disadvantage of all this research is that theory and its verification have been based on the single particle approach. In this approach each particle is considered to behave individually on the disc or in the spout. In practice, however, one has to deal with mass flows and to consider the influences of particle interactions. For these reasons, research based on mass flows on a scale similar to that found in practice is required.

Physical properties of fertilizers and their influence on the motion of fertilizer particles are studied because they are one of the most important factors that affect the spreading of fertilizers. This study requires measuring methods that result in representative values for these properties. Many researchers measured physical properties in the past but did not provide a good description of the measuring method used. This makes that the given values have limited validity. An analysis of the factors that can influence the value of physical properties is needed and the measuring methods have to reckon with or the influence of these effects must be excluded.

3. Organization of the research

The research has been divided into three main parts:

(a) measuring techniques for the physical properties of fertilizer;
(b) development of a measuring technique for measuring the motion of fertilizer particles discharged by a fertilizer spreader;
(c) measuring the effect of physical properties and adjustment parameters on the motion of particles in or on the distributor device.

The first part consisted of a review of relevant literature (Chapter II-A) and the development and application of measuring techniques for relevant physical properties of fertilizer (Chapter II-B).

The measuring technique for measuring the motion of particles discharged by a fertilizer spreader and the accompanying measuring setup are discussed in Chapter III. The measurement setup has been used to study two different fertilizer spreaders. The results obtained with a reciprocating spout type fertilizer spreader are discussed in Chapter IV-A and those with a spinning disc type fertilizer spreader in Chapter IV-B. The discussions of the measurement results are for both spreader types preceded by a theoretical analysis of the motion of particles for that specific spreader. The final interpretations of the findings and the conclusions are given in Chapter V.

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Chapter II

Physical properties of fertilizer

Chapter II-A

Physical properties of fertilizer in relation to particle motion

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REVIEW PAPER

Handling and Spreading of Fertilizers Part 1: Physical Properties of Fertilizer in Relation to Particle Motion

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The performance of fertilizer distributors and hence the evenness of the spread pattern depends to a large extent on the physical properties of the fertilizer. The influence of physical properties on the particle motion in the fertilizer distributor and through the air is discussed. Particle motion in the fertilizer distributor device is discussed for both spinning disc and reciprocating spout fertilizer distributors. The particle motion in the hopper and/or metering device is excluded from the discussion.

Five important properties which affect particle motion are reviewed, namely particle size and particle size distribution, coefficient of friction, coefficient of restitution, aerodynamic resistance, and particle strength. The latter is indirectly related to particle motion. The coefficient of friction, the aerodynamic resistance, and the particle size and particle size distribution are most important because they influence the spread pattern to a large extent. The influence of the coefficient of restitution is not very clear and the particle strength is important in relation to quality requirements that fertilizers have to meet.

Methods for determining the properties and the results of different tests are discussed; relevant data for the five properties reviewed are presented in tables or figures.

1. Introduction

This literature review is part of a research project on the physical properties of fertilizer. The objective of the research is to acquire fundamental information about the influence of physical properties on the distribution of fertilizer and to find an optimum between fertilizer properties and distributor design and/or operation. In this literature review an inventory of research done by others is given.

More than 20 physical properties of a fertilizer can be distinguished. The importance of a property depends on the 'process' the fertilizer is in at any moment. 'Processes' that can be distinguished are production, storage, transport, blending, particle motion (both in or on the distributor device and through the air), and plant response. Table 1 summarizes these 'processes' and the most relevant physical properties. The properties in relation to production, storage, transport, and blending are of interest for manufacturing, trade, and transport. The properties related to these processes are discussed extensively by Hignett.[1]

Properties affecting particle motion, and hence the distribution, are of interest to fertilizer distributor manufacturers and farmers and therefore also to manufacturers of fertilizer.

An even distribution, both longitudinally and transversely, is of concern to the farmer. The realization of such a distribution requires collective action of manufacturers of fertilizers and fertilizer distributors to obtain an optimum matching of fertilizers and fertilizer distributors.

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Notation

d_{50}	mass median diameter, m	x	position in X direction, m
$\bar{d}_m$	relative deviation from mean	x_d	position on the disc, m
$d_{m,max}$	maximum relative deviation from mean	x_{sp}	position along spout wall, m
		y	position in Y direction, m
d_p	particle diameter, m	z	position in Z direction, m
d_{pa}	projected particle diameter, m	C_D	drag coefficient
g	gravitational acceleration, m/s^2	F_b	breaking force, N
		F_f	friction force, N
k	volume coefficient	F_n	normal force, N
m_p	particle mass, kg	F_{st}	static particle strength, N/m^2
n_d	disc rotational speed, rev/s	K	aerodynamic resistance coefficient, m^{-1}
r_a	delivery point radius, m		
r_d	disc radius, m	R	irregularity number,
r_p	particle radius, m	Re	Reynolds number
r_{spe}	spout entrance radius, m	V_p	particle volume, m^3
t	time, s		
v	velocity, m/s	ε	coefficient of restitution
v_0	initial velocity, m/s	η_a	air dynamic viscosity, kg/m · s
v_p	particle velocity, m/s	μ	coefficient of friction
v_{p1}	particle velocity before impact, m/s	μ_d	coefficient of friction between fertilizer and disc
v_{p2}	particle velocity after impact, m/s	μ_v	coefficient of friction between fertilizer and vane
v_{pt}	particle terminal velocity, m/s	ρ_a	air density, kg/m^3
v_{px}	particle velocity X direction, m/s	ρ_p	particle density, kg/m^3
		ϕ_{sp}	spout oscillation angle, rad
v_{py}	particle velocity Y direction, m/s	ω_d	disc angular velocity, rad/s
v_{pz}	particle velocity Z direction, m/s		

2. Particle motion

Important physical properties appear from the analysis of the particle motion. Two main motions can be distinguished as follows.

(a) Particle motion in or on the fertilizer distributor device. Many types of fertilizer distributors exist, each with its own characteristics. They can be divided in two main types:

(1) Fertilizer distributors with variable bout width, e.g. a reciprocating spout fertilizer distributor and a spinning disc fertilizer distributor.

(2) Fertilizer distributors with fixed bout width, e.g. a pneumatic fertilizer distributor.

The motion inside the first mentioned distributor type will be discussed here.

(b) Particle motion through the air. The particle motion through the air is independent of the fertilizer distributor; only the initial conditions are determined by the distributor.

2.1. *Motion in or on the distributor device*

2.1.1. *Spinning disc fertilizer distributor*

Many researchers[2–8] have studied the motion of particles on the disc of a centrifugal distributor. Patterson and Reece[2] were among the first to describe this motion. Based on

Table 1
Processes in the use of fertilizer and important physical properties

Property	*Production*	*Storage*	*Transport*	*Blending*	*Particle motion in: Distributor*	*Air*	*Plant response*
Particle size	X	X	X	X	X	X	X
Particle size distribution	X	X	X	X	X	X	
Coefficient of friction					X		
Coefficient of restitution					X		
Particle strength		X	X		X		
Particle density		X		X		X	
Particle shape		X		X	X		
Aerodynamic resistance						X	
Chemical compatibility				X			
Salt index							X
Melting point	X						
Critical relative humidity		X	X	X			
Segregation properties		X	X				
Moisture content	X	X					
Dust and conditioner adherence		X	X				
Caking tendency		X					
Bulk density		X	X				
Angle of repose		X	X				

an equilibrium of forces acting on a particle, they derived the following differential equation for sliding particles (disc and vane) for centre-feed and straight radial vanes:

$$\frac{d^2x_d}{dt^2} + 2\mu_v\omega_d\frac{dx_d}{dt} - \omega_d^2x_d + \mu_d g = 0 \qquad (1)$$

Taking into consideration friction forces due to the Coriolis force, which can cause the transition from sliding to rolling along the vane, the following equation was derived for rolling particles:

$$\frac{d^2x_d}{dt^2} - (5/7)\omega_d^2x_d + (5/7)\mu_d g = 0 \qquad (2)$$

Inns and Reece[3] derived equations for the off-centre feed situation. Cunningham[4] developed a set of equations for straight-pitched and curved vanes. Cunningham and Chao[5] developed equations for composite vanes (a combination of straight and curved vanes). Brinsfield and Hummel[7] derived the equations for a centrifugal distributor using tubes instead of vanes to accelerate the fertilizer particles. Galili and Shteingauz[8] developed a model for the simulation of particle motion in a centrifugal spreader of general blade shape. This model was used for the design of a wide-swath vertical spreader for granular fertilizers.

In all these models and/or equations the coefficient of friction (μ) is one of the parameters needed to describe particle motion. In most models this is the only physical property that appears in the equations describing the particle motion on a disc. Inns and Reece[3] introduced a coefficient of restitution (ε) to describe the influence of bouncing of the particles on the disc on the particle motion in the case of off-centre feed.

2.1.2. *Reciprocating spout fertilizer distributor*

The principle of this distributor was first described by Coduille,[9] and the oscillation characteristic of the spout was first described by Cassella,[10] Pellizzi,[11] and Romanello.[12] Speelman[13] made a more extensive analysis of the oscillation characteristics and described the particle motion inside the spout. He derived equations for the two possible modes of particle motion along the spout wall, namely sliding (3) and rolling (4). In case of sliding, the motion can be described by:

$$\frac{d^2x_{sp}}{dt^2} - 2\mu\frac{d\phi_{sp}}{dt}\frac{dx_{sp}}{dt}p - \mu\frac{d^2\phi_{sp}}{dt^2}x_{sp}p - \left(\frac{d\phi_{sp}}{dt}\right)^2 x_{sp} - \ldots$$
$$\frac{d^2\phi_{sp}}{dt^2}r_{spe}p + \mu\left(\frac{d\phi_{sp}}{dt}\right)^2 r_{spe} = 0 \qquad (3)$$

and in the case of rolling, it can be described by:

$$\frac{d^2x_{sp}}{dt^2} - (5/7)\left(\frac{d^2\phi_{sp}}{dt^2}r_{spe}p + \left(\frac{d\phi_{sp}}{dt}\right)^2 x_{sp}\right) = 0 \qquad (4)$$

The variable p is a spout wall indicator ($p = -1$ for the left wall and $p = +1$ for the right wall). The coefficient of friction (μ) is only used in the sliding motion Eqn (3). The coefficient of restitution (ε) is important when the particles bounce against the spout wall. The influence of particle rotation has also to be considered. Adam[14] has described an impact model which takes the particle rotation into account. This model makes a distinction between stick impact and sliding impact. Stick impact results in an angle of reflection which is dependent on the initial particle rotation. Only the elastic properties of the impacting materials affect the process. Sliding impact results in an angle of reflection which does not depend on the initial particle rotation and both elastic and friction properties affect the process. Particle trajectories based on the Eqns (3) and (4) were verified by Speelman[13] with the aid of high-speed film and good agreement was obtained for certain values of μ and ε.

Bahasoean and Brouns[15] conducted a study to increase the spread width of a reciprocating spout fertilizer distributor. They developed a set of equations similar to those of Speelman.[13] However, they considered particle packets instead of single particles. A consequence of this approach is that the impact on the wall can be considered to be perfectly inelastic, i.e. the coefficient of restitution equals zero. Their computed throwing distances agreed with the throwing distances realized in some spread tests with polyethene particles.

2.2. *Motion through the air*

The motion of particles through the air has been described by many researchers.[4,6,8,15–22] Forces acting on a particle include buoyancy forces, gravity forces, inertial forces, and frictional forces (air resistance). The buoyancy forces can be neglected because the density of air (ρ_a) is much smaller than the density of the particle (ρ_p). The aerodynamic resistance coefficient K is a widely used parameter in equations that describe the particle through the air. This coefficient can be computed from:

$$K = (3/8)C_D\rho_a\frac{1}{\rho_p r_p} \qquad (5a)$$

or:

$$K = \frac{g}{v_{pt}^2} \tag{5b}$$

The value of the drag coefficient (C_D) depends on the Reynolds number (Re), where

$$\mathrm{Re} = \frac{2r_p v_p \rho_a}{\eta_a} \tag{6}$$

There is no exact analytical relation between Re and C_D. The corresponding values can be found with the aid of tables,[16] diagrams,[16,23] or approximate equations.[24] The value of K can be best computed by determining the terminal velocity of the particles. Eqn (5a) indicates the properties that influence the aerodynamic resistance coefficient, and which have to be considered when K is determined.

Consider a three dimensional cartesian space, with the positive Y axis in the direction opposite to the gravitational field. The XZ plane corresponds to the horizontal plane. The equation for the particle motion in the X direction is given by

$$\frac{d^2x}{dt^2} = -Kv_{px}\sqrt{(v_{px}^2 + v_{py}^2 + v_{pz}^2)} \tag{7a}$$

and in the Y direction by

$$\frac{d^2y}{dt^2} = -Kv_{py}\sqrt{(v_{px}^2 + v_{py}^2 + v_{pz}^2)} - g \tag{7b}$$

and in the Z direction by

$$\frac{d^2z}{dt^2} = -Kv_{pz}\sqrt{(v_{px}^2 + v_{py}^2 + v_{pz}^2)} \tag{7c}$$

3. Physical properties which affect particle motion

Four physical properties which directly affect particle motion are particle size, coefficient of friction, coefficient of restitution, and aerodynamic resistance. A fifth property, particle strength, will also be discussed because this property affects the particle size after mechanical treatment by the distributor device.

3.1. *Particle size and particle size distribution*

Particle size has a large influence on particle motion; especially during motion through the air (Section 2.2). The influence of particle size on this kind of motion will be discussed in Section 3.4. In this section the influence of particle size on the spread pattern will be discussed. This discussion is based on the mixture of particles, with a variation in size, in a mass flow and not on single particles. An important aspect of particle size distribution is the distribution required to obtain a good spread pattern.

Particle size and particle size distribution are determined with the aid of test sieves used under prescribed conditions (shaking intensity, amount of fertilizer and duration of shaking). Hignett[1] discusses several test sieve series used in the U.S.A. and Europe. A suitable range used by the fertilizer industry in The Netherlands is 1·0, 1·4, 1·7, 2·0, 2·36, 2·8, 3·35, 4·0, 4·75, and 5·6 mm aperture size (woven wire sieves, square apertures).

A measure for the particle size is the screen size and for the particle size distribution the d_{50} (mass median diameter). The screen size of a particle is equal to the aperture size of the sieve through which it could not pass (e.g. a particle with a screen size of 3·35 mm will actually have a diameter between 3·35 and 4·0 mm). The d_{50} of a sample corresponds to the diameter where the mass of the particles with a diameter smaller than that diameter equals 50% of the total mass of the sample.

Most researchers determined a lower limit for the particle size. An upper limit is often not given. An upper limit for most fertilizers used in agriculture is a diameter in the range 4·0–4·75 mm, which is mainly owing to the production process. The upper limit of the required particle size depends on the agronomic response. Large sized fertilizers may cause an uneven spatial distribution of the nutrients. This effect depends on the root system of the crop, the solubility of the fertilizer, the application time, and the transport of the nutrients in the soil. These problems are beyond the scope of this paper.

Hollmann[25] compared a series of fertilizers with different particle sizes. The distance projected increased by 100–150% when the particle size (screen size) increased from 0·3 to 3·0 mm. His experiments showed a small influence of the particle size variability on the distribution in the field. The distribution of different fertilizers in combination with some fertilizer distributors showed no difference when the particles had a size larger than 1·0 mm. A heterogeneous particle size distribution, with the restriction that particles smaller than 1·0 mm are removed, was considered to be an advantage. However, there must be some limits to the width of the distribution to prevent segregation during flow out of the hopper.

Hoffmeister *et al.*[26] studied the effect of particle size on segregation. Using a mixture of equal parts by weight of triple superphosphate (2·38–3·35 mm) and potassium chloride (1·4–2·0 mm), they found a rapid decrease of the smaller material beyond a projected distance of about 3 m. To prevent segregation, they recommended that all materials of a blend must have the same distribution of particles in the sieve ranges 1·2–2·0, 2·0–2·38, and 2·38–3·35 mm.

Heymann *et al.*[27] studied the influence of particle size distribution on the efficiency of the use of aircraft for fertilizer distribution. The working width (capacity) increased by about 1 m for every increase of the fraction particles > 2·0 mm by 10%, expressed by the regression curve $Y = 18{\cdot}98 + 0{\cdot}952\,X$, in which Y is the working width and X is the percentage of particles > 2·0 mm.

Porskamp[28] reported research on the influence of the particle size distribution on the distribution pattern of three different fertilizer distributors (twin disc, reciprocating spout, and pneumatic). Both standard products and narrow sieve ranges were used. Tests with the reciprocating spout fertilizer distributor showed that products with a larger variation in particle size resulted in a lower value of the irregularity number R as defined by Burema[29] than narrower sieve fractions with the same d_{50}. The irregularity number R includes both the mean deviation from the mean ($\bar{d}_m$, in percents of the mean) and the maximum deviation from the mean ($d_{m,max}$, also in percents of the mean). The irregularity number R can be computed with:

$$R = 100\sqrt[8]{\left(\frac{\bar{d}_m}{40}\right)^8 + \left(\frac{d_{m,max}}{20}\right)^8} \tag{8}$$

The value $R = 100$ corresponds to a coefficient of variation of about 20% for a tray width of 0·50 m (Speelman[13]).

Tests with a twin disc distributor showed that the value of R increased when d_{50} was larger than 3·5 mm. In general, the particle size distribution did not appear to have a clear effect on the distribution. Davies[30] compared a fine blend, a coarse blend and a standard blend of superphosphate. The maximum working width was 5·40 m for the coarse blend, 7·80 m for the fine blend and 9 m for the standard blend, based on a limit of the coefficient of variation of 10%.

Speelman[13] studied the influence of particle size and particle size distribution on the distribution of fertilizer with a reciprocating spout fertilizer distributor. He recommended that sieve fractions < 1·6 mm should be eliminated from fertilizers that have to be spread with a reciprocating spout distributor since this limits the working width. He found a positive effect of variation in particle size on the evenness of the compound transverse spread pattern in contrast to what is generally noticed for spinning disc types.

Tests with a stationary fertilizer distributor showed hardly any effect on both optimum and maximum working width. Tests with a moving fertilizer distributor showed a continuous increase of maximum working width with increased values of d_{50}.

Heege and Hellweg[31] studied the influence of particle size on segregation during the distribution of fertilizer. They determined for each collecting tray the absolute deviation of the mass fraction of a particle size from the mass fraction of that particle size in the fertilizer. The mean total deviation, equal to the mean of the absolute deviations of all collecting trays, decreased when a smaller sieve range was used. This mean was smaller for a twin disc distributor than for a reciprocating spout distributor with the same working width. The mean increased with the working width and decreased when the range of the particle size decreased. However, the mean total deviation does not reflect the evenness of the pattern but only reflects the segregation during distribution due to particle size.

Hellweg and Heege[32] discussed the influence of particle size of blend components on segregation. They composed blends out of two components. The difference in d_{50} of the two components increased up to 1 mm while the d_{50} of the blend itself remained constant at 2·55 mm. They determined the difference in coefficient of variation between the coefficient of variation of one of the components and coefficient of variation of the blend. The difference in coefficient of variation increased up to 8% for both a twin disc and a reciprocating spout fertilizer distributor when the difference in d_{50} increased by up to 0·75 mm. The pneumatic fertilizer distributor did not show a difference in coefficient of variation.

From their work, it can be concluded that the d_{50} of the components of a blend must be close to each other to prevent a considerable increase of the coefficient of variation of the spread pattern.

Pitt *et al.*[21] performed a simulation to study the influence of particle size variability on the variability in particle placement. A Weibull distribution was used to represent particle size variability. The simulation showed an increase in particle placement variability when the particle size variability increased. The coefficient of variation as measured purely by distance was much greater than that by weight (distances were biassed for particle weight). The variation in particle size had only a slight influence on lateral distribution of particles by a spinning disc distributor, although the mean particle size was still important. Particle size variability had the effect of slightly smoothing out the spread pattern. Particle size (d_{50}) and the characteristics of the machine itself, e.g. design of the vane, position of the vane on the disc, and position of the drop location on the disc, primarily determined the shape of the spread pattern.

Kämpfe *et al.*[33] determined the influence of the percentage fines (particles with $d_p < 1$ mm screen size) on the coefficient of variation of a spread pattern. The coefficient of variation increased with an increase of the percentage of fines, according to the equation $CV = 14{\cdot}1 + 0{\cdot}177X + 1{\cdot}56\,10^{-3}\,X^2$ (where X is the percentage of fines).

Broder and Balay[34] used prilled urea ($d_{50} = 1{\cdot}71$ mm) and two sizes of forestry grade urea ($d_{50} = 4{\cdot}7$ and $3{\cdot}94$ mm) to study the influence of particle size on spread width. The spread width increased from 10 to 20 m when the larger size urea was used. Adjustments of the drop location on the disc were necessary to realize optimum patterns. Some tests showed an influence of the particle size on the metering rates.

Achorn and Broder[35] studied the use of large size granular fertilizer in relation to blending of fertilizers with different particle size. The distribution pattern of blends is very sensitive for differences in particle size distribution due to segregation during flow in the hopper and metering device and ballistic segregation during motion through the air. Based on results with bulk blenders, the average particle diameter of each compound should be within 10% of the size of the other(s) to prevent segregation. This means that, when one of the components has a d_{50} of e.g. 3·0 mm, the d_{50} of the other components must be between 2·7 and 3·3 mm. They also discussed differences in spread width between smaller ($d_{50} = 1{\cdot}86$ mm) and larger sized urea ($d_{50} = 2{\cdot}31$ mm). The spread width increased from 10·5 m to 19·5 m. However, the differences are not only due to the particle size because of different production processes for the two ureas, namely prilling and granulation.

3.2. *Coefficient of friction*

The coefficient of friction between fertilizer and structural surface is included in some equations in Section 2. The friction force can be defined with the Coulomb's law of friction:

$$F_f = \mu F_n \tag{9}$$

This force acts in a plane containing the contact point (or points) and in such a manner as to resist relative motion of the contact surfaces.

A distinction can be made between the static and the dynamic friction force. The static friction force is the force necessary to start the motion of a body (fertilizer particle). Once the motion is started, the friction force usually decreases so that a smaller force is required to maintain motion. The friction existing between surfaces in relative motion is the kinetic friction force.

The coefficient of friction is determined by measuring the tangential force (friction force) required to maintain relative motion between the fertilizer (one particle or a mass) loaded with a mass, and a structural surface. The following laws apply to the friction force according to Mohsenin.[36]

(1) The friction force is directly proportional to the actual contact area.
(2) The friction force depends on the sliding velocity of the containing surfaces.
(3) The friction force depends on the nature of the materials in contact.
(4) The friction force is not dependent on the surface roughness, except at the extremes of very fine and rough surfaces.

3.2.1. *Measurement of coefficient of friction*

A very simple method of determining the coefficient of friction used by Inns and Reece[3] consists of an adjustable-angle plate. A group of fertilizer particles, stuck on adhesive tape to prevent rolling, were placed on the plate. The angle of the plate with the horizontal was increased until sliding just occurred (with slight tapping). The tangent of the angle of inclination is equal to the coefficient of friction.

Brubaker and Pos[37] used a rotating plate to determine the coefficient of friction of grains on different surfaces. Brübach[18] and Brübach and Göhlich[19] used a metal plate that moved over an open tray filled with fertilizer. The plate was loaded with a mass and the force required to move the plate was recorded. The friction force measured with this method takes into account the possibility that particles are rotating. Speelman[13] used a device, developed by Huisman,[38] that measured the friction force between a single particle and a structural surface during forward and backward motion with an almost constant velocity.

Data for the coefficient of friction, obtained by different researchers, are given in *Fig. 1.* The values of Galili and Shteingauz,[8] Burmistrova,[39] and Galili *et al.*[40] are much higher than those of Speelman[13] and Brübach and Göhlich.[19] However, exact comparisons cannot be made because the values are determined with different[13,19] or unknown[8,39,40] methods.

3.2.2. *Influence on particle motion*

In this discussion, a distinction will be made between the main distributor types, spinning disc and reciprocating spout.

3.2.2.1. *Spinning disc.* The influence of the coefficient of friction on the particle motion manifests itself in an influence on:

(a) the discharge velocity of the particles;
(b) the discharge angle (the angle between the normal and the tangential discharge velocity of the particle); and
(c) the discharge position (or duration of stay on the disc).

Many researchers[2,4–8,18,19,41] have theoretically studied the influence of friction on the above three factors; no practical research has been conducted.

The influence of the coefficient of friction on the three mentioned factors is summarized in *Fig. 2,* which is based on the numerical solution of Eqn (1). The discharge velocity

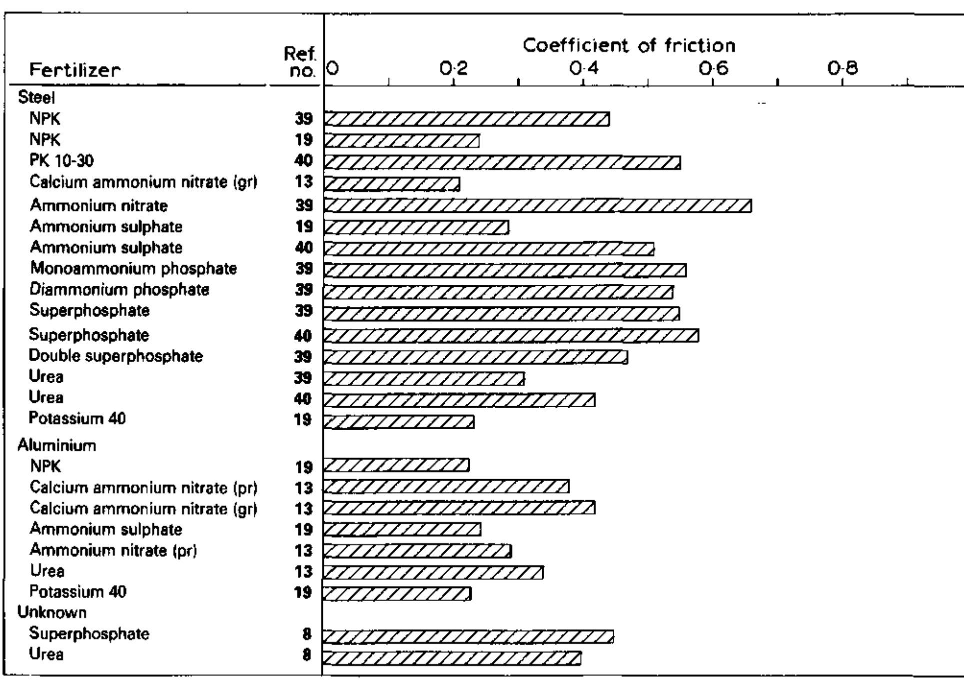

Fig. 1. Coefficient of friction between several fertilizers and structural surfaces: pr, prills; gr, granules

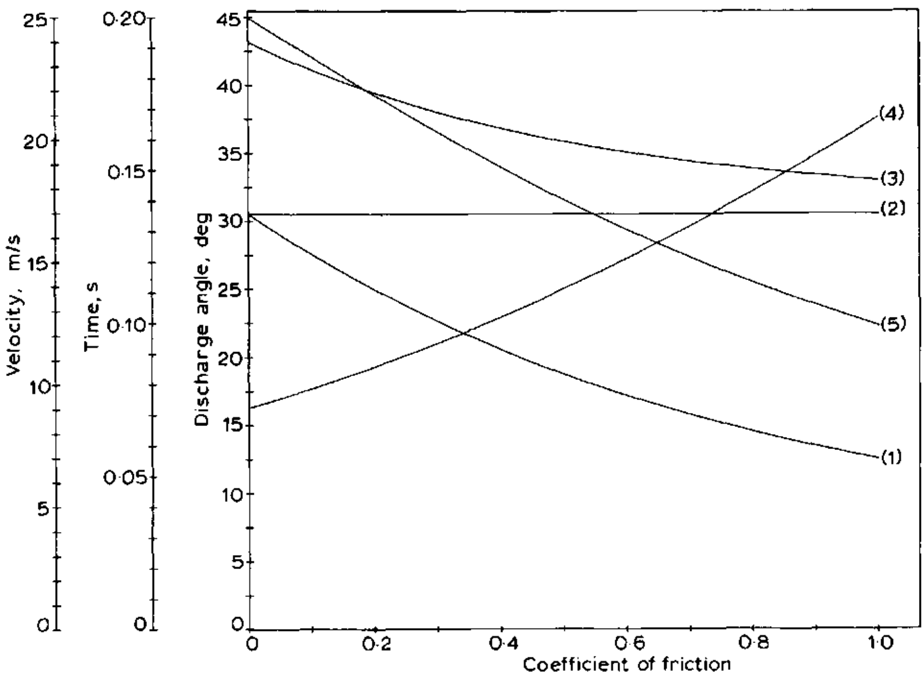

Fig. 2. Influence of the coefficient of friction between fertilizer and structural surface (vane or disc) on the motion of a particle on a spinning disc ($r_d = 0{\cdot}30\,m$; $n_d = 9\,rev/s$) where: (1), radial velocity: (2), tangential velocity: (3), discharge velocity: (4), duration of stay on the disc: (5), discharge angle (angle between the discharge velocity and the tangential velocity)

decreases and the duration of particle motion on the disc increases when the coefficient of friction increases.

Spinning disc fertilizer distributors with a single disc must have the facility to change the position of the delivery point to compensate for the influence of friction. This facility is recommended for fertilizer distributors with twin discs. Another possibility is the use of backward pitched vanes. Without one of these adjustments, asymmetric spread patterns may result when the fertilizer is changed. This adjustment is not strictly necessary for a distributor with twin discs because the discs compensate each other when they have an opposite rotation direction. Although the pattern remains symmetric, the coefficient of variation will change because the shape of the single transverse spread pattern will change.

Delitz[41] determined the amount of energy required to accelerate particles on a spinning disc. The amount of energy increased from 250/J kg for $\mu = 0$ to 260 J/kg for $\mu = 0{\cdot}14$ and decreased to 240 J/kg when μ increased further to 0·50. The amount first increases slightly because the increase of the friction energy (i.e. the energy required to overcome friction) is larger than the decrease of the kinetic energy (radial particle velocity decreases when μ increases (see *Fig. 2,* line 1)) and beyond $\mu = 0{\cdot}14$, the increase of friction energy is smaller than the decrease of the kinetic energy.

Brübach[18] studied the duration of particle motion on the disc in the case of pitched vanes. His research showed that the duration of particle stay was influenced only slightly by the coefficient of friction when the vanes were positioned backwards at the disc with an angle of about 17°.

Brinsfield and Hummel[7] theoretically analysed a distributor using tubes instead of vanes. Their model showed a decrease of the discharge velocity of about 10% when the coefficient of friction increased from 0·2 to 0·6. They found a much smaller discrepancy between theoretical and practical results when they considered both rolling and sliding of particles in the tube instead of only sliding.

The coefficient of friction was an independent variable in the research of Galili and Shteingauz[8] who used a distributor with a vertical disc. The friction influenced both the discharge velocity and the discharge angle. An increase in friction resulted in a decrease of discharge velocity and angle.

3.2.2.2. *Reciprocating spout.* The influence of the coefficient of friction on particle motion manifests itself for this type of distributor on:

(a) the duration of particle motion in the spout;
(b) the discharge velocity.

Speelman[13] reported attempts to obtain equations that express the relations between physical properties (independent variables) and the quality aspects of the distribution pattern (dependent variables). However, Speelman[13] concluded that, due to unavoidable imperfections in the set up of the experiments, a complete statistical treatment of the results was at least debatable. The coefficient of friction was one of the variables studied. Speelman[13] used the coefficient of friction in his model to describe particle motion inside the spout. Simulations showed an influence of friction on duration of motion in the spout and on the outlet velocities. However, this effect depended very strongly on the coefficient of restitution and, to a smaller extent, on the particle rotation. No conclusions could be drawn about the influence of friction on particle motion.

Kolsteren[42] studied the influence of friction and restitution on particle motion and found a small influence of friction on particle motion (see discussion in Section 3.3).

3.3. *Coefficient of restitution*

The coefficient of restitution (ε) is important when bouncing of particles is considered. Some researchers[3,13,42] have used the coefficient of restitution in their models to describe the motion of single particles. It is expected that these models are not valid when mass flows have to be considered.

The coefficient of restitution is obtained from:

$$\varepsilon = -v_{p2}/v_{p1} \tag{10}$$

The coefficient of restitution expresses the relative amount of impulse returned to the particle after impact on a surface.

3.3.1. *Measurement of coefficient of restitution*

Some methods to determine the coefficient of restitution are:

(1) measuring the time between subsequent impacts on a plate (Sharma and Bilanski[43]);
(2) photographing the particle trajectory during impact followed by an analysis of the trajectory (Hoedjes[44]);
(3) using a miscue device (Heijning and Meuleman[45]) which includes the influence of particle rotation and is based on equations derived by Adam.[14]

The value of the coefficient of restitution has been determined by some researchers; data are summarized in Table 2.

Table 2

Coefficient of restitution of some fertilizers (CAN = calcium ammonium nitrate; ld = low density; hd = high density)

Fertilizer	*Structural surface*	*Ref. no.*	*Coefficient of restitution*
Nitrochalk	Aluminium	3	0·17
Fison's 41	Aluminium	3	0·17
Ammonium sulphate	Aluminium	3	0·17
Urea	Unknown	8	0·40
Superphosphate	Unknown	8	0·04
Ammonium nitrate	Polyester	13	0·73
CAN (granules)	Polyester	13	0·46
CAN (prills; ld)	Polyester	13	0·46
CAN (prills; hd)	Polyester	13	0·57
Urea	Steel	42	0·35

3.3.2. *Influence on particle motion*

Inns and Reece[3] studied the motion on the disc for the off-centre feed situation. The effect of impacts becomes important when the off-centre distance increases. A particle dropped on the disc will make contact with a vane and will either:

(a) escape from the disc after the first or subsequent impacts with a velocity gained as a result of these impacts, or
(b) escape from the disc after the impacts have subsided and after having moved radially along the vane under influence of the vane.

Computations for one set of conditions ($\omega_d = 10\pi$ rad/s; $\mu = 0{\cdot}3$; $\varepsilon = 0{\cdot}3$; $r_d = 0{\cdot}30$ m $r_a = 0{\cdot}15$ m) showed that, due to the influence of the coefficient of restitution, the discharge velocities were 3–8% smaller than the values obtained by Patterson and Reece[2] and the discharge angle became 3–6% smaller. The size of the difference depended on the motion mode chosen (sliding only or rolling/sliding along the vane).

Speelman[13] studied the motion of particles inside the spout. The results of the simulation showed a small increase of outlet velocities when the coefficient of restitution increased. However, differences were small and also depended on the coefficient of friction and particle rotation.

Kolsteren[42] investigated the influence of the coefficient of restitution (and friction) on the performance of the reciprocating spout fertilizer distributor. He used high speed films to register the particle motion. The mass flow was very low (about $4{\cdot}10^{-3}$ kg/s), in order to be able to distinguish the trajectory of single particles. Different spout linings were used to obtain different physical properties. The dependent variables were the number of particles in a certain area, particle velocity and outlet angle. Kolsteren[42] found an influence of both restitution and friction on the three variables. However, differences were small and difficult to establish statistically. It must be kept in mind that the mass flow was much lower than occurs in practice.

3.4. *Aerodynamic resistance*

The aerodynamic resistance coefficient, K, is the only property influenced by the fertilizer that plays a role during particle motion through the air. Properties and factors which can influence K can be obtained from Eqn (5a). They are particle size (r_p), particle density (ρ_p), drag coefficient (C_D), and density of air (ρ_a).

The particle shape may influence the drag coefficient C_D and so the Reynolds number. Thus, fertilizers with the same particle diameter and density may still have a different aerodynamic resistance coefficient. Particle size and particle density are fertilizer dependent. Each sieve range will have its own terminal velocity; so there is a range of terminal velocities (and values of K) for every fertilizer.

The advantage of determining the terminal velocity is that all influencing factors are included. Determining K with Eqn (5a) can cause problems because there is no mathematical relation between C_D and Re. The relation depends on the type of flow. Three types of flow can be distinguished.[16] Namely, laminar flow ($Re \leq 1$), transitional flow ($1 < Re \leq 800$), and turbulent flow ($Re > 800$).

The value of the Reynolds number is influenced by the particle velocity, so C_D changes during particle motion. This influence is small when the Reynolds number lies in the turbulent area, because C_D remains approximately constant. The Reynolds number corresponding to the particle velocity during motion through the air is greater than 500 for most of the particle trajectory.

The terminal velocity can be determined with an elutriator. An elutriator consists of a vertical tube with a fan. The velocity of the air in the tube can be varied within a certain range. A range up to at least 15 m/s is necessary to measure terminal velocities of fertilizers. This device has been used by several researchers[18,19,46] to determine the terminal velocity of agricultural particulates, such as seeds, grains, and fertilizers.

Fig. 3 shows the terminal velocities of several fertilizers. The diameters of the particles used by Law and Collier[46] (lines 7 to 11 in *Fig. 3*) are estimated because they were not

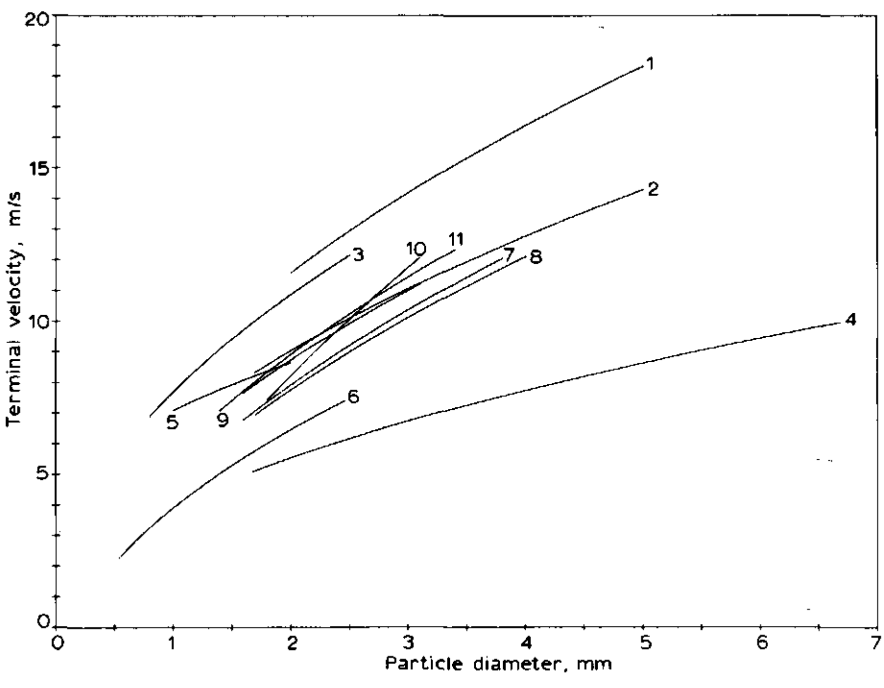

Fig. 3. Terminal velocities of several fertilizers. (1, NPK;[18,19] 2, potassium 40;[18,19] 3, ammonium sulphate;[18,19] 4, superphosphate;[8] 5, urea;[8] 6 Scott Fairway Fertilizer;[22] 7, granular 7–14–21;[46] 8, granular 6–12–12;[46] 9, prilled 34–0–0;[46] 10, prilled 16–16–16;[46] 11, prilled 18–9–18[46]

given. The given particle mass and an estimated particle density of 1500 kg/m^3 are used to estimate the diameter. This estimation of the density can cause a maximum error of 13% in the particle diameter within the density range of 1000–1800 kg/m^3.

The value of K is required in the differential equations (7a) to (7c) to compute the particle trajectory. A larger value of K (smaller particles) results in a smaller projected distance. *Fig. 4* shows some particle trajectories for different values of K and different initial horizontal velocities. The projected distances are based on an initial height of 0·75 m above the ground. *Fig. 4* shows that a low value of K is required to produce large projected distances for a given initial velocity. This can be achieved by having relatively large values of the particle density or particle radius or a relatively low value of C_D. Heywood[47] studied the influence of particle shape on aerodynamic resistance, though not for fertilizer particles. He introduced a volume coefficient, k, determined by the relationship:

$$V_p = kd_{pa}^3 \tag{11}$$

where d_{pa} is the diameter of the circle which has the same projected area as the particle when viewed in a direction perpendicular to the plane of greatest stability. The value of k is 0·524 ($\pi/6$) for a spherical particle and averages 0·25 to 0·2 for most mineral particles, though very flat particles may have values of 0·1 or less. A decrease of k results in a decrease in the terminal velocity of the particle and hence, in an increase of K, the aerodynamic resistance coefficient. The decrease in terminal velocity is about 50% when $k = 0{\cdot}2$, which results in K increasing by a factor of about 4. It is expected that fertilizer particles will show a similar effect.

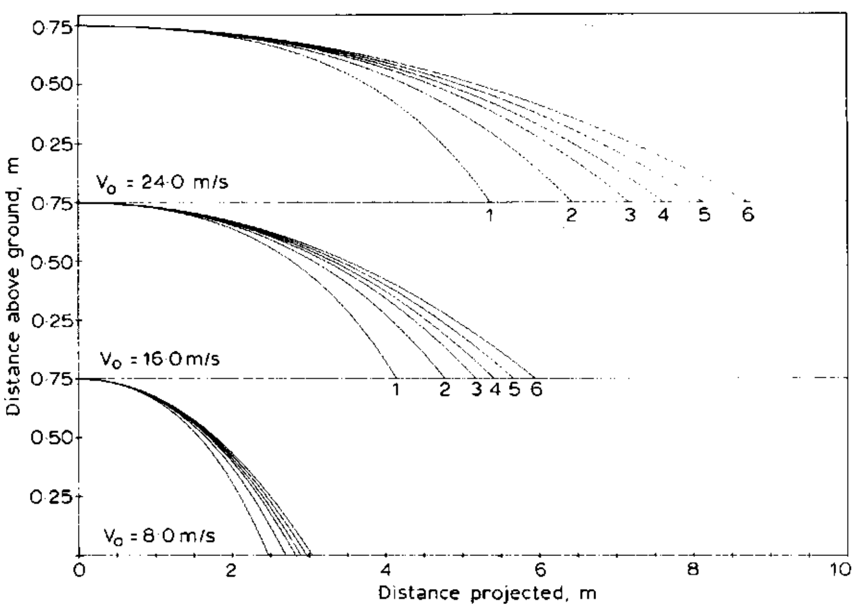

Fig. 4. Influence of initial horizontal velocity (v_0) and aerodynamic resistance coefficient (K) on the particle trajectory. (1) $K = 0{\cdot}250$; (2) $K = 0{\cdot}150$; (3) $K = 0{\cdot}100$; (4) $K = 0{\cdot}075$; (5) $K = 0{\cdot}050$; (6) $K = 0{\cdot}025$

3.5. *Particle strength*

The particle strength has an indirect effect on the particle motion. Particles that do not have sufficient strength will break during motion in the fertilizer distributor. This results in a change in the particle size distribution which in turn influences the particle motion.

Brübach[18] reviewed several methods for the determination of particle strength (each method resulted in a different strength). Three important kinds of particle strength can be identified. The first is the static particle strength which is the maximum load a particle is capable of sustaining, divided by the area of the cross-section of the particle. It is measured by loading a single particle by means of compression and recording the force when the particle fractures. The second is the dynamic particle strength and is the resistance of a particle to a dynamic load (e.g. impact). It is measured by determining the percentage degradation to fines. The fines are removed before the test. This test is known as the shatter-test. The third is the abrasion resistance which is the resistance of a particle to wear. This can cause degradation and dust formation. It is measured by rotating a sample of the fertilizer in a drum together with metal balls for a defined time at a defined rotational velocity. The percentage degradation to fines is a measure of the abrasion resistance.

3.5.1. *Static particle strength*

Fertilizer particles are not loaded statically during particle motion. However, static particle strength can be a good indication of overall particle strength. Most researchers have determined the maximum load a particle can sustain (breaking force).

Brübach[18] determined the static particle strength of several fertilizers for particles of different size. He found an increase of the breaking force with an increase of the particle diameter. The particle strength decreased with an increase in particle diameter. He derived, with the aid of regression analysis, Eqn (12a) for the maximum load a particle can sustain:

$$F_b = a d_p^b \tag{12a}$$

and Eqn (12b) for the particle strength:

$$F_{st} = (\pi/4) a d_p^{(b-2)}. \tag{12b}$$

The values for the regression coefficients a and b for the fertilizers are given in Table 3. These regression coefficients are based on d_p in mm and F_{st} in N/mm^2.

Brinschwitz and Hagemann[48] determined the breaking force by compressing particles with a constant velocity of the die. They found an increase in the breaking force of 140% when the velocity of the die decreased from 180 mm/min to 3 mm/min for ammonium phosphate granules. They also compared the strength of calcium ammonium nitrate particles from different manufacturers. The strongest particles had a breaking force that was 2·9 times that of the weakest particles.

Achorn and Broder[35] determined the breaking force of different makes of urea and

Table 3

Regression coefficients for different fertilizers (Brübach and Göhlich[19])

Fertilizer	*a*	*b*	*Particle size, mm*
NPK	16·8	1·78	0·9–4·5
Potassium 40 (large)	9·12	1·76	1·0–4·5
Ammonium sulphate	11·5	1·71	0·6–2·3

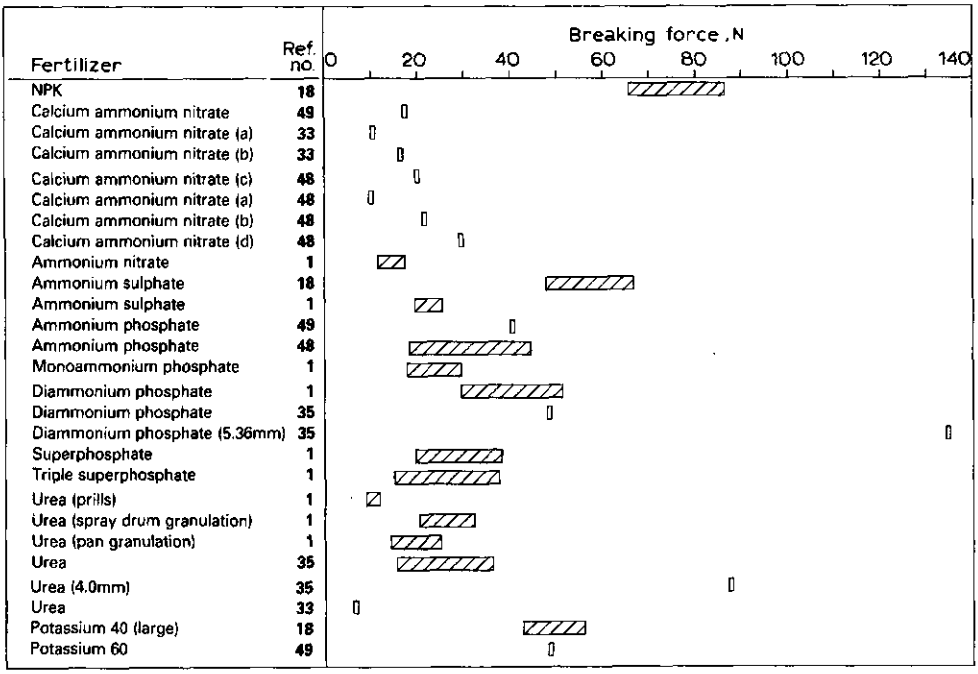

Fig. 5. Breaking forces for several fertilizers. The forces apply to one particle. Manufacturing locations: (a) GDR (Schwedt); (b) Austria (Linz); (c) GDR (Wolfen); (d) The Netherlands (Geleen)

diammonium phosphate. The strength of the urea depended not only on the particle size and the production process, but also on the formaldehyde content.

Hignett[1] suggested a minimum breaking force of at least 15 N per particle to prevent particle damage during handling. Data for several fertilizers, obtained from different researchers, are given in *Fig. 5.*

3.5.2. *Dynamic particle strength*

Fertilizer particles are loaded dynamically during motion in a fertilizer distributor. Some researchers[18,19,48] used the shatter test while others[33,49] determined the dynamic particle strength in relation to the rotational velocity of a spinning disc. Results of the different studies are given in Table 4 and *Fig. 6.*

Table 4

Dynamic particle strength of some fertilizers in relation to the number of revolutions of a spinning disc (fines are particles with $d_p < 1{\cdot}0$ mm; CAN is calcium ammonium nitrate).

Fertilizer	*Ref. no.*	*Breaking force (N)*	*Increase in % fines*	
			1000 *rev/min*	1350 *rev/min*
Urea	**33**	6·0	22	
CAN (Schwedt)	**33**	10·7	9–15	
CAN (Linz)	**33**	16·1	3–4	
CAN	**49**	17·9	8–10	18–28
Ammonium phosphate	**49**	40·7	8–11	11–16
Potassium 60	**49**	48·3	5–8	14–18

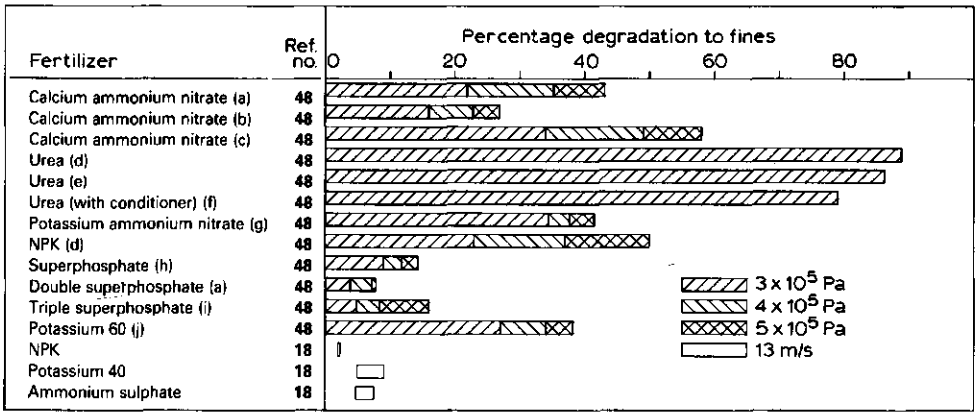

Fig. 6. Dynamic particle strength of several fertilizers determined by the shatter test with three constant pressures[48] *(shaded bars, values are cumulative) or constant velocity*[18] *(unshaded bar, indicating the range). Manufacturing locations: (a) Poland, (b) GDR (Wolfen), (c) GDR (Schwedt), (d) Poland, (e) Hungary (Pet), (f) GDR (Piesteritz), (g) GDR (Sondershausen), (h) Hungary (Szolnok), (i) USA, (j) GDR (KB Werra). (Note: The pressures correspond to a velocity, but these are not given by the researchers)*

The results of Brübach[18] and Brinschwitz and Hagemann[48] are difficult to compare because the impact velocities of the latter are not known. Only the used pressure to accelerate the particle is mentioned. However, the small strength of the urea particles is clearly shown in *Fig. 6.*

Kämpfe and Greiner[49] studied the influence of the rotational velocity (550–1350 rev/min) of the disc and the size of the mass flow on the particle damage. The mass flows corresponded to an application rate varying from 75 to 500 kg/ha. The particle damage of the calcium ammonium nitrate was much larger than that of the ammonium phosphate and potassium 60 particles, mainly because of the larger breaking force of the last two. However, the potassium 60 particles had a larger particle damage than the ammonium phosphate particles despite an almost equal breaking force. This was explained by a greater brittleness of the potassium 60 particles.

3.5.3. *Abrasion resistance*

Abrasion between fertilizers occurs during handling of fertilizer, due to friction between fertilizer particles and friction between fertilizer and the surfaces it comes in contact with. Good resistance to abrasion is necessary to prevent the formation of small particles ($d_p < 1{\cdot}0$ mm) because this fraction causes a large coefficient of variation in spreading.

The determination of abrasion resistance is very sensitive to the testing device, so data must be compared carefully. Data for abrasion resistance, obtained from some researchers,[1,18,19,48] are given in *Fig. 7.*

Fig. 7 shows clearly the large difference in the percentage degradation to fines of the different makes of urea. Both the production process and the use of additives and/or conditioners have a large influence on the strength. Calcium ammonium nitrate also shows the large differences between the different manufacturing locations. The calcium ammonium nitrate fertilizers from Eastern Europe show an especially high percentage degradation to fines.

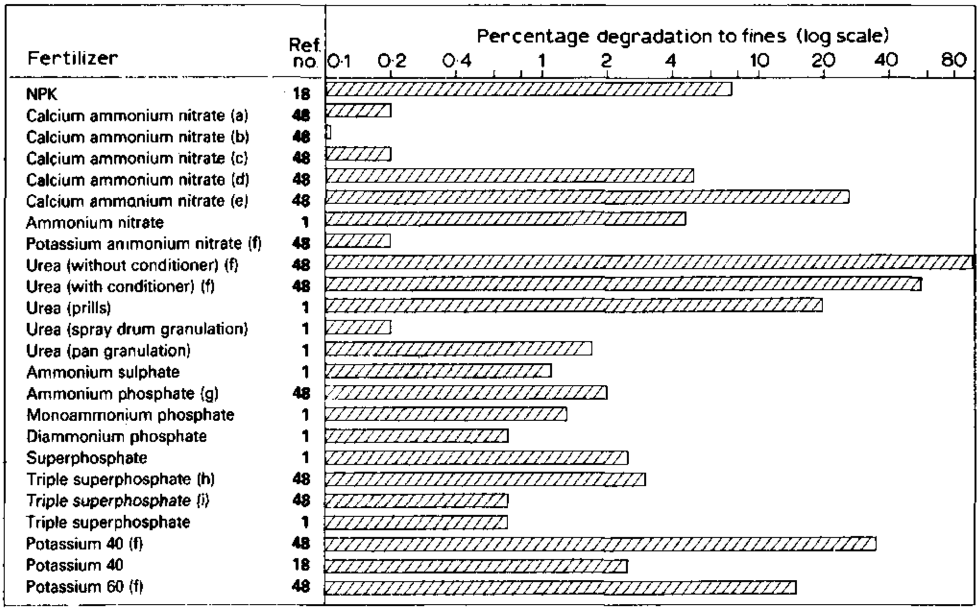

Fig. 7. Abrasion resistance for several fertilizers based on the rotating drum method. (Note that the scale for percentage degradation is logarithmic.) Manufacturing locations: (a) Austria (Linz, 1977), (b) Austria (Linz, 1979), (c) The Netherlands (Geleen, 1978), (d) GDR (Wolfen), (e) GDR (Schwedt), (f) GDR, (g) USSR, (h) USA (1977), (i) USA (1978)

4. Conclusions

Physical properties of fertilizer are very dependent on the production process and additives such as conditioners. Values assigned to physical properties depend on the method of determination and the conditions during the measurement.

4.1. *Particle size and particle size distribution*

Particle size and particle size distribution affect the distribution of the fertilizer but the influence on the spread pattern is difficult to establish. Some researchers suggest the use of narrow sieve ranges because large differences in diameter cause an increase of the coefficient of variation. Other researchers, however, have suggested the use of a wider range of particle diameters because this results in a more regular spread pattern than narrow sieve ranges. A reciprocating spout fertilizer distributor seems to require a wide sieve range of particles and a spinning disc fertilizer distributor a narrow range.

Particles with $d_p < 1{\cdot}0$ mm must be removed before spreading because these particles cause a higher coefficient of variation and a smaller working width. The fraction of particles with $d_p < 2{\cdot}0$ mm should be kept as small as possible because these particles tend to decrease the coefficient of variation.

The particle size range of the fertilizers used to compose a blend must be as close as possible and the average particle diameter of the fertilizers should not deviate more than 10% from each other.

4.2. *Coefficient of friction*

The influence of the coefficient of friction on the particle motion has been determined, usually theoretically. Empirical studies to verify the theoretical influences are rarely conducted and then, mostly with single particles.

In the models used, an increase in the coefficient of friction resulted in a smaller discharge velocity and a longer duration of stay on the disc and, hence, another discharge position.

Values of the coefficient of friction vary from 0·15 to more than 0·70. These values depend on the structural surface and can be influenced by additives, conditioners, and the production process.

More research is required to obtain more information about the influence of friction on particle motion, especially for the situation of mass flows. When this information is available, it will be possible to adjust the fertilizer distributor for a specific fertilizer.

4.3. *Coefficient of restitution*

Limited information about the influence of the coefficient of restitution on particle motion is available. It is debatable whether the coefficient of restitution affects the particle motion as described in the single particle motion studies when mass flows are used.

However, the coefficient of restitution remains important when mass flows are considered. Although the bouncing of particles is limited due to particle–particle interaction, it is expected that the bouncing will result in a lower value of the coefficient of friction than measured in friction studies. Research needs to be conducted to verify this assumption.

Values of the coefficient of restitution depend on the impact material and the structure of the fertilizer. The values range from 0·20 to 0·50 with some lower and higher extremes.

4.4. *Aerodynamic resistance*

The aerodynamic resistance coefficient, K, is influenced by several properties of the fertilizer. The advantage of K is that it combines all relevant properties and its value can be easily determined from the terminal velocity of the distinct sieve fractions. Only a few researchers have determined values of K for fertilizers. Particle size has the greatest influence because it varies over a wide range for a fertilizer. Particle density and drag coefficient vary over a much smaller range. The value of K varies for fertilizers in the range 0·025 to 0·25 m^{-1}.

4.5. *Particle strength*

Fertilizer particles must have sufficient strength to withstand several kinds of loads during the handling of the fertilizer. The methods used for measuring the different strength are not standardized which makes comparison of results difficult. It is recommended that the methods are standardized or, at least, a description is given of the method and the conditions when data for particle strength are discussed.

Particles should have a breaking force of at least 15 N. Not all fertilizers meet this requirement. Urea, in particular, shows a low particle strength. However, additives and production process can influence the particle strength to a large extent.

Static and dynamic particle strength are not directly related. The kind of fertilizer material determines the behaviour when the stress in the particles increases due to compression or impact. Particles with a high static strength can have a relatively low dynamic particle strength because of the characteristics of the fertilizer material. However, static particle strength can be an indication of dynamic particle strength.

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Chapter II-B
Physical properties of fertilizer, measuring methods and data

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Handling and Spreading of Fertilizers: Part 2, Physical Properties of Fertilizer, Measuring Methods and Data

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Handling and spreading of fertilizer is affected by the physical properties of the particles and so a knowledge of these properties is helpful in understanding fertilizer handling and use. Methods for measuring the coefficient of friction, the coefficient of restitution, the aerodynamic resistance coefficient, and the breaking force (particle strength) of fertilizers are discussed. Measuring devices for the four properties are developed and their characteristics are described. The results of experiments with these devices are presented.

The coefficient of friction is influenced to a minor extent by the velocity relative to the friction surface layer. There was almost no influence of normal load but a significant effect of fertilizer type, friction surface layer and environmental conditions. The coefficient of restitution measurements showed a large effect of the impact surface and smaller effects of particle diameter and fertilizer type. A large difference was found between two methods for measuring the aerodynamic resistance coefficient. A new shape parameter was introduced in this paper, as a parameter to determine the aerodynamic resistance of fertilizer particles. Coarser particles were shown to have a higher aerodynamic resistance coefficient than particles with a smooth surface texture. The breaking force measurements showed that the relationship between strength and particle size depended on the fertilizer type.

1. Introduction

The interest in physical properties of fertilizers and the methods for measuring them has increased during the last few years. One of the main reasons is that the uniformity of the spread pattern of fertilizers is becoming more and more important for both economic and environmental reasons to ensure that fertilizer is not applied unnecessarily. Physical properties of fertilizers are among the important factors that influence the uniformity of the spread pattern. Other important factors are the design, adjustment, and maintenance of the fertilizer spreader, and their mutual interactions. A second reason is that fertilizer manufacturers have to produce a high quality product for market reasons. The quality of fertilizers is usually expressed in terms of physical properties, such as particle size and particle size distribution, breaking force, porosity, and so on, and this requires the development of reliable measuring techniques.

Hofstee and Huisman[1] recently discussed much of the research related to the physical properties and the spreading of fertilizer. Large differences were found between the values of the physical properties obtained by different researchers for one and the same fertilizer type. Comparisons of results were difficult since many researchers did not mention or describe the method they used and the conditions under which they measured the physical properties.

At the Department of Agricultural Engineering and Physics of Wageningen Agricultural University a research project was started in 1987 to study the physical properties of fertilizer that are relevant to the spreading and handling of fertilizers. Part of this project is the measurement of physical properties of fertilizers.

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Notation

d_p	particle diameter, m	F_b	breaking force, N
d_{pg}	particle geometric mean diameter, m	F_f	friction force, N
d_{pm}	particle diameter according to model, m	F_N	normal force, N
d_{ps}	particle diameter equivalent sphere, m	I_1	impulse before impact, kgm/s
g	gravitational acceleration, m/s^2	I_2	impulse after impact, kgm/s
h_i	initial fall height, m	K	aerodynamic resistance coefficient, m^{-1}
k	volume coefficient	Re	Reynolds number
m_p	particle mass, kg	V_{pr}	particle real volume, m^3
q	diameter coefficient	V_{pa}	volume of a sphere with same projected area as a particle, m^3
r_p	particle radius, m	ε	coefficient of restitution
t	time, s	η_a	air dynamic viscosity, kg/m s
v_p	particle velocity, m/s	μ	coefficient of friction
v_{p1}	particle velocity before impact, m/s	ρ_a	air density, kg/m^3
v_{p2}	particle velocity after impact, m/s	ρ_p	particle density, kg/m^3
v_{pt}	particle terminal velocity, m/s	ρ_{pa}	particle apparent density, kg/m^3
A_c	particle cross-section area, m^2	ρ_{pt}	particle true density, kg/m^3
C_D	drag coefficient	σ	standard deviation
		σ_p	static particle strength, N/m^2
		ϕ_p	porosity
		ϕ_s	shape factor

This paper describes (in Section 2) the methods used and the devices developed to measure the coefficient of friction, the coefficient of restitution, the aerodynamic resistance coefficient, and the breaking force and static particle strength. These properties, together with particle size and particle size distribution were found to be important in relation to fertilizer spreading.[1] Particle size and particle size distribution are not discussed further in this paper since they are covered to a large extent by existing standards for wire screen sieves [ISO 565 (Ref. 2), ISO 3310 (Ref. 3), ASTM E11:87 (Ref. 4)]. The size of individual particles is obtained from their screen size. A more detailed measurement of the size of individual particles requires other techniques and goes beyond the scope of this research project. Measuring techniques and data for other physical properties of fertilizer such as caking tendency, moisture content, and bulk density are discussed by Hoffmeister[5] and Rutland[6]

The results of the measurements with the devices developed are presented in Section 3. The conclusions and some suggestions for improvement and standardization of measurement methods are given in Section 4.

2. Measuring methods

2.1. *Coefficient of friction*

2.1.1. *Theory*

The coefficient of friction is obtained by dividing the friction force (F_f) by the normal force (F_N):

$$\mu = F_f / F_N \tag{1}$$

2.1.2. *Review of friction measuring techniques*

The three main devices for measuring the coefficient of friction are an inclined plate,[7] a shear apparatus,[8–11] and a positively driven table or rotating plate.[10,12–14]

The inclined plate is a very simple device. Some particles are stuck together on a small piece of paper to prevent rolling. The angle of inclination is varied from zero degrees up to the point where the particles start to slide. The tangent of this angle is equal to the coefficient of friction.

The shear apparatus consists of a box which is open at the bottom. A sample of the material is placed in this box and loaded with a dead load. The box is placed on a surface (friction material) and moves relative to the surface while the force that is required for this motion is measured. The relative velocity is usually very low [less than 1 mm/s and sometimes less than 1 mm/min (Ref. 8)]. Brübach[11] used a similar principle but with a different device. A container was filled with fertilizer and a surface was placed on the fertilizer. The surface, loaded with a dead load, was pulled with a low velocity (1 mm/s) over the fertilizer surface and the force during the motion was recorded.

A rotating plate is made out of or covered with the friction material. A sample of the material is placed on the plate and the force that is required to keep the sample in the same position on the plate is equal to the friction force. Mohsenin[10] mentions use of a device with a rotating disc but no details are given. Brubaker and Pos[12] used a table with a friction surface on which the sample made a forward and backward motion. Speelman[13] used a device for his friction measurements that had been developed by Huisman[14] to measure the friction between pieces of straw. A friction surface, loaded with a dead load, was moved forwards and backwards over the fertilizer particle with a velocity of about 4 mm/s.

2.1.3. *Rotating plate measuring device*

From the previous discussion the conclusion can be drawn that the relative velocities of the devices are far lower than the values that occur in fertilizer spreaders (up to 25 m/s and sometimes higher). For this reason a new device was designed (*Fig. 1*).

The device consists of a circular flat aluminium plate, covered on one side with a layer of the friction material. The plate is driven by an electric motor and the rotational velocity can be varied continuously from almost zero to about 500 rev/min (52·4 rad/s) by means of a frequency controller. Two particles can be placed in the two conical holes (to prevent rolling) of the particle holder. The holder can be loaded by an interchangeable dead load and is connected to the force transducer. The particles were used only once.

The force transducer is connected to a strain gauge amplifier. The output signal of the amplifier is filtered (cut-off frequency 0·50 Hz, max flat filter type, and slope equal to 48 dB/octave) before sampling by a personal computer (PC) equipped with a data acquisition board. The filtering is necessary to eliminate the frequency equal to the rotational frequency of the plate. The PC with the data acquisition board also controls the rotational velocity of the plate.

The applied dead load was varied from 0·130 to 0·523 N. This load range corresponds with the range of the size of the Coriolis force that acts on a fertilizer particle that moves over a rotating disc along the vane of a spinning disc-type fertilizer spreader. The measurement started with the lowest possible velocity (about 1 m/s) and then the velocity was increased linearly in 8 s to the highest possible velocity (about 21 m/s).

Many factors can affect the coefficient of friction. The factors that were investigated are fertilizer type, normal load, relative velocity, and friction surface material. Moisture content can be an important factor also. Fertilizer particles start to absorb water when the relative humidity of the air is higher than the critical relative humidity (CRH) of the fertilizer. The CRH for most fertilizers has a value[5] higher than 60%. The conditions in

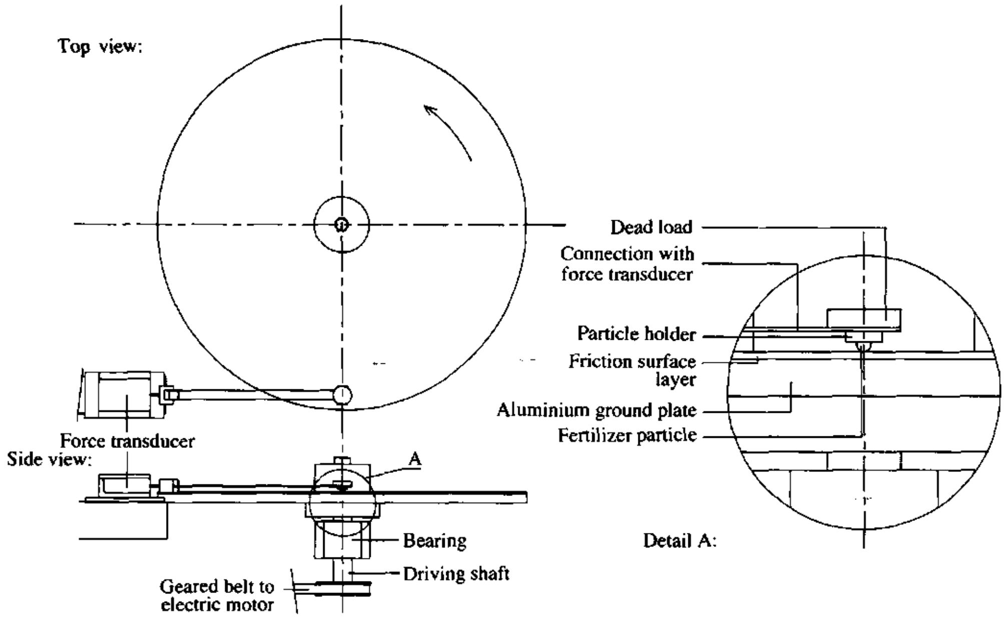

Fig. 1. Schematic drawing of the rotating plate friction measurement device

the laboratory were recorded during the measurements. The temperature varied between 20 and 22°C and the relative humidity varied between 55 and 65%. The fertilizers were stored in a closed container to minimize the contact with free air as much as possible. For these reasons it was assumed that the effect of moisture content is small.

2.2. *Coefficient of restitution*

2.2.1. *Theory*

The coefficient of restitution or elasticity of a fertilizer particle (ε) is equal to the ratio of the impulse after and before impact on a flat rigid surface and is, supposing that the particle mass does not change during impact, equal to the ratio of the particle velocity after and before impact:

$$\varepsilon = \frac{I_2}{I_1} = -\frac{m_p v_{p2}}{m_p v_{p1}} = -\frac{v_{p2}}{v_{p1}} \tag{2}$$

2.2.2. *Review of restitution measuring techniques*

Sharma and Bilanski[15] measured the time between two subsequent impacts on a metal plate. The coefficient of restitution is calculated from the measured time, the initial fall height (h_i) and the gravitational acceleration:

$$\varepsilon = -\frac{v_{p2}}{v_{p1}} = \frac{\frac{gt}{2}}{\sqrt{2gh_i}} \tag{3}$$

Air resistance and the effect of a rebound angle that deviates from the vertical (due to irregular particle shape) were neglected.

Hoedjes[16] used photography with stroboscopic lighting to register the trajectory of particles before and after impact and analysed the photographs afterwards. A disadvantage of this method is that it supposes that the impact takes place in a two-dimensional plane which is not necessarily true for irregular-shaped particles. Heyning and Meuleman[17] developed a device that also had the capacity to calculate the particle rotation after impact and the three-dimensional rebound velocity. The coefficient of restitution ε and particle rotation after impact were calculated from velocity, direction, and rotation before impact, and the type of impact (stick impact or sliding impact). Sliding impact also required knowledge of the coefficient of friction. The rebound direction was determined by an impact position measuring device. A considerable disadvantage of this device was that it was very sensitive to damage caused by impacting particles. A more rigid impact position measuring device has been developed but further investigations[18] have shown that it was not possible to obtain the required accuracy.

2.2.3. *Restitution measuring device*

The review of the measuring techniques showed that it is very difficult to develop a measuring device that also accounts for the rebound direction and particle rotation. The developed measuring device is simple and is based on the measurement of the velocity before and after impact on a flat rigid surface and does not account for rebound direction and particle rotation. A schematic drawing of the device is given in *Fig. 2.* The device consists of a pneumatic cylinder with a particle holder to accelerate the particle up to a velocity of about 11 m/s. The particle passes a light sensor which starts timer 1. Next, the particle passes through a small opening in a vertical plate and impacts on the impact surface. A vibration transducer registers this impact and timer 1 is halted and timer 2 is started. The particle rebounds from the impact surface and impacts on the vertical plate. A second vibration transducer on this plate registers the second impact and timer 2 is halted.

The velocity of the particle before and after impact can be calculated from the two times since the distances between the light sensor and the impact surface (253 mm) and the impact surface and the vertical plate (106 mm) are known. The computed particle velocities are the mean velocities over the measurement trajectory. Due to air resistance the actual velocity before impact will be slightly smaller ($<1{\cdot}0\%$) and the velocity after

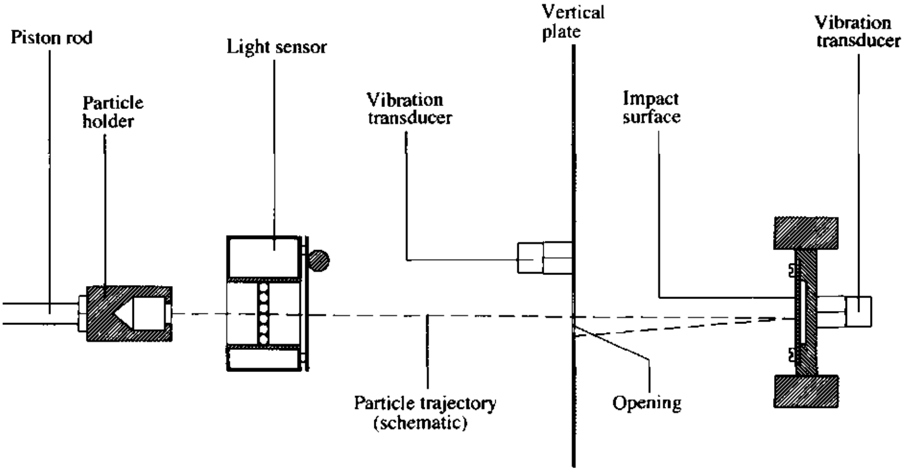

Fig. 2. Schematic drawing of the restitution measurement device

impact slightly higher (<1·0%) than the measured velocity. The resulting error in the coefficient of restitution is about 1% and can be neglected.

The measuring method requires that the rebound direction deviates at least 5° from the perpendicular impact direction because otherwise the particle will escape through the opening instead of impacting on the vertical plate. A rebound angle of 8° with the normal results in an underestimation of v_{p2} and ε of about 1%.

2.3. *Aerodynamic resistance coefficient*

2.3.1. *Theory*

The aerodynamic resistance coefficient, K, is an important parameter in the differential equations which describe the motion of particles through the air and is equal to:

$$K = \tfrac{3}{8} C_D \rho_a \frac{1}{\rho_p r_p} \tag{4}$$

Calculation of K according to Eqn (4) requires the knowledge of C_D, ρ_a, ρ_p, and r_p.

The drag coefficient, C_D, can be indirectly obtained from the Reynolds number, Re:

$$\mathrm{Re} = \frac{2 r_p v_p \rho_a}{\eta_a} \tag{5}$$

The relationship between Re and C_D is usually expressed by diagrams, tables, and/or approximating equations since there is no analytical relationship between the two numbers. The most important range of Re for this relationship is $0{\cdot}1 < \mathrm{Re} < 2000$ (transitional flow). For $\mathrm{Re} < 0{\cdot}1$ (laminar flow) the relationship between Re and C_D is $C_D = 24/\mathrm{Re}$ (Stokes law) and for $\mathrm{Re} > 2000$, C_D can be considered almost constant (0·44). Von Zabeltitz[19] derived several approximating equations for the transitional flow range. The best approximating equation yielded values which were about 3% higher than those found by Lapple.[20,21]

The air density, ρ_a, can be calculated[22] from air temperature, air pressure, and air relative humidity and varies between 1·15 and 1·25 kg/m^3 for normal atmospheric conditions. The air dynamic viscosity η_a, remains almost constant under normal atmospheric conditions and is equal to $18{\cdot}25 \times 10^{-6}$ kg/m s.

For the particle density, ρ_p, a distinction can be made between particle apparent density (ρ_{pa}) and particle true density (ρ_{pt}). The particle apparent density is the mass per unit volume of a material, excluding voids between particles but including the porous space and the particle true density is the mass per unit volume of a material, excluding voids between particles and all porous space. Measurements by a mercury pycnometer, as used by Tennessee Valley Authority,[5,6] result in the particle apparent density because the mercury is not able to fill up all the porous space and for this reason the porous space is considered to belong to the particle. Measurements by a dry pycnometer[23] or a plethysmometer[24,25] will result in the particle true density because the air in the porous space is also compressed and for this reason the porous space is considered not to be a part of the particle. The calculation of the volume of the particles with both latter methods is based on Boyle's law and presupposes isothermal compression of measurement and reference chamber. The porosity ϕ_p, of a fertilizer particle can be calculated from true and apparent density:

$$\phi_p = \frac{\rho_{pt} - \rho_{pa}}{\rho_{pt}} \tag{6}$$

Fertilizer particles are irregularly shaped particles and for this reason the particle diameter, d_p, is difficult to determine. The geometric mean diameter (d_{pg}) and the diameter of the equivalent sphere (d_{ps}) are regularly used diameters to compensate for this deviation. The geometric mean diameter, d_{pg}, is difficult to determine because this requires the measurement of the major, intermediate, and the minor particle diameter. The diameter of the equivalent sphere is easier to determine since it ony requires particle density and particle mass. Another possibility to compensate for the deviation is the use of a correction factor. Heywood[26] introduced a volume coefficient, k, to correct the particle diameter of irregularly shaped particles. This coefficient is equal to:

$$k = \frac{\pi}{6} \frac{V_{pr}}{V_{pa}} \tag{7}$$

where V_{pr} is the real volume of the particle and V_{pa} is the volume of the sphere that has the same projected area as the particle when viewed in a direction perpendicular to the plane of greatest stability. Keck and Goss[27] introduced the shape factor, ϕ_s, equal to the ratio of the geometric mean diameter to the diameter of the equivalent sphere.

The aerodynamic resistance coefficient can also be computed from the terminal velocity of the particle, which is the velocity the particle reaches when it falls from an infinite height in stagnant air.

$$K = \frac{g}{v_{pt}^2} \tag{8}$$

A problem that arises with this method are the large distances the particle have to fall before they reach their terminal velocity. A velocity that deviates less than 1% from the terminal velocity requires, for fertilizer particles, a fall height varying from about 4 m ($d_p = 1{\cdot}0$ mm and $\rho_p = 1000\ \mathrm{kg/m^3}$) to more than 55 m ($d_p = 5{\cdot}0$ mm and $\rho_p = 2000\ \mathrm{kg/m^3}$).

2.3.2. *Review of aerodynamic resistance measuring techniques*

2.3.2.1. *Time versus distance relationship.* Keck and Goss[27] were among the first who tried to measure the aerodynamic resistance and the terminal velocity of agronomic seeds in free fall. They used drop tubes varying in height from about 0·60 m to about 9 m. The fall time of rose clover, alfalfa, and nylon spheres (3·175 mm diameter) was measured. The latter were used for comparison with the classical data for spheres. They used an approximation rule to compute the velocity for each drop. The particle terminal velocity was calculated by substitution of Eqn (4) into Eqn (8) and with C_D taken to be 0·44, which is the value that corresponds to a sphere in the turbulent region.

Another implementation of the time versus distance relationship method is based on the solution of the differential equation that describes the motion of a particle in stagnant air. Mohsenin[10] gives an analytical solution of this equation for the relationship between distance s and time t. This time versus distance relationship is based on the assumption that the value of C_D or K is constant and known during the fall of the particle. The error due to this assumption depends on the duration of the movement in the laminar and transitional flow range and the goodness of the estimation of C_D. Small particles with a relative low density will have a Reynolds number corresponding to the terminal velocity which lies in the transition area. For this reason, the estimated value of v_{pt} will not be correct. This can also provide an explanation for the differences Keck and Goss[27] found between experimental and theoretical data.

Fig. 3 shows the fall trajectories of particles for both $C_D = 0.44$ and $C_D = \mathrm{f(Re)}$. The difference between the two becomes smaller when the particle size increases. The difference also decreases when the particle density increases (not shown in the figure).

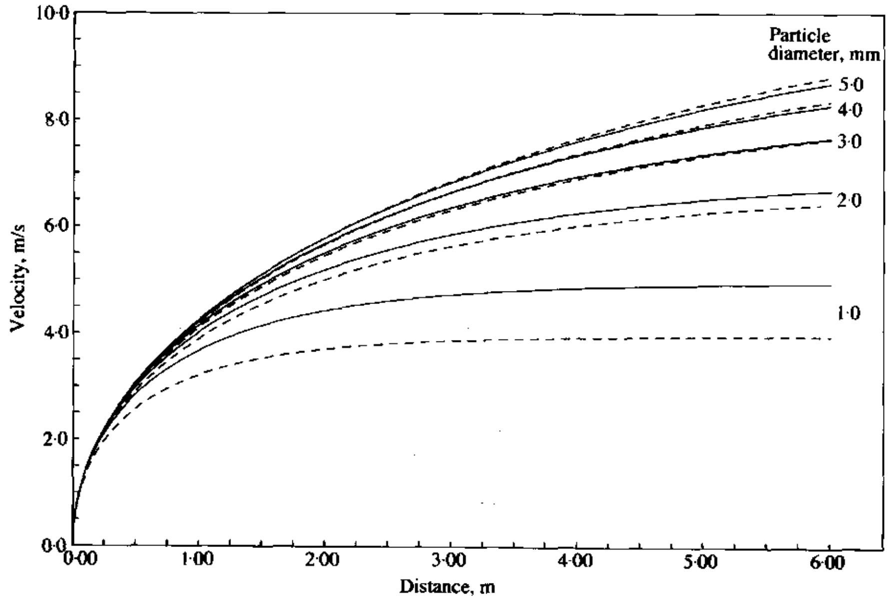

Fig. 3. Fall trajectories of fertilizer particles with five different diameters and a density of 1000 kg/m^3 *and for two approximations of the relationship between Re and* C_D. (——, $C_D = 0{\cdot}44$; – – – –, $C_D = f(Re)$)

Experimental data can be obtained by measuring a time versus distance relationship of falling particles. The measured times are plotted against the distances and, if the height of fall is sufficient for the particle to reach the terminal velocity, the time versus distance curve becomes linear. The slope of this curve can be used to determine the terminal velocity. Bilanski *et al.*[28] computed the aerodynamic properties of seed grains using this method.

2.3.2.2. *Elutriator.* An elutriator consists of a vertical tube in which an airflow is supplied by a fan. The air velocity in the tube is measured with a pitot tube and a micromanometer. The air velocity is not constant over the cross-section of the tube but decreases in the direction of the wall according to a one-seventh power.[29]

To determine the suspension velocity of grains and straw pieces Gorial and O'Callaghan[23] used a tube with a rectangular cross-section and two diverging walls (2°). A centrifugal fan delivered the air through a flow straightener section, which consisted of two layers of fine wire mesh above and below a honeycomb grid.

Brübach[11] used a vertical plexiglas tube to measure the terminal velocity of fertilizer particles. The air was supplied at the bottom side and the air velocity was regulated with a reduction valve.

Law and Collier[30] used a blower, a plenum chamber and a vertical tube. The air velocity was regulated by an adjustable restrictor mounted onto the inlet of the blower. The length/diameter ratio of the tube was six and this allowed the formation of a relatively flat velocity profile in the upper test zone. A 0·60 mm (30 mesh) stainless steel screen separated the test channel from the plenum and supported the particles until the test began.

2.3.3. *Measurement methods*

2.3.3.1. *Time versus distance relationship.* The terminal velocity of a particle can be derived from the time versus distance relationship.[10] This method requires the analytical or numerical solution, of the differential equation that describes the motion of a falling particle in air:

$$\frac{d^2y}{dt^2} = Kv_p^2 - g \tag{9}$$

A computer model, based on the numerical solution of the differential equation, has been developed to compute the time versus distance relationship of falling particles. The model uses the Re versus C_D relationship according to Lapple[20,21] and recalculates the value of K after each integration step. The model is used in conjunction with measurements in which the particles fall over a certain distance. The measurement method consists of a metering device (a slow rotating plate with holes), a photo-electric cell as timer-starter, a striking plate with a piezo element as timer-stopper and an electronic timer/counter connected to a PC to collect the time data.

The calculation of the fall time by the model is divided into two steps since only time data of the second step is available. The first step corresponds with the trajectory from the initial drop off point to the trigger point of the light sensor and the second step corresponds with the trajectory from the trigger point to the striking plate. The length of the two trajectories depend slightly on the particle size because a larger particle will trigger the light sensor earlier than a smaller particle. The length of the first trajectory varies between 64·6 mm (1·00 mm particle diameter) and 63·9 mm (5·60 mm particle

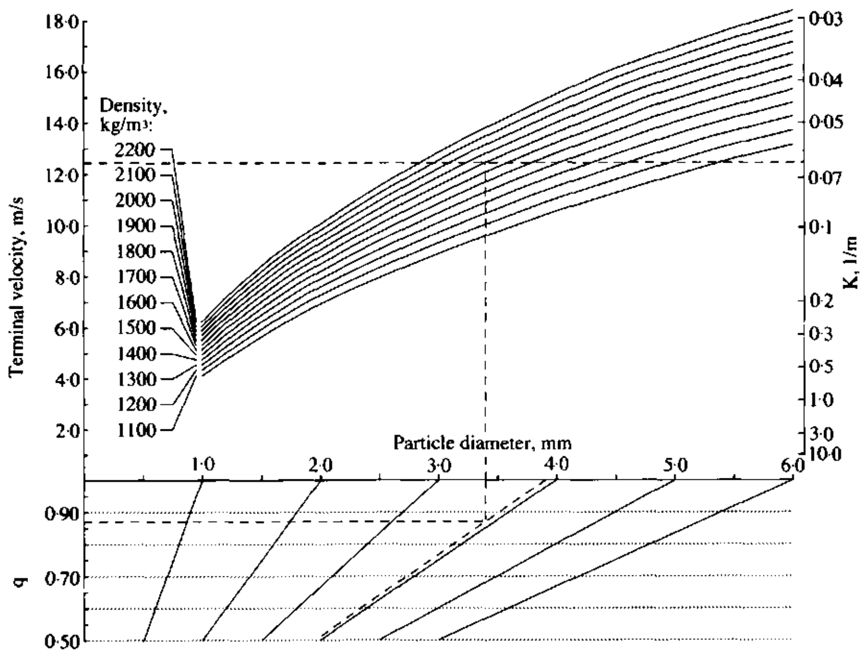

Fig. 4. Nomograph for the calculation of the particle terminal velocity and the aerodynamic resistance coefficient from the particle density, particle diameter coefficient, and the diameter of the equivalent sphere

diameter). The length of the second trajectory is equal to the total trajectory (3720 mm) minus the length of the first trajectory. The computer program calculates by iteration the diameter of a particle that has a fall time equal to the measured fall time. This diameter (d_{pm}) will usually be smaller than d_{ps} due to the irregular shape of the fertilizer particle. The ratio of these two diameters is the diameter coefficient q ($=d_{pm}/d_{ps}$) and is a measure for the shape of the particle and can be considered to be a physical property of a fertilizer. The diameter coefficient together with the diameter of the equivalent sphere and the particle density can be used to calculate the particle terminal velocity and the aerodynamic resistance coefficient from *Fig. 4*.

For example, (dashed lines in *Fig. 4*) a fertilizer particle with an equivalent sphere diameter, $d_{ps} = 3{\cdot}91$ mm, diameter coefficient $q = 0{\cdot}87$, and density $\rho_p = 1800\,kg/m^3$ will have a terminal velocity, v_{pt}, equal to about 12·5 m/s and an aerodynamic resistance coefficient, K, equal to about 0·061.

2.3.3.2. *Elutriator.* The elutriator used in the experiments has a vertical tube with an inner diameter of 0·29 m and a length of 1·00 m. The tube is mounted on a large axial fan and the air velocity in the tube can be regulated by varying the size of the air inlet. A screen is mounted half way up the tube to support the particles before the test starts. A calibrated pitot-static tube, mounted about 0·05 m above the screen, is used to determine the air velocity. The pitot tube is connected to a difference pressure transducer and the output signal is amplified by a strain gauge amplifier. The amplifier is connected to a PC equipped with a data-acquisition board.

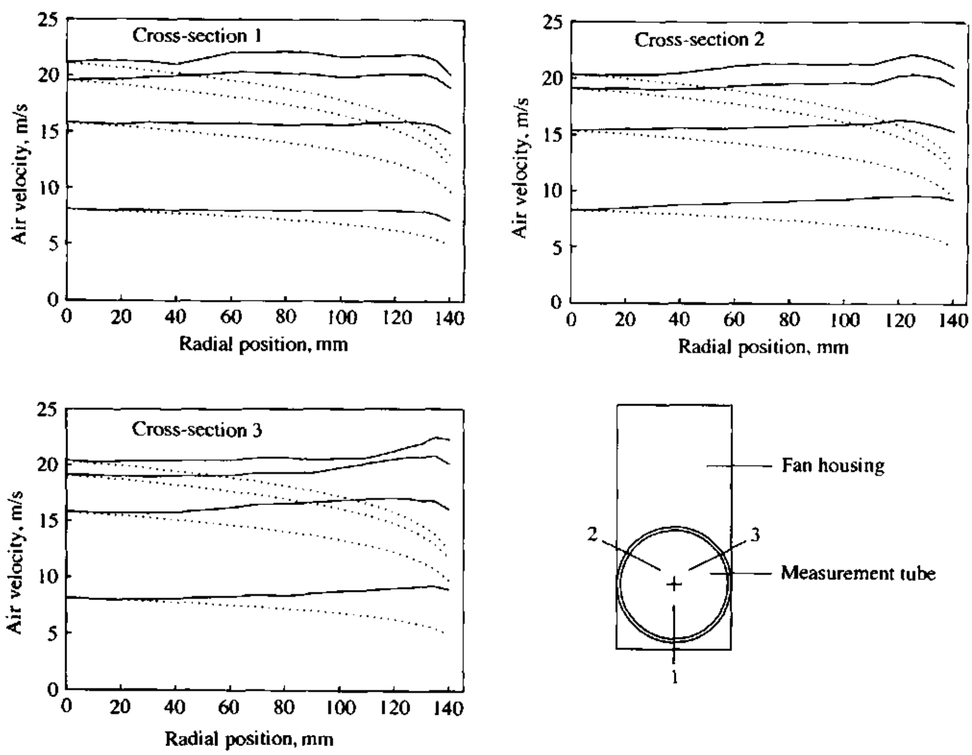

Fig. 5. Velocity profile of three cross-sections of the elutriator for four sizes of the air inlet. (——, measured velocity profile; · · · · ·, calculated velocity profile)

The air velocity over the cross-section of the tube (up to 5 mm from the wall) has been measured for four sizes of the air inlet and three cross-sections. The results are given in *Fig. 5* and show that the measured velocity profile is flatter than the predicted air velocity according to the one-seventh power law. It is expected that the air velocity will fall off within about 5 mm from the wall.

A sample of about 200 particles (same screen size of a fertilizer) was placed on the screen and for each sample the air velocity was determined both when particles started to float and when almost all particles were floating. This was repeated five times for each sample.

2.4. *Breaking force and particle strength*

2.4.1. *Theory*

Particle strength is an important property in relation to the resistance of fertilizer particles to the loads they encounter during storage, handling and spreading. The breaking force of a particle is measured directly. The particle strength (σ_p) is calculated from the breaking force (F_b) and the area of the cross-section over which the particle breaks (A_c):

$$\sigma_p = \frac{F_b}{A_c} \tag{10}$$

2.4.2. *Review of strength measuring techniques*

Several strength measure methods for fertilizer particles are described by Hoffmeister[5] and Rutland.[6] The devices vary from a small kitchen scale to hand-powered or motor-driven compression testers. Brübach[11] used a compression tester with an electro magnet to load the particles (forces up to 10 N). The tester was equipped with a displacement and a force transducer to measure the relevant data during the compression. For the higher forces (up to 200 N), the load was applied by an electric motor-driven screw (velocity 3 mm/min) which compressed the fertilizer particles. The compression of the particles continued until they broke and the force during compression was measured.

2.4.3. *Particle strength measuring device*

The device developed for measuring static particle strength (*Fig. 6*) consists of a force transducer with a small platten, a second platten connected with an actuator and a displacement transducer. One particle at a time is positioned between the plattens. The pressure in the actuator, regulated by an electronic pressure controller, increases linearly with time and so does the force acting on the particle. The maximum force that can be realized is about 125 N. The measurement process is controlled by a PC equipped with a data-acquisition board which also delivers the control signal for the electronic pressure controller and samples the signals from the force and the displacement transducer.

In 8 s the load increases from zero to the maximum value. The moment of breaking of the particle is obtained from the derivatives of the signals from the displacement and the force transducers. The breaking force is equal to the force at the moment of breaking and is obtained by interpolating the recorded force just before and after the moment of breaking.

The particle cross-section area (A_c) is based on the particle height and the assumption that the vertical cross-section is circular. The particle height is equal to the distance between the plattens just before the compression of the particle starts. The particle height

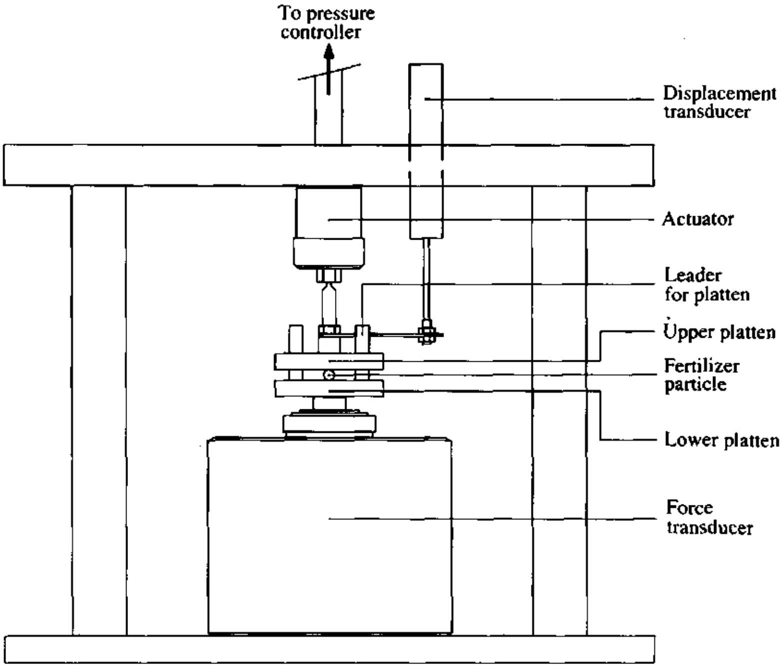

Fig. 6. Schematic drawing of the breaking force measurement device

is the best available estimator for the diameter of the cross-section of the particle. A vertical breaking plane has also been viewed by Priemer[31] in his research on the breaking of glass spheres by compressing them between two plattens.

3. Experimental results

3.1. *Coefficient of friction*

A total of 1800 friction measurements (six fertilizers, five normal loads, four friction surfaces, three series and five repetitions) has been made and within each measurement the influence of the relative velocity on the coefficient of friction has also been measured. The very large number of available data has been reduced by distinguishing the velocity trajectory of each measurement in four groups (1·0 to 6·0 m/s, 6·0 to 11·0 m/s, 11·0 to 16·0 m/s, and 16·0 to 21·0 m/s). The coefficient of friction trajectory is approximated within each of these intervals by a first order regression equation. An additional transformation has been applied to the data before the calculation of the regression equation to let the intercept values have a meaningful value. The intercept values are now the estimated values of the coefficient of friction at respectively 5·0, 10·0, 15·0, and 20·0 m/s. The slopes of each trajectory indicate whether there is a decreasing or an increasing trend with respect to the relative velocity. The procedures ANOVA[32] and GLM[33] were used for the analysis of the data. Factors for which $P(F \geq f) < 0{\cdot}05$ are considered to have a significant effect on the coefficient of friction.

The effect of the normal load on the coefficient of friction is illustrated in *Fig. 7*. The data show that an increase of the normal load results for most cases in a decrease of the coefficient of friction. The statistical analysis showed that the differences between the normal loads for each velocity were not significant for the stainless steel and the

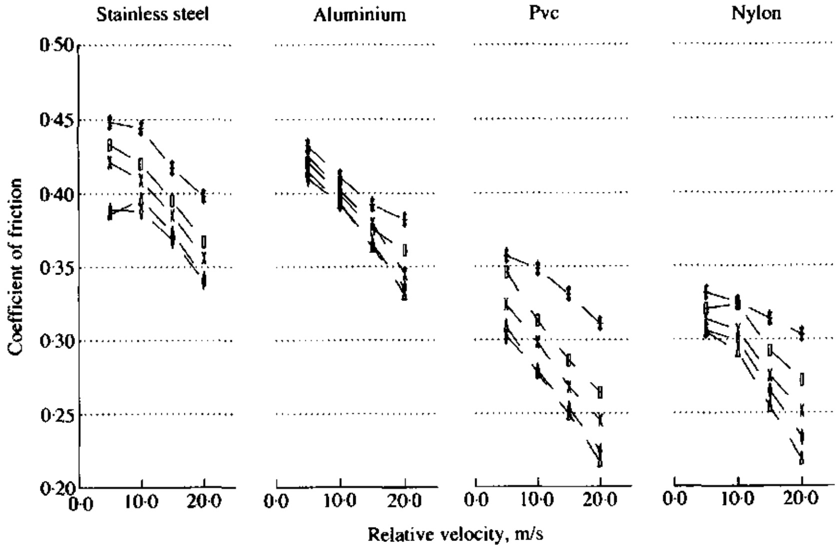

Fig. 7. Influence of relative velocity and normal load on the coefficient of friction for four friction surface layers. (, 0·130 N; □, 0·227 N; ×, 0·331 N; ◇, 0·424 N; △, 0·522 N)*

aluminium surface. On the other hand, the differences were significant for the pvc surface (all velocities) and partly for the nylon surface (significant for the two highest velocities).

The measurements have been executed in three consecutive series. The difference between the series can be considered as the effect of environmental conditions. The differences between the coefficient of friction for each measurement series, friction surface and fertilizer are illustrated in *Fig. 8.* Statistical analysis of the differences between the time series showed that they were all significant.

Fig. 8 shows that NP 26-14 (A) and NPK 17-17-17 (B) have for each surface and measurement series combination values for the coefficient of friction which are relatively high. Analysis has been carried out to determine whether the coefficients of friction of the remaining four fertilizers can be considered equal. This analysis showed that the coefficients of friction of the remaining four fertilizers were significantly different, except for the pvc surface. Further, it has been analysed whether there was a difference between the two makes of calcium ammonium nitrate (A and B) fertilizers. This analysis showed that the difference was significant for the two metal surfaces and the first two measurement series. The differences for the last measurement series of the metal surfaces and all measurement series of the synthetic material surfaces were not significant. From this it can be concluded that the coefficients of friction of calcium ammonium nitrate of both manufacturers are almost equal but differences can occur under specific conditions. A combination with metal surfaces appears to be more sensitive than a combination with synthetic material surfaces.

The friction surface appeared to have a large influence on the coefficient of friction (*Fig. 7*). The mean values of each surface show that there is a small difference between the metal surfaces themselves and the synthetic materials themselves. Statistical analysis showed that, when averaged over the measurement series, there is no significant difference between the metal surfaces and the synthetic material surfaces. When the surfaces are compared within each measurement series, the differences between the

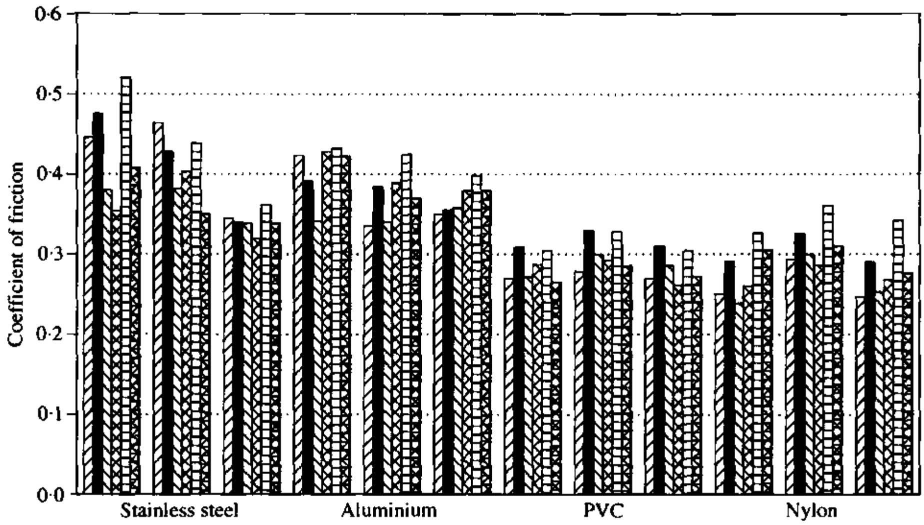

Fig. 8. Influence of fertilizer type on the coefficient of friction for four friction surface layers and three measurement series per surface layer. Fertilizer: , CAN 27N (A); , NP 26-14 (A); , CAN 27N (B); , NPK 12-10-18 (B); , NPK 17-17-17 (B); , NP 26-7 (A); A/B: manufacturer

surfaces are significant. From these results it can be concluded that both metal surfaces result in a value of the coefficient of friction which is about 30% higher than the values for both synthetic material surfaces. The differences between the metals themselves and the synthetic materials themselves are small and not significant when averaged over the measurement series.

Analysis of the intercept values of the coefficient of friction shows a small decrease when the relative velocity increases (*Fig. 7*). Analysis of the slope values in combination with the normal loads shows that for the stainless steel surface the coefficient of friction is almost independent of the relative velocity for the two lower velocity ranges. The slope values for all normal loads are almost equal to zero and the differences from zero are not significant. The slope values of the two higher velocity ranges are less than zero and deviate significantly from zero. The slope values of the aluminium surface are all less than zero and all deviate significantly from zero. The data of the pvc and the nylon surface show for the lowest velocity range that the coefficient of friction is almost independent of the relative velocity since the slope values do not deviate significantly from zero. The slope values of the other three velocity ranges are all less than zero and also deviate significantly from zero.

3.2. *Coefficient of restitution*

The coefficient of restitution has been measured in relation to three main effects: fertilizer (calcium ammonium nitrate (manufacturers A and B), NPK 12-10-18 (manufacturers A and B), urea granules and ammonium nitrate), impact surface (stainless steel, aluminium, nylon, and PVC), and particle size (2·0, 2·36, 2·80, 3·35, and 4·0 mm screen size). Ten repetitions have been executed for each of the 120 possible combinations. The results are summarized in *Fig. 9*. The error bars have a length equal to 2σ.

The data show that the mean values of the coefficient of restitution of the nylon surface

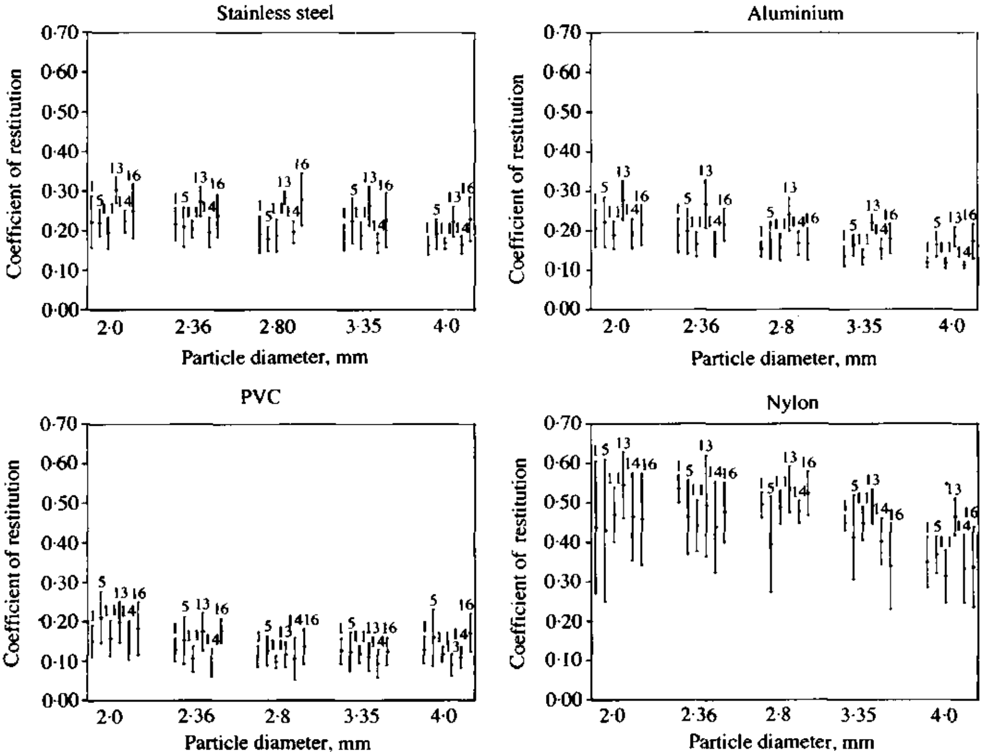

Fig. 9. Measurements of coefficient of restitution. (1, calcium ammonium nitrate (A); 5, NPK 12-10-18 (A); 11, calcium ammonium nitrate (B); 13, urea granules (2.9mm) (B); 14, ammonium nitrate (B); 16, NPK 12-10-18 (B); A/B: manufacturer)

(0·442) are much higher than those of the other surfaces. The PVC surface results in the lowest mean value (0·135), followed by the aluminium (0·180) and the stainless steel surface (0·215).

All fertilizers and all surfaces show an increase of the coefficient of restitution with an increase of the particle diameter. This indicates that larger particles are less elastic than smaller particles.

Statistical analysis of the data showed a significant surface effect [$P(F \geqslant f) < 0{\cdot}01$ for all cases], mainly due to the large difference between the nylon surface and the three other surfaces. Analysis of the effect of other factors did not show a very clear trend. About 50% of the cases showed a significant effect of a factor. The most important reason for this is the relatively large standard deviation of the measurements (about 25% of the mean value), which makes it difficult to prove differences between effects.

The large standard deviations are caused by the inevitable differences between fertilizer particles. The shape can be especially important because an irregular shape can result in a large variation of the rebound angles. Rebound angles that deviate too much from the normal will result in an underestimation of ε. This also implies that the measured values can be considered at least as minima.

From the experiments it can be concluded that all three factors examined have a significant influence on the coefficient of restitution. The influence of an effect strongly depends on the measuring conditions since most interaction effects between the three main effects were found to be significant.

3.3. *Aerodynamic resistance coefficient*

The aerodynamic resistance measurements were executed with 17 fertilizers with screen sizes varying from 1·70 to 4·75 mm and stainless steel balls with diameters ranging from 2·0 to 5·0 mm. The elutriator measurements were carried out only for the fertilizer particles (about 200 particles per screen size) since the maximum achievable air velocity was not sufficient to let the stainless steel balls float (minimum required air velocity about 25 m/s). The time versus distance relationship measurements were carried out with 100 particles of each screen size (fertilizers) or diameter (stainless steel balls).

A first analysis of the measurement results shows that there is a large difference between the values obtained by the two methods. For one fertilizer the difference between the two methods is illustrated in *Fig. 10.* The lower solid line indicates the terminal velocities where the particles with the same screen size started to float and the upper solid line the terminal velocities where all particles of a screen size floated. The terminal velocities obtained from the elutriator method are about 1 to 3 m/s lower than those obtained from the measured fall times and the time versus distance relationship. The length of the vertical bars is equal to 2σ and is an indication of the reproducibility of the (human) observations. The dashed line indicates the terminal velocities corresponding to the median fall time of a screen size. The lowest point of the vertical bar corresponds to the mean of the ten largest fall times (out of 100) and the highest point to the mean of the ten smallest fall times (out of 100). The total length of the bar is an indication of the variation of terminal velocities that can occur within a certain screen size and is about equal to the distance between the two solid lines.

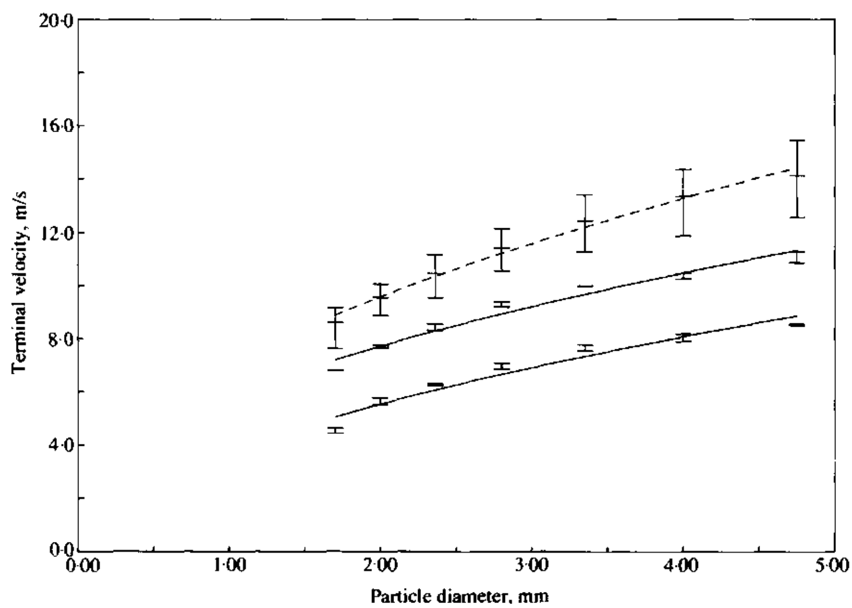

Fig. 10. Terminal velocities of fertilizer particles measured with the elutriator method and the time versus distance relationship method for NP 26-14 (A). (——, elutriator method; – – – – –, time versus distance method)

Possible explanations for the difference between the two methods are as follows.

(a) The measured air velocity in the pitot tube is not the velocity which lets the particles float. The instantaneous air velocity profile in the tube can show some peak velocities that are not measured by the pitot tube since this is a slow measuring device. The particles start to float on the peaks and this results in an underestimation of the particle terminal velocity since the mean velocity is measured.

(b) The particles start to rotate. Mohsenin[10] reported on investigations of some researchers who observed a lower terminal velocity of rotating or tumbling grain particles. However, this effect is difficult to quantify.

(c) Errors due to the integration process and the initial values. The possible errors due to the integration and the initial values used are much smaller than the observed differences between the two methods and can almost be neglected.

It can be concluded from this discussion that there are some doubts about the values resulting from the use of the elutriator device. The results obtained will not be discussed further.

The values of q of the fall time measurements are presented in *Fig. 11.* The q value of the median fall time is marked with a vertical bar. The horizontal bar goes from the q value corresponding to the highest, to the q values corresponding to the lowest fall time. The q values corresponding to the median fall times can be best used for comparison of fertilizers. The variation in q is due to the fact that for each screen size only one mean value for d_{ps} has been determined. The variation would have been much smaller when d_{ps}

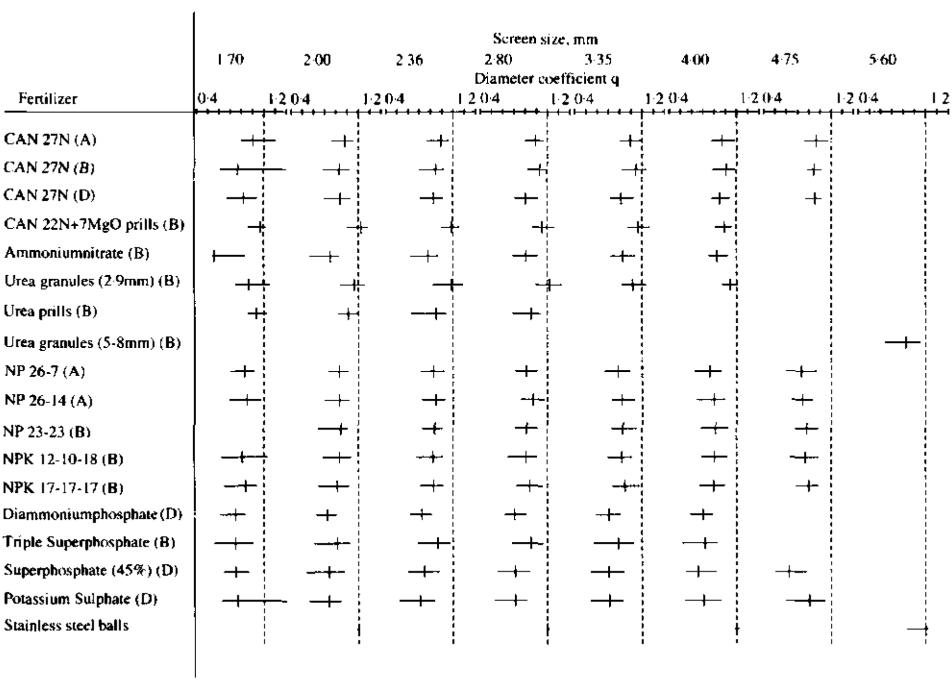

Fig. 11. Values of the diameter coefficient q of fertilizers and stainless steel balls. Note: The values for the stainless steel balls are given in the columns 2·00 mm (2·00 mm), 2·80 mm (3·00 mm), 4·00 mm (4·00 mm), and 5·60 mm (5·00 mm), A/B/D: manufacturer

of each particle had been measured. The results show that fertilizers with a very smooth surface texture such as CAN 22N + 7MgO prills, urea prills and urea granules (2·9 mm) have a median q value close to 1. This indicates that they behave almost like an ideal sphere. The calcium ammonium nitrate (CAN 27N) fertilizers also have a relatively smooth surface texture and their shape is almost spherical. These fertilizers have a q value between about 0·85 and 0·95. NP(K) fertilizers have a rougher surface texture and more asperities and this results in a relative low value of q (values between about 0·57 and 0·86). The q values for the several screen sizes of a fertilizer do not change much with respect to the screen size. Analysis of variance of the q values showed that the fertilizer effect was significant $[P(F \geqslant f) < 0{\cdot}001)]$ and that both the diameter effect and the interaction effect were not significant $[P(F \geqslant f) > 0{\cdot}05)]$. This means that the value of q can be used as a shape parameter of a fertilizer which can be used for the calculation of the aerodynamic resistance coefficient K or the terminal velocity v_{pt}. The q value does not say anything about the aerodynamic resistance itself because this also depends on the particle density and particle size. The value can be used in conjunction with *Fig. 4* to determine the aerodynamic resistance coefficient for a fertilizer or the terminal velocity of a fertilizer particle.

3.4. *Breaking forces and particle strength*

Particle strengths were measured for nine fertilizers and 20 particles of each screen size (2·0, 2·36, 2·8, 3·35 and 4·0 mm). The "actual" particle diameter was obtained from the particle height.

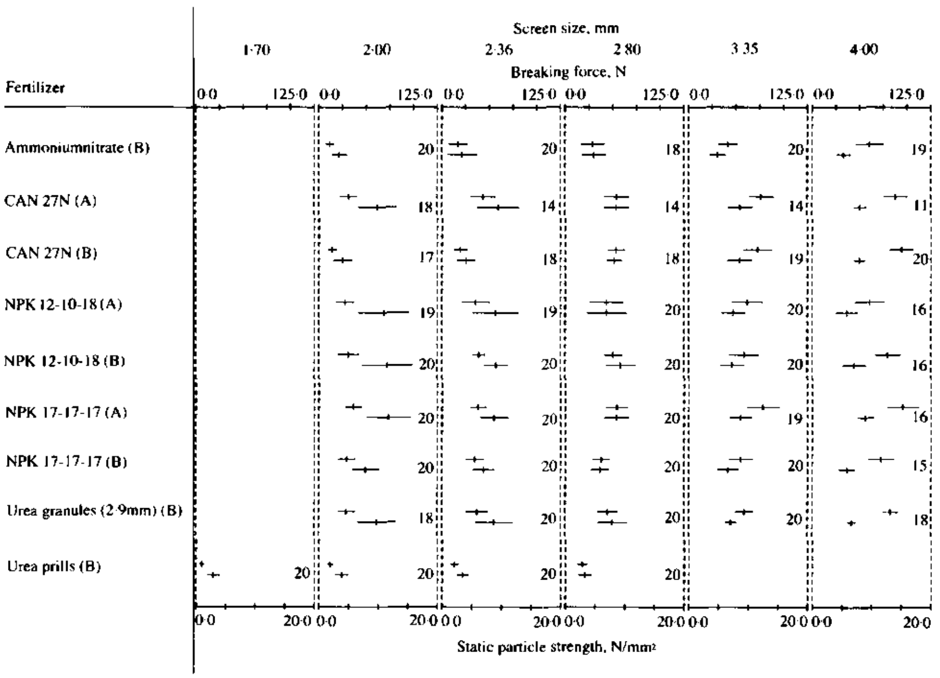

Fig. 12. Breaking forces and strengths of fertilizers. The upper bar indicates the force (N) and the lower bar indicates the strength (N/mm²). The numbers associated with the bars indicate the number of broken particles (out of 20) on which the force and strength data are based. A/B: manufacturer

The results of the breaking force and particle strength measurements are presented in *Fig. 12.* The upper line indicates the breaking force and the lower line the particle strength. The bar length is equal to 2σ. The numbers at the right side of the bars indicate the number of broken particles (out of 20). The maximum applied load was 100 N, except for both CAN fertilizers and NPK 17-17-17 (A) for which a maximum of 125 N was applied. The values for breaking force and particle strength are based on the broken particles only. This means that values for sieve fractions with many unbroken particles are not representative.

The main factors that affect the breaking force are the particle size and the fertilizer material (cohesion). The data in the figure show that the breaking force of all fertilizers increases when the particle diameter increases. The particle strength decreases with an increase of particle diameter for the NPK fertilizers. The particle strength of the ammonium nitrate and the two CAN fertilizers increases with an increase of the particle diameter. The strength of CAN 27N (A) in the figure decreases but the large number of unbroken particles also has to be taken into account. The strength of the urea granules decreases slightly and the strength of the urea prills remains at the same level.

The decrease of the strength of the NPK fertilizers and the increase of the ammonium nitrate-based fertilizers can possibly be explained by the production process. The ammonium nitrate-based fertilizers are manufactured from a homogeneous material but the NPK fertilizers are usually manufactured out of two or three ground basic fertilizers.

Fertilizer particles must have a minimum strength to withstand the several loads they encounter during handling. A minimum breaking force of 15 N has been mentioned by serverál researchers (Hofstee and Huisman[1]). Except for most of the urea prills, almost all the fertilizers tested met this limit.

4. Conclusions

4.1. *Coefficient of friction*

The friction measurements showed a significant influence of the material from which the friction surface was made. The stainless steel and the aluminium surfaces created a value of the coefficient of friction which was about 30% higher than the PVC and nylon surfaces. An increase of the relative velocity from about 1 m/s to about 21 m/s resulted in a decrease of the coefficient of friction of about 10 to 20%. The coefficient of friction appeared to be almost independent of the normal load. Only the PVC surface and the nylon surface in combination with a high relative velocity showed a significant effect of the normal load.

The differences between the measurement series are, for the large part, ascribed to the environmental conditions in the measurement room. The differences between some of the measurement series were large despite the fact that the conditions did not vary much during the measurements. The measurements further showed that NPK 17-17-17 (B) and NP 26-14 (A) have a value for the coefficient of friction which is relatively high with respect to the other fertilizers. The differences between the two makes of calcium ammonium nitrate are small and depend greatly on the measurement conditions.

4.2. *Coefficient of restitution*

The impact surface was shown to have a very large influence on the coefficient of restitution. The values for the stainless steel, the aluminium, and the PVC surface were about 50% of the values of the nylon surface. The standard deviations are also high and this is ascribed mainly to the irregular shape of the particles. As a result a large variation in rebound angles and hence in the coefficient of restitution was found.

4.3. *Aerodynamic resistance coefficient*

The aerodynamic resistance measurements showed a large difference between the results of the elutriator method and the time versus distance relationship method. This gives rise to some doubts about the results and the suitability of the elutriator method. The diameter coefficient, q, appears to be a simple shape parameter that can be used to calculate, together with the particle density, the terminal velocity and the aerodynamic resistance coefficient of fertilizer particles. The experiments showed that fertilizers with a relatively smooth surface texture have a lower aerodynamic resistance coefficient than fertilizers with a rougher surface texture.

4.4. *Breaking force and static particle strength*

The breaking force of the particles increases when the size increases. The strength of the particles decreases for the NPK fertilizers. It increases for the ammonium nitrate-based fertilizers, and remains almost constant for the urea fertilizers. Some fertilizers showed a large number of unbroken particles and this made it difficult to compare all results quantitatively. The maximum affordable load was restricted to 125 N and a maximum affordable load of about 200 or 250 N would have been more appropriate. It can be concluded that all fertilizers, except the urea prills, had a breaking force higher than the minimum required value of 15 N.

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Chapter III
Measurement of particle velocities and directions with ultrasonic transducers, theory, measurement system and experimental arrangements

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Handling and Spreading of Fertilizers Part 3: Measurement of Particle Velocities and Directions with Ultrasonic Transducers, Theory, Measurement System, and Experimental Arrangements

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A new technique for measuring the velocity and direction of fertilizer particles discharged by a fertilizer distributor is discussed. The technique is based on the Doppler frequency shift of an ultrasonic beam. The instantaneous amplitude and frequency of the received Doppler signals are computed by digital signal processing. The velocity and the direction of each detected particle are calculated from the instantaneous frequency and the particle diameter is estimated from the instantaneous amplitude.

The technique is used to quantify the influence of physical properties of fertilizer on the motion of fertilizer particles in the distributor device. A first series of experiments shows that this technique can measure the velocity and direction of fertilizer particles. The estimation of the particle diameter is more difficult because of the non uniform frequency response of the ultrasonic transducers in the frequency band used.

1. Introduction

Physical properties of fertilizer such as the coefficient of friction and the aerodynamic resistance coefficient influence the motion of fertilizer particles in the distributor device and through the air. Hofstee and Huisman[1] discussed much of the literature related to this subject. Many researchers developed models to describe the motion of fertilizer particles and to study the influence of physical properties on this motion. However, most of these models are based on the theory of the single particle approach.

Particle motion, from the point where they are metered to the distributor device until they reach the soil, can be divided into (a) motion in or on the distributor device and (b) motion through the air. Properties can have different and even opposite effects for both motions. Therefore it is necessary to make a distinction between the two motions when the influence of physical properties is being studied. This distinction cannot be realized when existing methods are used for determination of the spread pattern as described by the standards ISO 5690 (Ref. 2) or ASAE S341.1 (Ref. 3). These methods only measure the resulting spread pattern and do not provide any information about how the spread pattern is achieved

Notation

a	radius ultrasonic transducer, m
c	propagation velocity of sound, m/s
$\hat{d}_{p,i}$	estimated particle diameter direction i (i = X, Y, Z)
f_0	frequency emitted by transducer, Hz
f_1	frequency received by moving object, Hz
f_2	frequency received by transducer, Hz
f_d	Doppler frequency shift, Hz
f_{di}	Doppler frequency shift in direction i (i = X, Y, Z), Hz
$\vec{r}_i$	vector corresponding with the receiver in direction i (i= X, Y, Z)
$\vec{t}$	vector corresponding with the transmitter direction
t	time, s
$u_a(t)$	analytic signal
$u_r(t)$	received signal
$u_t(t)$	transmitted signal
$\vec{v}$	vector corresponding with velocity and direction of the particle
v_p	particle velocity, m/s
v_{pi}	particle velocity in direction i (i = X, Y, Z), m/s
v_{pXZ}	particle velocity in the horizontal plane (XZ-plane), m/s
z	axial distance, m
$H\{...\}$	Hilbert transformer
N	impulse response duration in points
$U_r(t)$	instantaneous amplitude received signal, V
U_t	amplitude transmitted signal, V
θ	diffraction angle ultrasonic beam, rad
λ	wave length, m
σ	standard deviation
τ	time between transmission and receipt of signal, s
ϕ_r	angle between velocity vector and receiver axis, rad
ϕ_{riy}	angle between the Y axis and the axis of receiver i (i = X, Y, Z), rad
ϕ_{riXZx}	angle between the X axis and the projection on the XZ plane of the axis of receiver i (i = X, Y), rad
ϕ_{rZXZz}	angle between the projection of the axis of receiver Z on the XZ plane and the Z axis, rad
ϕ_{ri}	angle between velocity vector and axis of receiver i (i = X, Y, Z), rad
ϕ_t	angle between velocity vector and transmitter axis, rad
ϕ_{ty}	angle between the transmitter axis and the Y axis, rad
ϕ_{tXZx}	angle between the projection of the transmitter axis on the XZ plane and the X axis, rad
ϕ_{XZ}	direction of a particle in the horizontal plane (XZ plane), rad
ϕ_{YXZ}	direction of a particle in the vertical plane, rad
$\varphi_r(t)$	instantaneous angle received signal, rad
ω_t	angular frequency transmitted signal, rad/s
$\omega_r(t)$	instantaneous angular frequency received signal, rad/s
$\Omega(t)$	instantaneous angular frequency shift, rad/s

and what the contribution is of the individual physical properties.

The motion of the particles in or on the distributor device is usually described by differential equations that are based on the motion of single particles. This gives the equations a limited practical value because mass flows and interactions between the particles are ignored. Application of these equations to mass flow conditions requires additional knowledge about the interaction between the mass flow and the relevant physical properties. Up to the present time, only very limited information has been available about this interaction effect.

The motion through the air can be described by a set of differential equations[1]. The aerodynamic resistance coefficient that appears in these equations includes almost all important properties. It can be calculated from the particle density, the diameter of the equivalent sphere and the diameter coefficient[4]. Real particle trajectories are expected to deviate only slightly from the theoretical particle trajectories. Deviations can be caused by eventual tumbling or rotating of the particles.

At the Department of Agricultural Engineering and Physics of Wageningen Agricultural University a new measuring method[5] has been developed that makes it possible to measure the particle motion with mass flows on a real scale. The method is based on the measurement of the discharge velocity and direction of fertilizer particles. Velocity and direction of individual particles are measured in a grid around and just behind the distributor device. In this way the motion in or on the distributor device is measured and is separated from the motion through the air.

The velocity measuring technique is based on the ultrasonic Doppler frequency shift. The Doppler effect is a widely used technique for measuring the velocity of moving objects. Doppler radar devices are used to measure the velocity of tractors and self propelled agricultural machinery. Doppler ultrasonic devices are widely used for measuring flow velocities in pipes. A specific application of this technique can be found in biomedical engineering where it is used for the measurement of blood flow in vessels[6,7,8]. An entirely different application is in measuring the spatial velocity of bubbles in water[9,10,11].

An optical velocity measuring method, which is regularly used to measure the velocity of particles, cannot be used for this purpose. It requires that the direction of the particle is known a priori and this is not so for fertilizer particles discharged by a fertilizer spreader.

This paper discusses the developed measuring technique. The use of the technique in combination with a fertilizer spreader is discussed separately[12,13].

2. Theory

2.1. *Doppler effect*

The Doppler effect in one dimension (one transmitter and one receiver) is illustrated in *Fig. 1*. The frequency received by the moving object (f_1) is, due to the Doppler effect, not equal to the frequency transmitted (f_0). For the same reason, the frequency received by the receiver (f_2) is not equal to f_1. The Doppler frequency shift depends not only on the velocity of the object and the propagation velocity of sound in air but also on the angle of the transmitter and receiver with respect to the velocity direction of the object. The Doppler frequency shift (f_d) is equal to[9,10,11]:

$$f_d = f_2 - f_0 = f_0 \frac{v_p(\cos(\phi_r) - \cos(\phi_t))}{c - v_p\cos(\phi_r)} \tag{1a}$$

and when $v_p \ll c$:

$$f_d = \frac{v_p f_0}{c}\left(\cos(\phi_r) - \cos(\phi_t)\right) \tag{1b}$$

In Section 3.1.2. the three-dimensional configuration of the measurement system is discussed.

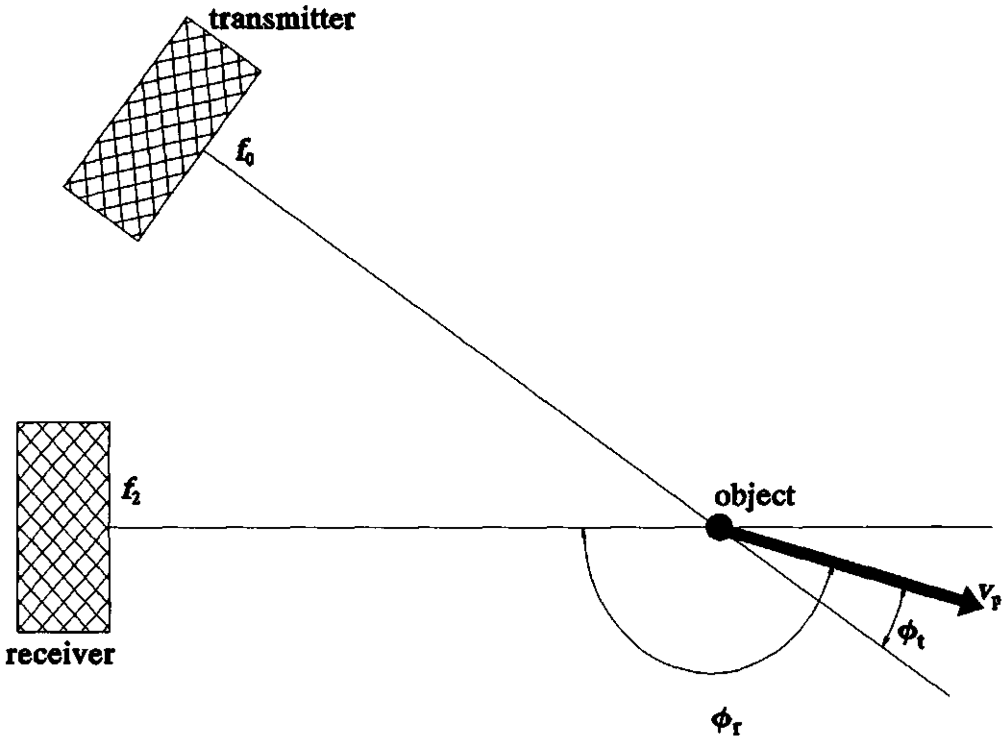

Fig. 1 Geometry of a one dimensional Doppler velocity meter with one transmitter and one receiver.

2.2. *Instantaneous frequency and amplitude*

The Doppler frequency shift of the reflected signal with respect to the transmitted signal has to be calculated from both the transmitted and the received signal. The transmitted signal is equal to:

$$u_t(t) = U_t \cos(\omega_t t) \tag{2}$$

and the received signal to:

$$u_r(t) = U_r(t) \cos(\varphi(t)) \tag{3}$$

where:

$$\varphi(t) = \int_{\tau}^{t} \omega_r(s)\, ds \tag{4}$$

and:

$$\omega_r(t) = \omega_t \frac{c - v_p(t)\cos(\phi_t)}{c - v_p(t)\cos(\phi_r)} \tag{5}$$

τ is the time between the transmission and the receipt of the signal. The received signal is demodulated by multiplying it with the transmitted signal and subsequent lowpass filtering to remove the upper side band. The angular frequency of the remaining lower side band is equal to the angular Doppler frequency shift and can be obtained from the analytic signal[8,10,11]. The analytic signal is a complex function of a real variable whose imaginary part is equal to the Hilbert transform of its real part:

$$u_a(t) = u_r(t) + j\,H\{u_r(t)\} \tag{6}$$

Depending on the Nyquist location, the Hilbert transform shifts all Fourier components by $\pi/2$ or $-\pi/2$. The instantaneous angular frequency of the demodulated Doppler signal or the Doppler frequency shift is equal to the differentiated unwrapped phase of the analytic signal:

$$\Omega(t) = \frac{d}{dt}\left(\text{unwrap}\left(\arctan\left(\frac{H\{u_r(t)\}}{u_r(t)}\right)\right)\right) \tag{7}$$

The unwrap operator is necessary to remove the branch cuts each 2π from the instantaneous phase of the analytic signal.

The instantaneous amplitude of the Doppler signal is equal to the square root of the magnitude of the analytic signal:

$$U_r(t) = \sqrt{u_r(t)^2 + H\{u_r(t)\}^2} \tag{8}$$

3. Measurement system

The measurement system (*Fig. 2*) consists of a fertilizer spreader (A), a raised floor (B), a frame (C) which can move horizontally over this floor, two transducer units (D1 and D2) mounted on a linear displacement unit, and the Doppler velocity meter hardware with amplifiers, multipliers, and oscillators (E). The measurement system further consists of a data acquisition and processing system for recording and analyzing the signals from the transducers and for control of the measurement installation. This acquisition and processing system is discussed in Section 4.

3.1. *Doppler velocity meter*

The Doppler velocity meter consists of two similar transducer units (*Fig. 3*), each with four ultrasonic transducers: one transmitter (A) and three receivers (B1-B3). Each transducer unit has three pre-amplifiers (C1-C3) to condition the received signals. The two units are mounted above each other and will be referred to in the rest of the paper as lower and upper transducer unit. The Doppler velocity meter further consists of an electric circuit (E) which contains the oscillators to generate the ultrasonic signals and hardware for demodulating and conditioning the output signals of the pre-amplifiers. A schematic layout is given in *Fig. 4*.

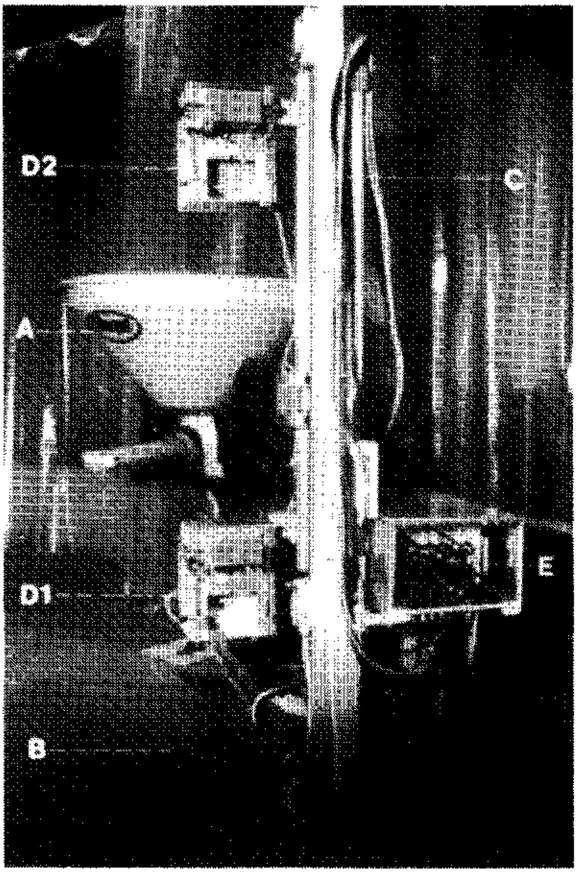

Fig. 2 Measurement system for measuring velocities and directions of fertilizer particles leaving a fertilizer distributor. (A fertilizer distributor; B raised floor; C measurement frame, D1 and D2 transducer units; E Doppler velocity meter hardware).

The Doppler velocity meter measures the velocity of particles that pass through the opening (see *Fig. 3*). A particle that passes through this opening (20 x 20 mm) passes also the ultrasonic beam from the transmitter (A) and reflects a part of this beam in all directions. The reflected signals are received by each of the three receivers (B1-B3) and further processed by the electric circuit. The performance of the Doppler velocity meter depends on the performance of the ultrasonic transducers and the geometry of the transmitter and the receivers with respect to each other.

3.1.1. *Ultrasonic transducer sensitivity*

The ultrasonic transducers used are of the plane piston type. Analysis of this type of transducers[14] showed that for distances z for which $z < a^2/\lambda$ (see *Fig. 5* for definition of the parameters) the acoustic beam tends to remain confined to its original radius. Beyond this point its intensity varies with θ and several lobes appear in the radiation pattern. The intensity $I(z)$ falls of as $I(0)/z^2$. The relative power intensity of a transducer with radius 5.5 mm and at a distance of 0.05 m from the piston plane (which is about the distance between a particle and the transmitter in the unit used) is illustrated in *Fig. 6*. The figure

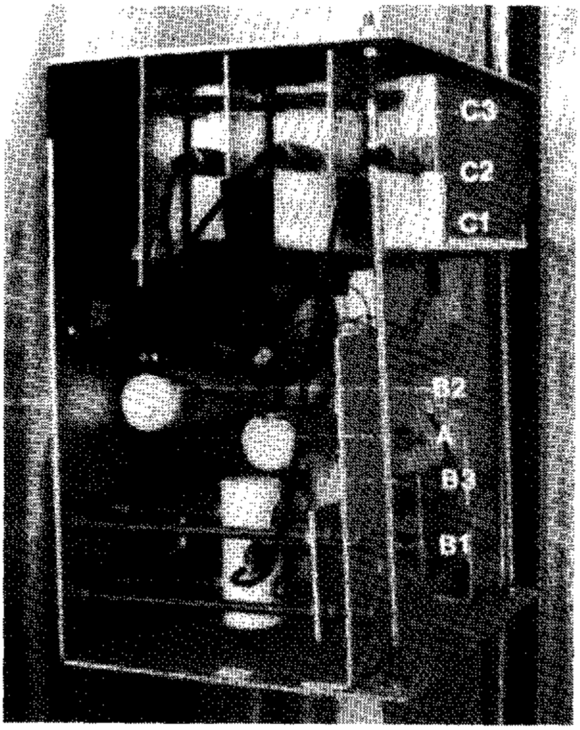

Fig. 3 Transducer unit. (A transmitter; B1, B2 and B3 receivers; C1, C2 and C3 pre-amplifiers).

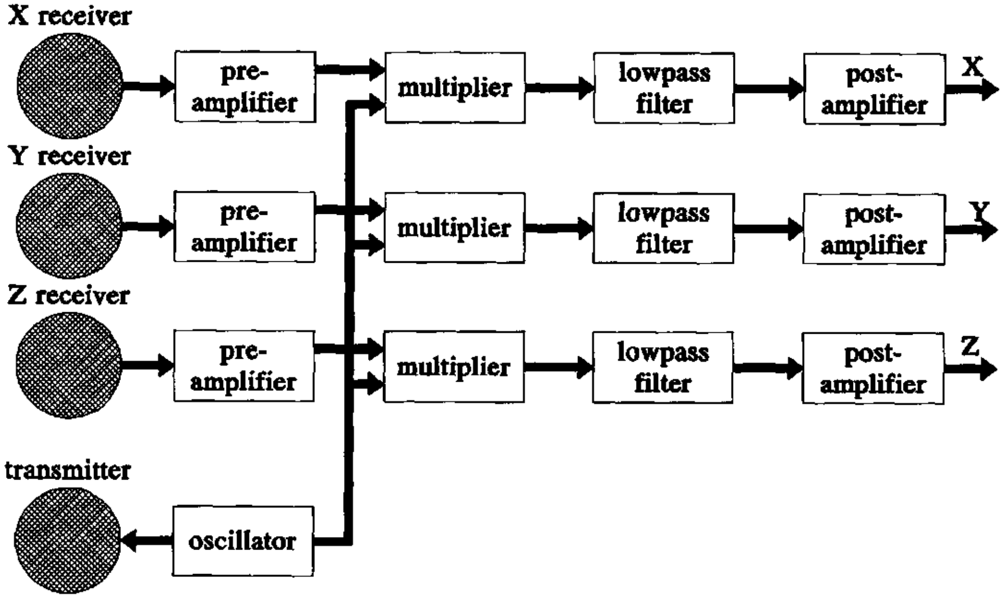

Fig. 4 Schematic outline of the Doppler velocity meter.

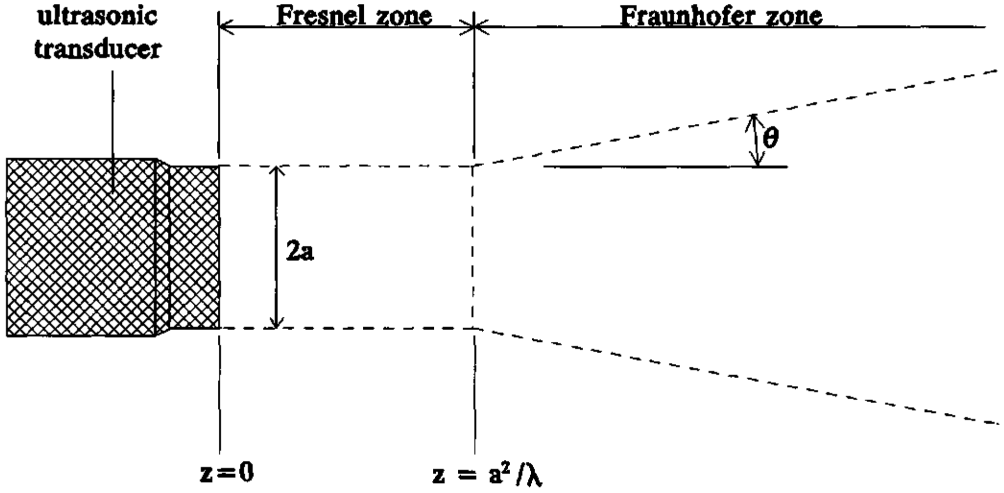

Fig. 5 Definition of parameters to calculate the radiation pattern of an ultrasonic transducer.

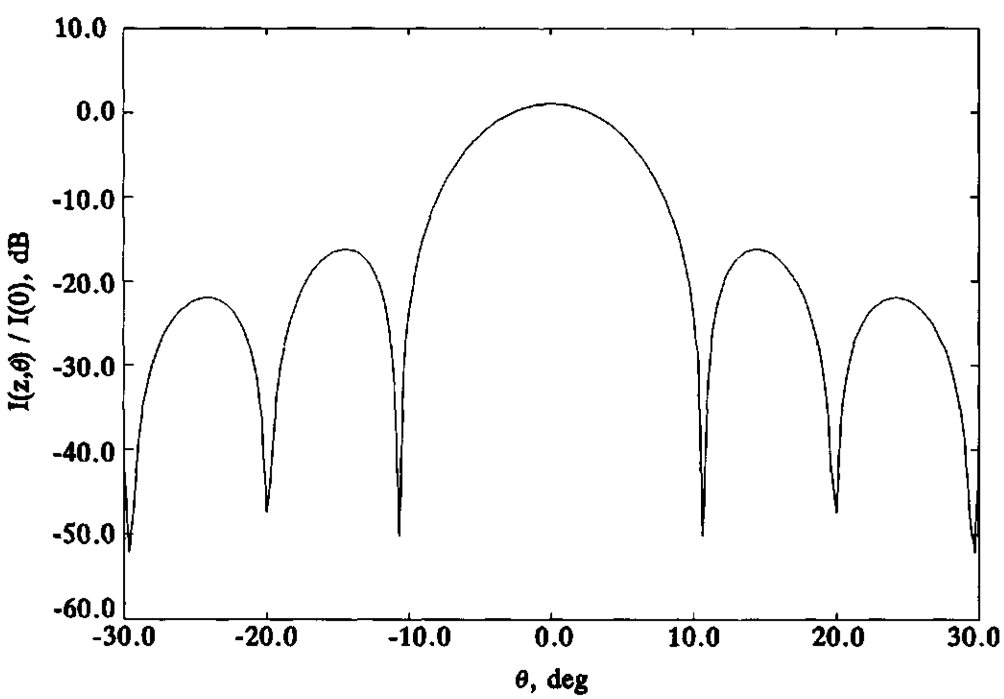

Fig. 6 Radiation pattern of an ultrasonic transducer.

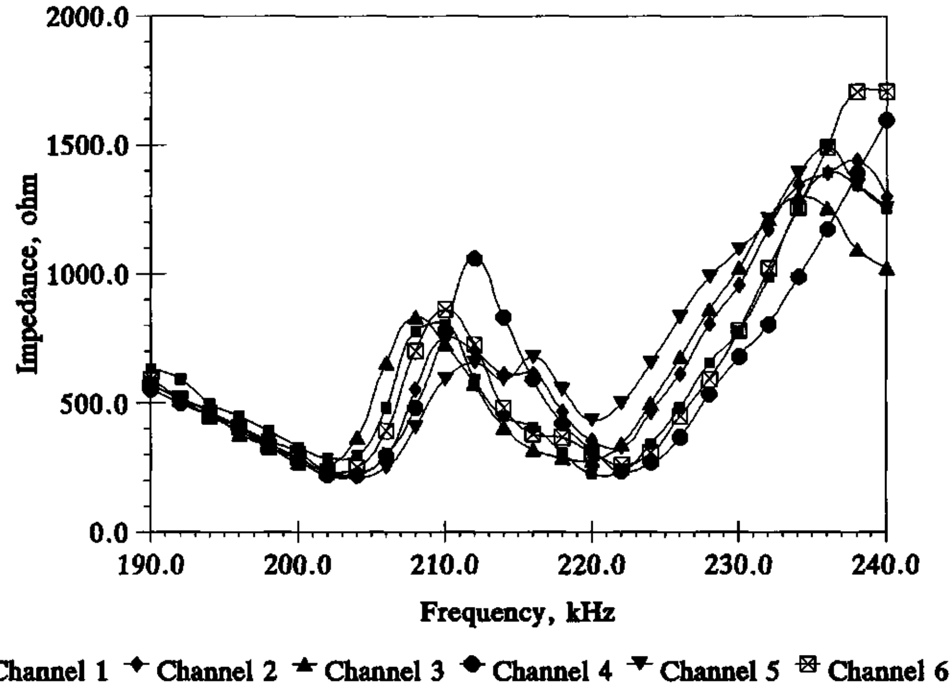

Fig. 7 Impedance of the six ultrasonic transducers used.

shows that the -6dB point is located at an angle $\theta=6.7°$. The diameter of the beam at this point is equal to 22.7 mm. A diameter of 20 mm corresponds with $\theta=5.1°$ and the relative power intensity is equal to about -3dB.

Another important property of the transducers is that their sensitivity depends on the frequency, i.e., the resulting output signal depends not only on the intensity of the reflected ultrasonic beam but also on the velocity of the particle. The sensitivity of the six receivers used is shown in *Fig. 7.*

3.1.2. *Sensor geometry*

The transmitter and the three receivers are arranged in a three dimensional orthogonal configuration (*Fig. 8*). The Doppler frequency shift in each direction (X, Y, and Z) is, when assuming that $v_p << c$, equal to:

$$f_{di} = \frac{\omega_t}{2\pi}\frac{v_p}{c}\left[\cos(\phi_{ri}) + \cos(\phi_t)\right] \quad i = X,Y,Z \tag{9}$$

ϕ_{ri} is the angle between the velocity vector $\vec{v}$ and the axis of the receiver $\vec{r}_i$ (i = X,Y,Z):

$$\cos(\phi_{ri}) = \frac{(\vec{v},\vec{r}_i)}{|\vec{v}||\vec{r}_i|} \quad i = X,Y,Z \tag{10}$$

and ϕ_t is the angle between the velocity vector $\vec{v}$ and the axis of the transmitter ($\vec{t}$):

$$\cos(\phi_t) = \frac{(\vec{v},\vec{t})}{|\vec{v}||\vec{t}|} \tag{11}$$

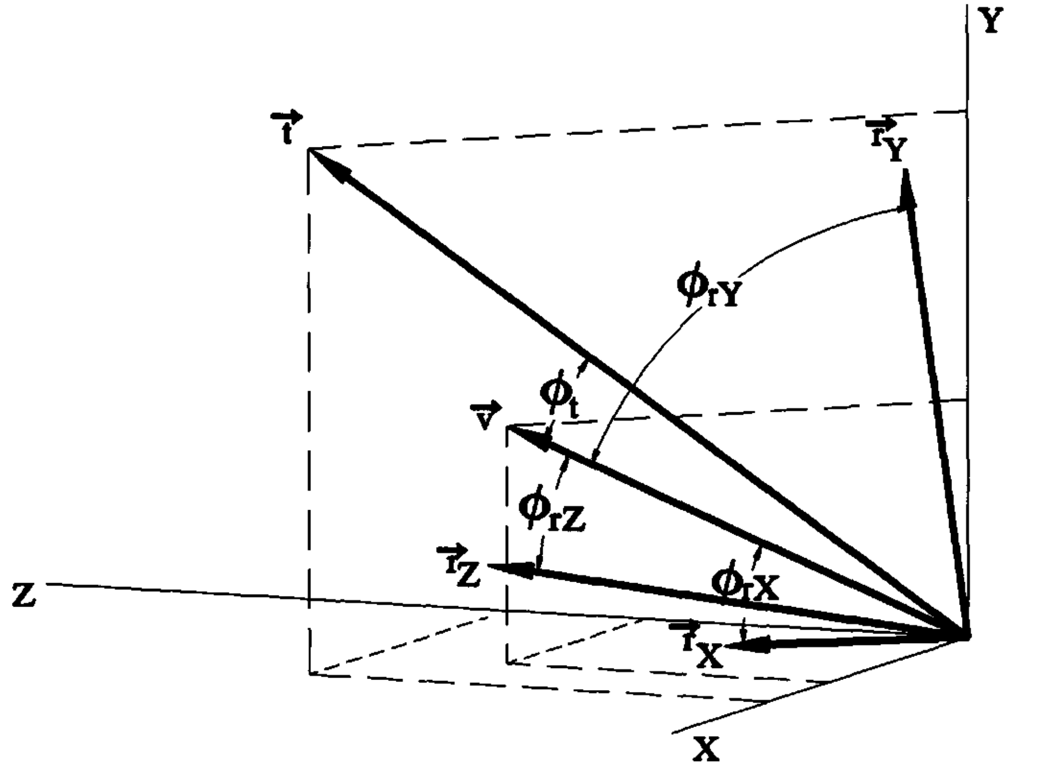

Fig. 8 Layout and most important geometrical parameters of a three dimensional Doppler velocity meter.

The propagation velocity of sound (c) in still air with a temperature of 20°C is equal to 343.4 m/s (Ref. 15). The transmitter angular frequency (ω_t) has been set to 1.275×10^6 rad/s (203 kHz). Substitution of the Eqns (10) and (11) into Eqn (9) results in:

$$\begin{pmatrix} f_{dX} \\ f_{dY} \\ f_{dZ} \end{pmatrix} = \frac{\omega_t}{2\pi c} \begin{pmatrix} r_{Xx}+t_x & r_{Xy}+t_y & r_{Xz}+t_z \\ r_{Yx}+t_x & r_{Yy}+t_y & r_{Yz}+t_z \\ r_{Zx}+t_x & r_{Zy}+t_y & r_{Zz}+t_z \end{pmatrix} \begin{pmatrix} v_{px} \\ v_{py} \\ v_{pz} \end{pmatrix} \qquad (12)$$

The parameters r_{ij} (i = X,Y,Z; j = x,y,z) and t_j (j = x,y,z) are help variables and are equal to:

$$r_{Xx} = \sin(\phi_{rXy})\cos(\phi_{rXXZx}) \qquad r_{Zx} = \sin(\phi_{rZy})\sin(\phi_{rZXZz})$$
$$r_{Xy} = \cos(\phi_{rXy}) \qquad r_{Zy} = \cos(\phi_{rZy})$$
$$r_{Xz} = \sin(\phi_{rXy})\sin(\phi_{rXXZx}) \qquad r_{Zz} = \sin(\phi_{rZy})\cos(\phi_{rZXZz})$$

$$r_{Yx} = \sin(\phi_{rYy})\cos(\phi_{rYXZx}) \qquad t_x = \sin(\phi_{ty})\cos(\phi_{tXZx})$$
$$r_{Yy} = \cos(\phi_{rYy}) \qquad t_y = \cos(\phi_{ty})$$
$$r_{Yz} = \sin(\phi_{rYy})\sin(\phi_{rYXZx}) \qquad t_z = \sin(\phi_{ty})\sin(\phi_{tXZx})$$

ϕ_{riy} (i=X,Y,Z) denotes the angle between the i receiver direction and the Y axis. ϕ_{riXZx} (i=X,Y) denotes the angle between the projection of the i receiver direction on XZ plane and the X axis. ϕ_{rZXZz} denotes the angle between the projection of the Z receiver direction on the XZ plane and the Z axis. ϕ_{ty} denotes the angle between the transmitter direction and the Y axis and ϕ_{tXZx} denotes the angle between the projection of the transmitter direction on the XZ plane and the X axis.

The equations show that the frequency shift depends on the sensor geometry. They also show that the frequency shift in a certain direction not only depends on the velocity in that direction but depends on the velocity in all three directions.

The transducers are positioned so that the transmitter makes an angle of $\pi/4$ with the XZ plane and the Y axis and the perpendicular projection of the transmitter direction on the XZ plane makes an angle of $\pi/4$ with both X and Z axis. This results in the following values for the angles in Eqn (12):

$$\phi_{rXy} = \pi/2 \qquad \phi_{rXXZx} = 0 \qquad \phi_{ty} = \pi/4$$
$$\phi_{rYy} = 0 \qquad \phi_{rYXZx} = \pi/4 \qquad \phi_{tXZx} = \pi/4$$
$$\phi_{rZy} = \pi/2 \qquad \phi_{rZXZz} = 0$$

Substitution of these values in Eqn (12) and consecutively solving Eqn (12) results in the following equation for the calculation of the velocity of the particle from the measured frequency shifts:

$$\begin{pmatrix} v_{pX} \\ v_{pY} \\ v_{pZ} \end{pmatrix} = \frac{\pi c}{7\,\omega_t} \begin{pmatrix} 10+\sqrt{2} & 2-4\sqrt{2} & -4+\sqrt{2} \\ -4+\sqrt{2} & 16-4\sqrt{2} & -4+\sqrt{2} \\ -4+\sqrt{2} & 2-4\sqrt{2} & 10+\sqrt{2} \end{pmatrix} \begin{pmatrix} f_{dX} \\ f_{dY} \\ f_{dZ} \end{pmatrix} \qquad (13)$$

3.1.3. *Spatial sensitivity*

The solution derived in the previous section showed that the frequency shift in each direction depends on the velocity in all three directions. The relation between the direction of a particle and the resulting frequency shift for a particle with a normalized velocity vector (with a length of 1 m/s) is given for the X and Y direction in *Figs 9a* and *9b*. The figure shows the constant frequency shift lines for a particle that has a velocity of 1 m/s in a certain direction. The pattern for the Z direction is equal to the mirrored (vertical axis) X-direction pattern. The meaning of the directions is shown in *Fig. 10*.

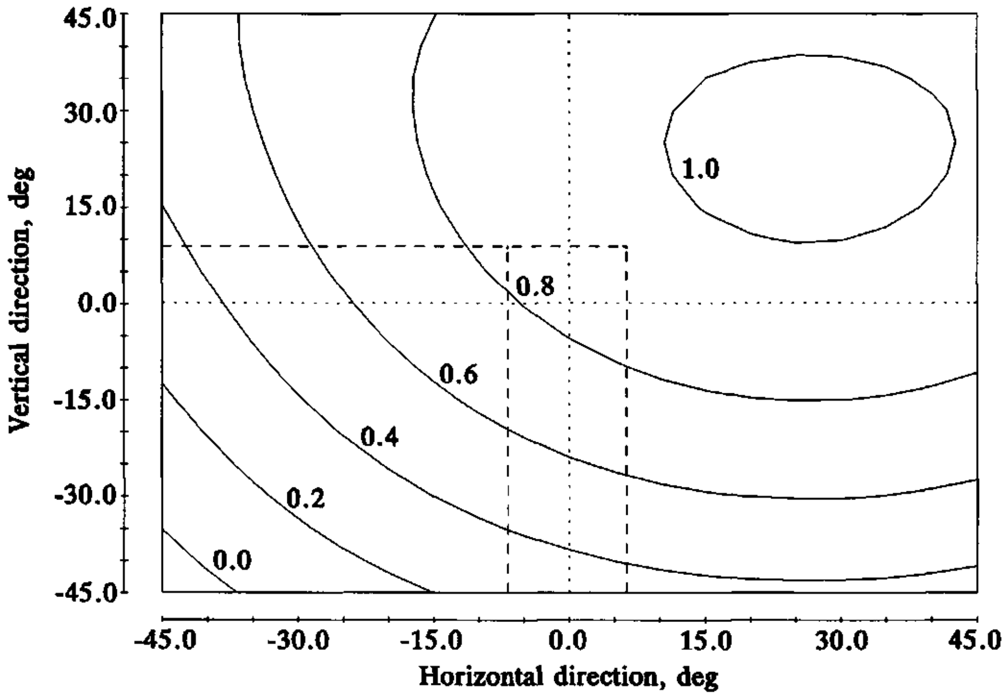

Fig. 9a Spatial sensitivity of the ultrasonic transducer for the X direction. The pattern for the Z direction is equal to the pattern for the X direction but mirrored with respect to the vertical line through 0. The solid lines are the Doppler constant frequency shift lines.

Consider a particle with a velocity of 4 m/s in the X direction, 5 m/s in the Z direction and 1 m/s in the Y direction for example. The absolute velocity of the particle is 6.481 m/s and the velocity in the XZ plane is 6.403 m/s. The horizontal direction of the particle is -6.34° ($= \pi/4 - \arctan(v_{pZ}/v_{pX})$) and the vertical direction is 8.88° ($=\arctan(v_{pY}/v_{pXZ})$). From the velocity of the particle and *Figs 9a* and *9b* (small dashed lines) the Doppler frequency shift for each direction can be obtained. The Doppler frequency shift is equal to the normalized frequency (from *Figs 9a* and *9b*) multiplied by the velocity. The frequency shift in the X direction is equal to 5.45 kHz ($=0.84\times6.481$), in the Y direction to 3.67 kHz ($=0.57\times6.481$), and in the Z direction to 6.04 kHz ($=0.93\times6.481$).

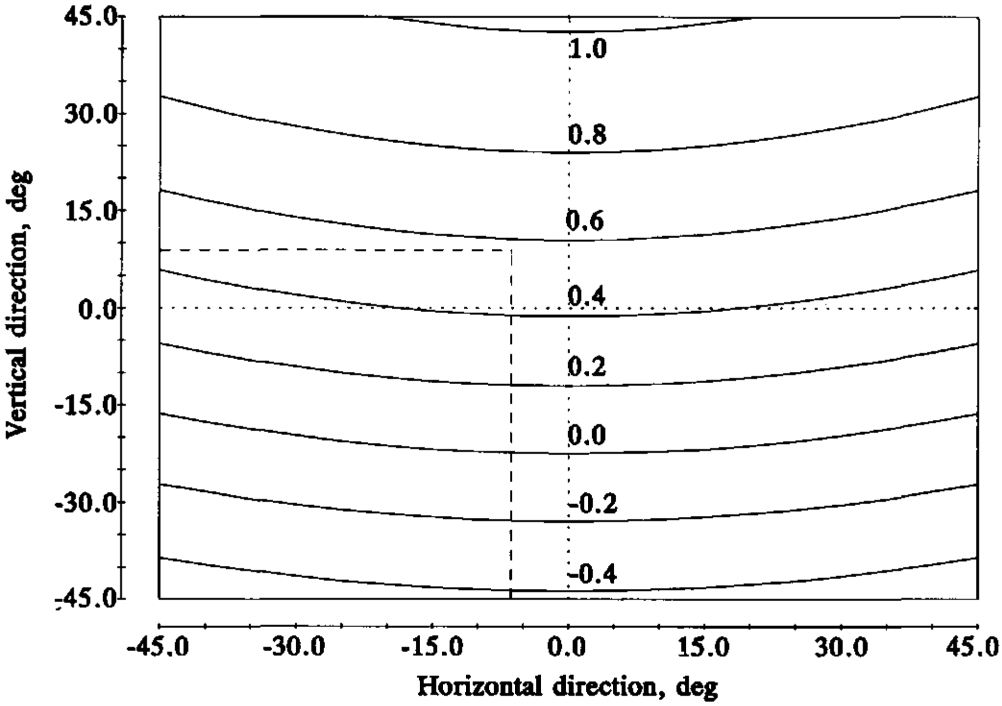

Fig. 9b Spatial sensitivity of the ultrasonic transducer for the Y direction.

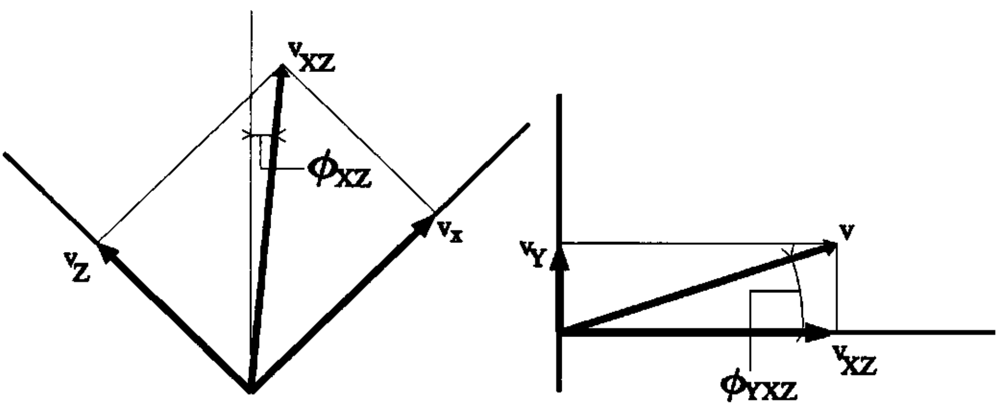

Fig. 10 Calculation of the horizontal (ϕ_{XZ}) and the vertical direction (ϕ_{YXZ}) of the particle from the velocities in the X, Y, and Z direction.

In the areas where the frequency shift approaches 0, the method is 'blind', i.e. it will not observe a particle. A negative frequency shift (for particles with a downward directed velocity) will be observed as a positive frequency shift. The occurrence of this situation can be determined from the calculated particle data and the position of the transducer unit. Direct detection of these negative frequency shifts requires another differently designed electronics for the Doppler velocity meter.

3.2. *Measurement frame*

The Doppler velocity meter must be able to measure the velocity of the particles discharged by the spreader at several points behind the spreader. To realize this, both transducer units (Dl and D2 in *Fig.* 2) are mounted on a frame (C in *Fig.* 2). This frame makes a circular motion behind the spreader to cover the circular area in the horizontal plane over which the fertilizer is spread. The transducer units must also be able to move in the vertical plane because the discharged particles have also a velocity in the vertical direction depending on the fertilizer spreader type. This vertical motion is realized by a linear displacement unit driven by an electric motor.

The frame (C) describes a reciprocating arc of about 210° around the spreader in the horizontal plane . The rotation axis of the frame coincides with the centre of the fertilizer spreader. The circumferential velocity of the frame is 0.34 m/s. The frame makes a certain number of strokes during one measurement. At the end of each stroke both transducers are raised a certain distance (in steps of 0.05 m) and the frame continues with the reverse motion. The number of strokes made and the vertical position at which they are measured is variable and depends on the fertilizer spreader whose discharge velocities are being measured.

The vertical positions are identified by 20 magnetic switches, each providing a unique voltage. The horizontal position of the frame is obtained from an accurate potentiometer. During the measurement the whole system is controlled by a computer that starts and stops the horizontal and vertical motions.

4. Data acquisition and processing

4.1. *Hardware for data acquisition and processing*

The central part of the data acquisition and processing system is an HP9000 Model 360 workstation. This computer controls the measuring devices of the system during the measurement and is the main processor for data-processing. The main task of the data acquisition system is recording the six output signals of the Doppler velocity meter and the horizontal position signal. A TEAC XR5000 datarecorder, equipped with FM amplifiers with a bandwidth ranging from d.c. to 40 kHz and a signal-to-noise ratio (SNR) of 47 dB is used for this purpose. The recorder uses VHS video tape and a high tape velocity (0.76 m/s) to realize the large bandwidth and the low SNR. The vertical positions of the frame are identified by event markers on the tape.

The main component of the data processing system is the HP3565S Measurement Hardware[16] in combination with the HP3565R Programmers Toolkit[17]. The measurement hardware consists of the following:

(1) An input module for simultaneous sampling of eight channels with a maximum sampling frequency of 32768 Hz per channel. Each channel is equipped with a pre-sampling filter to prevent aliasing. The module further has the opportunity to continuously throughput the digitized data to a hard disk;

(2) A source module (an accurate waveform generator) for internal calibration of the measurement hardware;

(3) A signal processing module with two Motorola 68000 processors for control of the measurement hardware and for signal processing and a Motorola DSP56000 for digital signal processing;
(4) A throughput hard disk with a capacity of 304 Mb and a data rate of at least 500 kbyte/s for storage of digitized data.

The programmers toolkit is a C-library with several functions and programs for control of the hardware and signal processing.

The data processing is divided into two steps. In the first step the tape is replayed event by event and the digitized data are stored on a hard disk. The replay velocity of the tape is a factor of four lower than the record velocity in order to reduce the frequency of the measured Doppler signals by a factor of four. This reduction is necessary because the maximum input frequency of the input module is limited to 12.8 kHz and the maximum frequency of the Doppler signals can be about 40 kHz. In the second step the digitized data are read block by block from the throughput hard disk and the instantaneous frequency and amplitude of the recorded Doppler signals are calculated. The three signals of each transducer unit are processed simultaneously and partly by parallel processing. The last part of the second step is the detection of particles from the computed instantaneous amplitudes and frequencies.

4.2. *Signal processing*

The signal processing consists of the following main steps:
(1) computation of the Hilbert transform of the time data $[H\{U_r(t)\}]$
(2) computation of the instantaneous amplitude of the time data $[U_r(t)]$
(3) computation of the instantaneous frequency of the time data $[f_d(t)$ or $\Omega(t)]$; this can be divided into:
   (1) computation of the phase of the analytic signal
   (2) unwrapping of the phase to remove the branch cuts each 2π
   (3) lowpass filtering of the unwrapped phase to remove the spikes before differentiating
   (4) differentiating the lowpass filtered unwrapped phase to calculate the instantaneous angular frequency

Digital filters are used for the Hilbert transformer, the lowpass filter, and the differentiator. Since the lowpass filter and the differentiator are successively executed, they are combined into one digital filter. Both digital filters involve time-consuming operations and they are therefore implemented in an assembler program running on the digital signal processor (DSP).

The designed digital filters are Finite Impulse Response (FIR) filters. Advantages of these filters are that they can be easily designed and they are stable[18]. One of the disadvantages is that large values of N, the impulse response duration, are required to adequately approximate sharp cutoff filters and consequently much processing time is required.

A widely used method for the design of digital filters is the Parks-McClellan algorithm[19,20]. This algorithm uses the Remez exchange algorithm and the Chebyshev approximation theory to design filters with optimal fits between the desired and the actual frequency response.

The designed Hilbert transformer is a 75 point digital filter, the low pass filter a 60 point digital filter and the differentiator a 10 point digital filter. Convolution of the last two resulted in a 69 point combined low pass - differentiator filter. The details of the filter design and the characteristics are described by Hofstee[5].

4.3. *Implementation*

The technique described in the previous section is translated into various computer programs that run on the workstation, the signal processing module, and the DSP. The processing of the data from one measurement of about 3 min takes about 15 h. This processing involves the calculation of the instantaneous amplitude and frequency of more than 300 Mb digitized data and the detection of particles from these signals.

The application of the signal processing technique on real Doppler signals is illustrated in *Fig. 11*. The figures at the left-hand side show the demodulated Doppler signals from the three receivers of the same particle. The figures in the centre show the envelopes of the Doppler signals and the three figures at the right-hand side show the instantaneous frequencies of the three Doppler signals. The small decrease of the Doppler frequency shift when the particle passes through the beam is due to the fact that the angles ϕ_{ri} and ϕ_t vary when the particle passes through the beam.

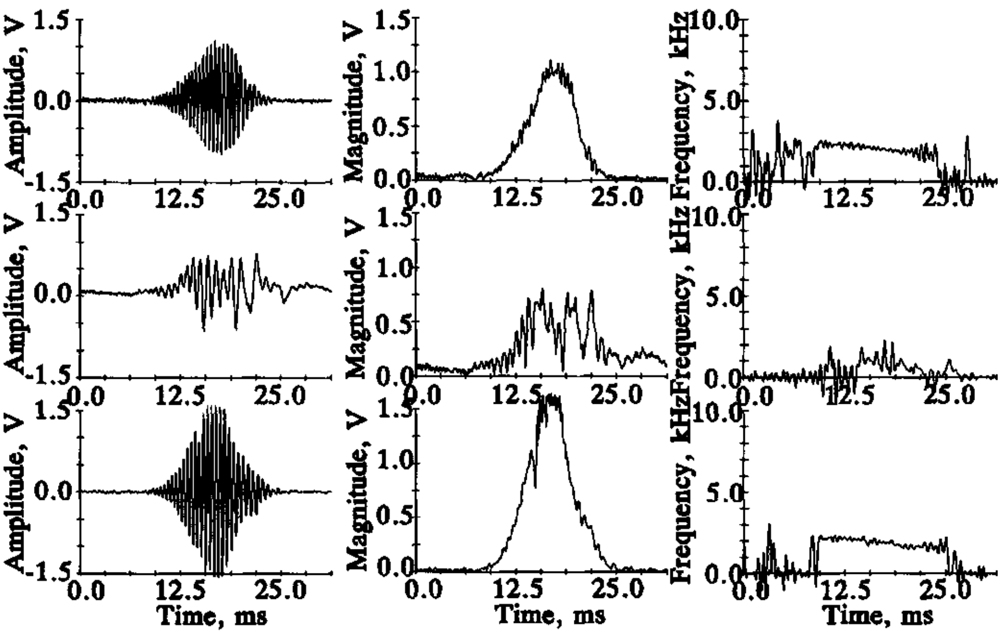

Fig. 11 Doppler signals (left), corresponding envelopes (middle) and instantaneous frequencies (right).

5. Experiments

A series of experiments were executed with the following objectives: (a) to test the developed hard- and software, (b) to obtain information about accuracies with respect to the velocity and direction that can be realized with the developed measuring method, and (c) to investigate the possibilities for the estimation of the particle diameters from the measured signals. Experiments where the velocities of particles that are discharged by a fertilizer spreader are measured, will be discussed separately[12,13].

5.1. *Experimental arrangement and materials*

In the experimental arrangement the fertilizer particles are discharged by a particle accelerator. This particle accelerator consists of an electric motor that drives two geared belts covered with cellular rubber, a very elastic rubber with a large amount of porous space. The particles are fed between the belts, accelerated, and projected through the opening in the transducer unit. The velocity of the belts can be varied continuously between 2.9 and 18.1 m/s.

The experiments are executed with six fertilizers (calcium ammonium nitrate (CAN 27N) from two different manufacturers, NPK 12-10-18, NPK 17-17-17, NP 26-7, and NP 26-14) and five screen sizes (2.00, 2.36, 2.80, 3.35, and 4.00 mm screen size) of each fertilizer and stainless steel balls with four diameters (2.0, 3.0, 4.0, and 5.0 mm). The particles are projected with nine velocities of the belts, ranging from 2.9 to 18.1 m/s in steps of 1.9 m/s. For each combination of fertilizer, velocity, and diameter between 100 and 200 particles were projected through the opening of each of the transducer units. The Doppler signals were recorded during 15 s and the tapes with data were processed afterwards according to the procedure described in Section 4.2.

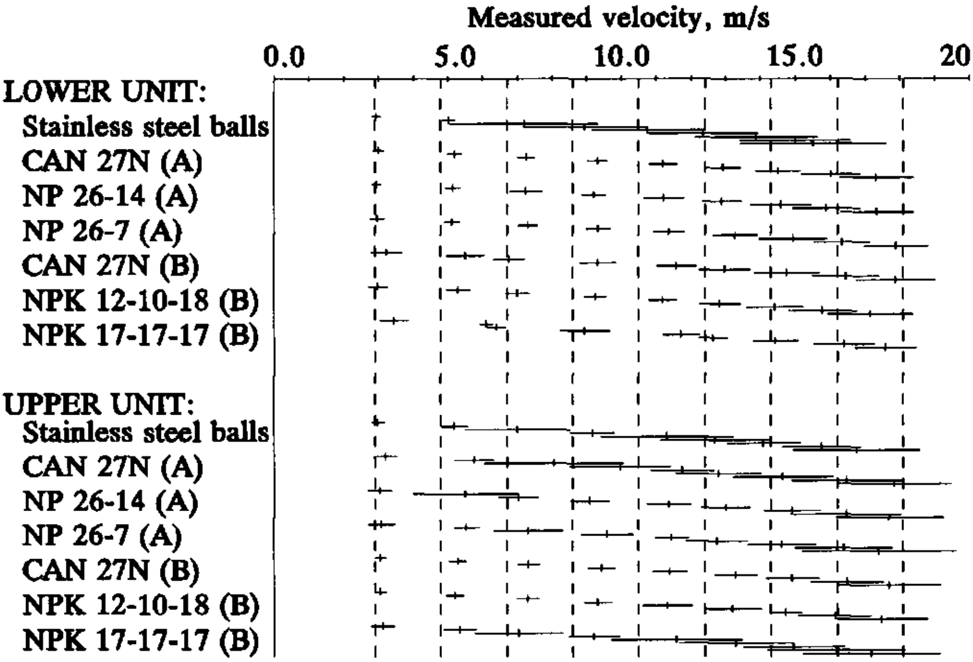

Fig. 12 Results of the velocity measurements with the fertilizers and the stainless steel balls. The vertical dashed lines indicate the nine velocities of the geared belts that were used. The means are indicated by a vertical bar and the length of the bar is equal to 2 σ.

5.2. *Velocity and direction*

The velocities of the particles are calculated from the three measured frequency shifts according to Eqn (13). *Fig. 12* gives the results of the measurements with respect to the velocities. The centre of each bar corresponds with the mean of a velocity setting and the total length of the bar is equal to 2 σ.

The data for each bar are based on all screen sizes of the fertilizers or diameters of the stainless steel balls at that velocity setting (about 500 observations per bar). The results show that the measured velocities of the lower velocity settings are higher and those of the higher velocity settings are lower than the belt velocities. However, almost all deviations of the means from the velocity settings are less than 10%. The main reason that the deviations show an increase in the negative direction when the velocity increases, is the assumption that $v_p \ll c$ which results in all velocities being underestimated. The actual underestimation depends on the velocity of the particle with respect to the propagation velocity of sound in

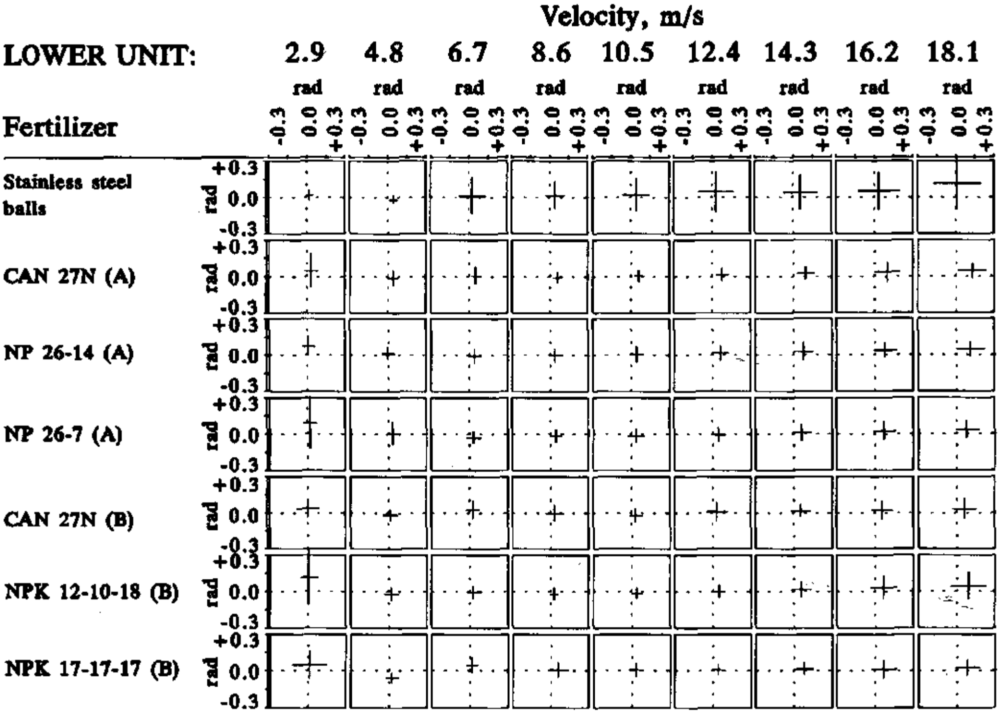

Fig. 13a Horizontal and vertical directions in radians of the observed fertilizer particles for each fertilizer and discharge velocity combination for the lower transducer unit. The point where the two bars (length 2 σ) cross each other is the mean for the horizontal and vertical direction. The intended discharge direction of the particles was such that the bars should cross each other at the centre of the square. The data are based on the average of the five screen sizes (fertilizers) or four diameters (stainless steel balls).

still air and the angles between velocity and receiver directions. For a particle with a velocity of 18.1 m/s the measured velocity will be about 7% lower than the real velocity. A second possible explanation for this difference is that the actual discharge velocity is not equal to the velocity of the geared belt. This can be due to interaction between cellular rubber and particle and to the stretching of the cellular rubber around the timing belt pulleys. The figure also shows that the standard deviations are especially large for the measurements with the stainless steel balls. The coefficient of variation (CV) of the stainless steel ball measurements ranges from about 5% to 30% and the CV of the fertilizer measurements ranges from about 4% to 11%. The exact reason for the large CV of the stainless steel ball measurements is not known. A possible explanation may be that more slip occurs between belt and stainless steel balls, because of the smoother surface of the stainless steel balls, than with fertilizer particles.

The directions of the particles are calculated from the computed velocities in the three directions. The directions of a particle (*Fig. 10*) are given by a direction in the horizontal plane (ϕ_{XZ}) and a direction in the vertical plane (ϕ_{YXZ}). The results of the measurements are shown in the *Figs 13a* and *13b* for both transducer units. Each square shows the mean direction of the discharged particles in the horizontal and the vertical plane for each fertilizer

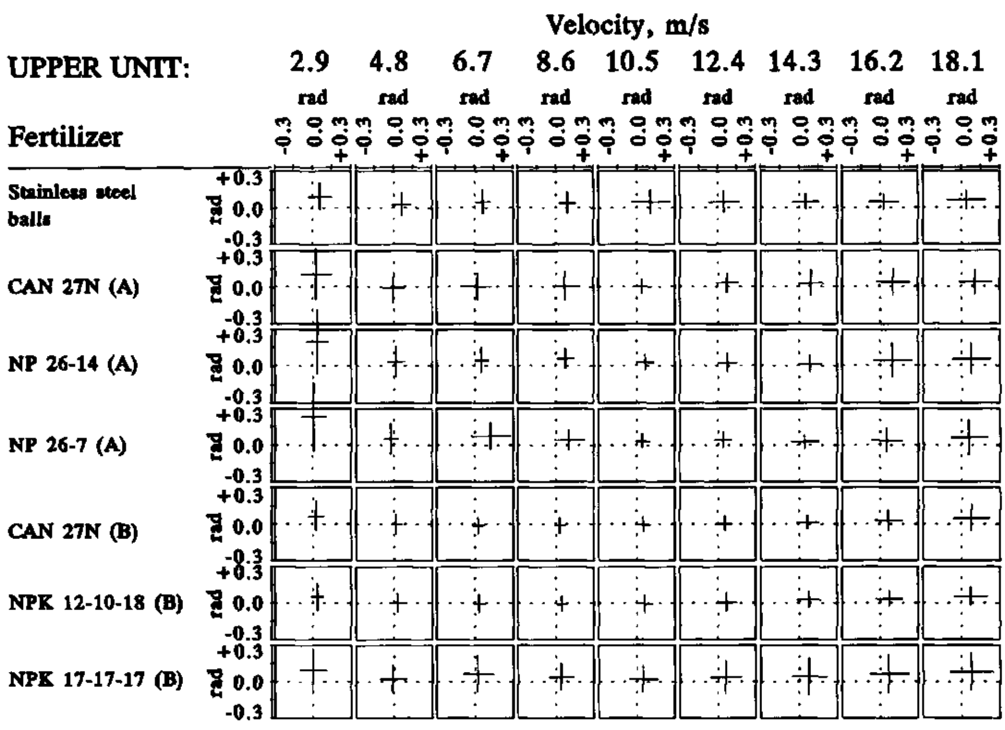

Fig. 13b Horizontal and vertical directions in radians of the observed fertilizer particles for each fertilizer and discharge velocity combination for the **upper** *transducer unit. The point where the two bars (length 2 σ) cross each other is the mean for the horizontal and vertical direction. The intended discharge direction of the particles was such that the bars should cross each other at the centre of the square. The data are based on the average of the five screen sizes (fertilizers) or four diameters (stainless steel balls).*

and discharge velocity combination. The point where the bars cross each other is the mean and the length of the bar corresponds with 2σ. All particles are discharged with equal velocities v_{pX} and v_{pZ} in the horizontal plane and no velocity in the vertical direction ($v_{pY} = 0$). Therefore the bars should coincide with the dotted grid lines.

The results for the upper and lower transducer unit show that the means for most of the combinations deviate in the horizontal plane about 0.07 rad from the centre direction. This deviation can be caused by the particles not being projected exactly in the centre direction through the openings of the transducer units. A deviation of the sensor geometry from the angles given in Section 3.1.2 can also contribute to the deviation. However, if these deviations are present, they are small. The results for the directions in the vertical plane are more varying. Both mean values < 0 (downward directed velocity) and > 0 (upward directed velocity) occur. However, upward directed mean velocities are in the majority.

5.3. *Particle size*

Each detected particle has three amplitudes that can be used for the particle diameter estimation. Theoretically a larger particle should give a larger amplitude of the Doppler signal. However, the amplitude of the reflected signal does not depend only on the particle

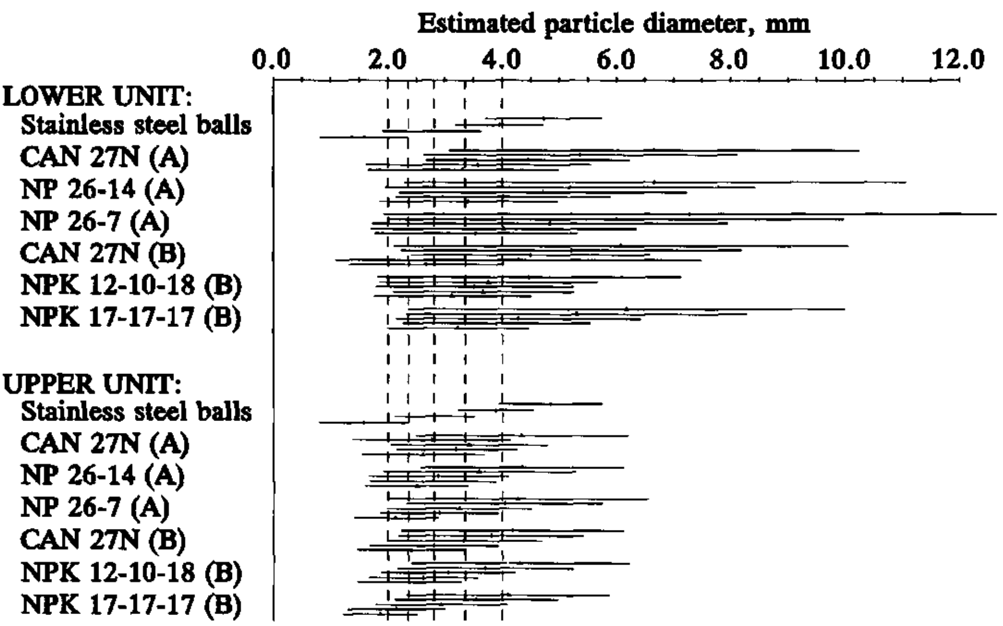

Fig. 14 Results of the application of the developed diameter estimators to the fertilizer data. Lower unit and upper unit refer to the two transducer units. The five bars above each other for each fertilizer correspond with the screen sizes of the fertilizers (from bottom up: 2.00, 2.36, 2.80, 3.35, and 4.00 mm screen size). The four bars above each other for the stainless steel balls correspond with the diameter of the stainless steel balls (from bottom up: 2.00, 3.00, 4.00, and 5.00 mm). The vertical dashed lines indicate the five screen sizes of the fertilizers.

size but also on the velocity of the particle (due to the frequency response curve), the transducer properties, and possibly environmental conditions such as temperature. Furthermore it can also be affected by the internal (absorption of sound) and external (reflection of sound) structure of the particle. A disturbance can also occur when the amplitude of the Doppler signal exceeds the input range of the data recorder.

Analysis of the measurements with the different screen sizes of the fertilizers and diameters of the stainless steel balls showed that a larger particle size resulted in a larger mean amplitude of the Doppler signal for almost all velocity settings for both fertilizers and stainless steel balls. The results of the stainless steel ball measurements have been used to develop a particle diameter estimator. The data of the fertilizers are not used because the diameters of the particles vary within each screen size. The development of the diameter estimation was carried out in two steps. In the first step, a diameter was estimated for each direction ($\hat{d}_{p,X}$, $\hat{d}_{p,Y}$, and $\hat{d}_{p,Z}$). This estimation was based on the amplitude, frequency, and diameter results of the measurements. The second step was the estimation of the parameters β_X, β_Y, and β_Z in the model:

$$\ln(d_p) = \beta_X \hat{d}_{p,X} + \beta_Y \hat{d}_{p,Y} + \beta_Z \hat{d}_{p,Z} \tag{14}$$

The ln of the original particle diameter has been taken to base the least squares estimation of the parameters on relative deviations instead of absolute deviations.

The two developed estimators (one for each of the two transducer units) are applied to the fertilizer data. The results are given in *Fig. 14*. The figure shows the mean estimated particle size for the six fertilizers and both transducer units. The five bars above each other correspond from bottom up with with the five screen sizes (2.00, 2.36, 2.80, 3.35, and 4.00 mm). The figure also shows the results when the diameter estimators are applied to the stainless steel measurements results, i.e. the data on which the estimators are based. The four bars above each other correspond from bottom up with the four diameters of the stainless steel balls (2.00, 3.00, 4.00, and 5.00 mm).

Very conspicuous are the very large values of the standard deviation of the estimated diameters, especially those from the lower transducer unit. The data also show that, in most cases, a larger screen size results in a larger mean estimated particle diameter. The estimated diameters of the fertilizers of the lower transducer unit are much larger than the original diameters. The mean estimated diameters of the upper transducer unit agree reasonably well with the original screen sizes. The results show that the estimators do not provide an accurate estimation of the diameter of individual particles. Since a larger mean diameter results in a larger estimated diameter the estimation of the diameter of individual particles can be improved when the particle size distribution of the tested fertilizer is also supplied to the estimator. The estimated particle size distribution can be brought into concordance with the physical particle size distribution as measured by testing sieves or other appropriate methods. However, the ranges are so large that it is expected that it will continue to be very difficult to make a good diameter estimation from the amplitude of the received signals. It can be improved by using ultrasonic transducers with a more uniform frequency response so that the amplitudes will be less velocity dependent.

6. Conclusions

6.1. *Measuring method*

The measuring method discussed is a new method for measuring the influence of the physical properties of fertilizer on the motion of these particles in the distributor device of a fertilizer spreader. The method measures the velocity and the direction of fertilizer particles by measuring the velocity in three orthogonal directions. The method also has potential for the measurement of particle diameters.

The current processing procedure for the data is relatively slow. It takes about 15 h to process all the data associated with one measurement of about 3 min. However, this is the best that can be achieved with the equipment available. Further improvemenys can be achieved by more parallel processing and by replacing parts of the software with hardware.

6.2. *Velocity and direction measurement*

The velocity measurement is based on the Doppler frequency shift of an ultrasonic beam. The velocity of the particle is obtained directly from the frequency shift and does not need any calibration. It only requires that the propagation velocity of sound in air and the sensor geometry are known.

The coefficient of variation of the measured velocities was about 10% and the mean measured velocities deviated to a maximum of about 10% from the velocity of the belts with which the particles were accelerated. The calculated directions showed a small systematic deviation (about 0.07 rad) from the zero horizontal or centre direction. This is probably caused by the fact that the particles were not projected exactly in the centre direction. The vertical directions showed both positive and negative deviations from the zero vertical direction.

6.3. *Particle diameter measurement*

The measurement of the particle diameter is based on the amplitude of the reflected signals and this is influenced by the frequency response of the ultrasonic transducers used. Since this frequency response is not flat in the frequency band used, the estimation of the diameters is very difficult. The estimation of the diameters of individual particles showed a large variation in estimated diameters of particles with the same screen size. The results further showed that there were, in some cases, large differences between mean estimated and mean real diameter. The results also showed that in most cases a larger original mean diameter also resulted in a larger mean estimated diameter. It is expected that use of the physical particle size distribution of the tested fertilizer can be helpful in bringing the estimated particle size distribution in concordance with the physical particle size distribution. Particle diameter estimation can further be improved by using ultrasonic transducers with a flat frequency response in the frequency band used.

Acknowledgements

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Chapter IV
Experiments

Chapter IV-A
The reciprocating spout type fertilizer spreader

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Handling and Spreading of Fertilizers Part 4A: The Reciprocating Spout Type Fertilizer Spreader

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The motion of particles as affected by physical properties as coefficient of friction and coefficient of restitution and the design of the spout (spout length, bow, spout angle) and the propulsion of the spout (angular velocity driving shaft, crank - connecting rod ratio) is discussed. The influences of the factors that may have an effect are studied theoretically, by means of a simulation model, and experimentally (Doppler velocity meter).

The results of the simulations and the measurements show that it is very difficult to model the behaviour of the fertilizer in this type of spreader because of the oscillatory action of the spout. Resulting values for velocities and durations of stay depend heavily on whether the motion of the particles along the spout is 'in phase' with the motion of the spout. The sorting-in process (from the hopper to the bowl at the beginning of the spout) plays a very important role.

1. Introduction

Physical properties of fertilizer affect the spread pattern. Determination of the ultimate ffect of a physical property on the spread pattern requires an analysis of the relation between he physical properties and the particle motion for a specific distributor device. The properties hat are relevant in relation to the particle motion have recently been discussed by Hofstee and Huisman[1] and methods for measuring these properties and some relevant data by Hofstee[2].

The Department of Agricultural Engineering and Physics, Wageningen Agricultural University, started a research project at the end of 1987 to study the physical properties of ertilizer that are relevant to its spreading and handling. Within this research project a new neasuring method has been developed that makes it possible to measure particle motion with nass flows on a real scale. The method is based on the measurement of the discharge velocity nd direction of fertilizer particles in a grid around the fertilizer distributor. The velocity neasuring technique is based on the ultrasonic Doppler frequency shift. The background heory and the important characteristics of this method are discussed by Hofstee[3,4]. This neasurement setup has been used to evaluate the effect of physical properties and design and perating parameters on the motion of fertilizer particles for a reciprocating spout type and spinning disc type fertilizer spreader. The results of the latter are discussed separately[5].

Notation

l_{sp}	length spout, m	$\alpha(t)$	instantaneous angle driving shaft, rad
p	spout wall indicator (-1 = left, +1 = right)	β	angle of dispatch, rad
q	diameter coefficient, -	γ	spout angle, rad
r_p	radius particle, m	ε^*	imaginary coefficient of restitution, -
r_{spe}	radius spout entrance, m		
t	time, s	ϕ_{sp}	oscillation angle spout, rad
v_{xsp}	velocity along spout wall, m/s	μ	coefficient of friction, -
v_p	velocity of the particle, m/s	μ^*	imaginary coefficient of friction, -
x_{sp}	position along spout wall, m		
		ρ_p	density particle, kg/m^3
C	crank - connecting rod ratio, -	ω_{ds}	angular velocity driving shaft, rad/s
		ω_1	initial angular velocity particle, rad/s

This paper first discusses the kinematics and the motion of particles in the spout of a reciprocating spout type fertilizer distributor. It then proceeds to give a description and analysis of the measurements that are executed.

2. Kinematics and spout design

Several researchers have studied the behaviour of the reciprocating spout type fertilizer spreader. Casella[6], Pellizzi[7], and Romanello[8] analyzed the kinematics of the reciprocating spout and did some additional spread tests. Speelman[9] continued this analysis because earlier researchers did not treat the possible relationships between the kinematics of the spout and the process of particle motion in sufficient detail. He started with a more detailed analysis of the effect of the design factors of the driving mechanism on the oscillation characteristics of the spout.

The oscillation angle of the spout is equal to:

$$\phi_{sp}(t) = \arctan\left(\frac{\cos\alpha(t)}{\sqrt{C^{-2}-1}}\right) \tag{1}$$

where $\alpha(t)$ is the instantaneous angle of the driving shaft and C the ratio between the length of the crank and the length of the connecting rod of the mechanism that drives the spout. The angular velocity and angular acceleration of the spout can be obtained by differentiating Eqn (1) respectively once and twice and are given in *Fig. 1* for three different values of C. The local minimum for the angular acceleration appears when $C \geq 1/\sqrt{6}$ (=0.408) (Ref. 9).

The spout of the spreader (*Fig. 2*) is a converging and slightly oval tube made of nylon strengthened with glass fibre. Inside the spout there are two ribs to prevent the particles starting a circular motion along the spout wall during transport. At the end the spout is equipped with a bow that has the task of transforming the default two peak single spread pattern into a one peak spread pattern. Part of the bow is also a bridge that makes an angle

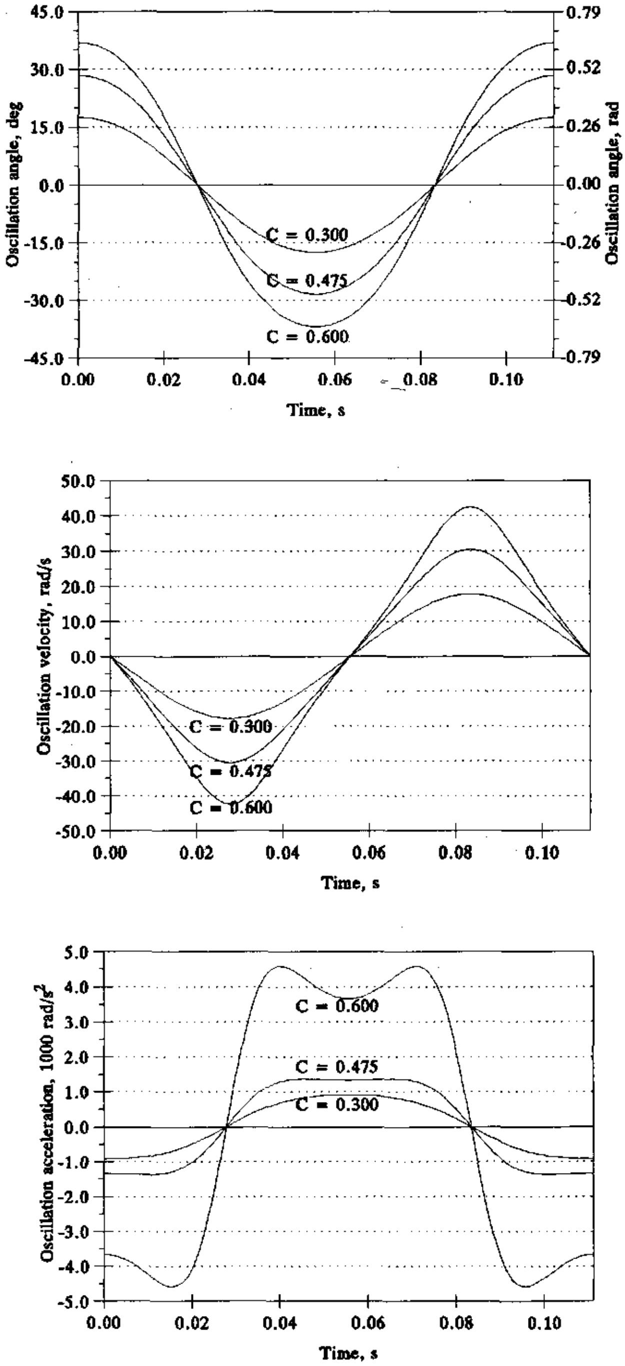


Fig. 1 Oscillation angle of the spout ($d\phi/dt$, $d\phi/dt$, $d^2\phi/dt^2$) as a function of the time for three different values of the crank - connecting rod ratio C.

of 45° with the horizontal and gives some of the particles an additional vertical velocity. The most important design parameters of the spout are illustrated in *Fig. 3*.

Bahasoean and Brouns[10] did some simulation and experimental work to study possibilities for enlarging the working width. A change of the kinematics (higher oscillation frequency or larger oscillation angle) or increase of the spout length are almost impossible because a linear increase results in a quadratic increase of the acceleration and hence the forces acting on the spout. The only opportunity is to change the construction so that the particles are discharged with a vertical velocity component. Consequently they changed the mounting of the spout so that the spout made an angle (up to 40°) with the horizontal and they also mounted a plate at the end of the spout (angle with respect to the spout up to 40°). The results of the experiments (with polyethylene) showed an increase of the maximum throwing distance from 7 m to 9.5 - 11.5 m. No research, however, was conducted with respect to the distribution pattern.

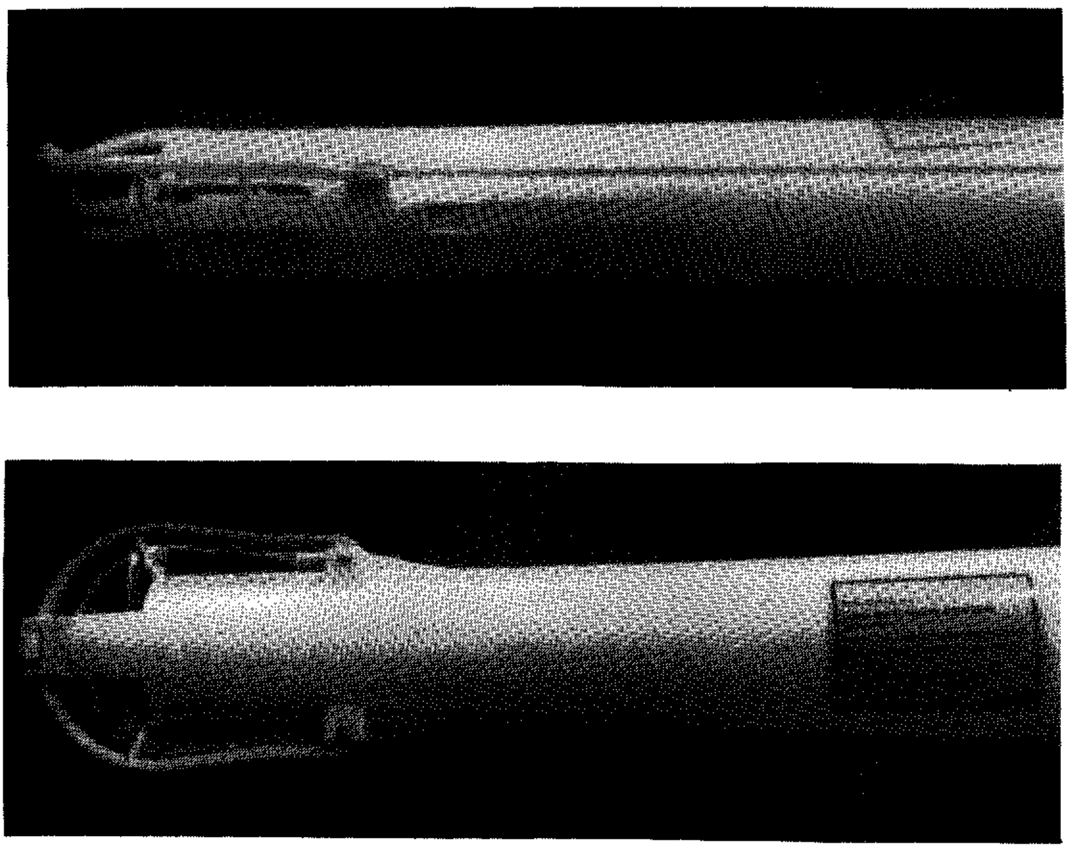


Fig. 2 Side view and top view of the spout of a reciprocating spout type fertilizer spreader.

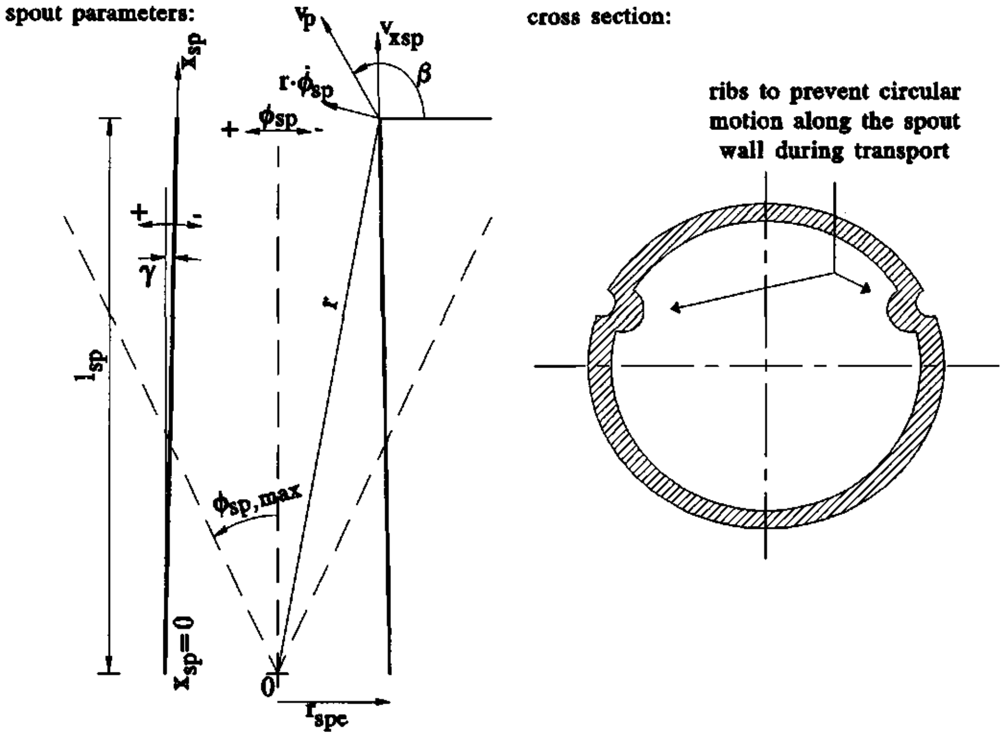


Fig. 3 Important parameters of the spout for the simulation of the motion of particles in the spout and the cross-section of the spout.

3. Particle motion

3.1. *Model of Speelman*

As derived by Speelman[9], the general equation for the motion of a particle that only slides along the spout wall is:

$$\frac{d^2x_{sp}}{dt^2} - 2\mu\frac{d\phi_{sp}}{dt}\frac{dx_{sp}}{dt}p - \mu\frac{d^2\phi_{sp}}{dt^2}x_{sp}p - \left(\frac{d\phi_{sp}}{dt}\right)^2 x_{sp} - \dots$$
$$\frac{d^2\phi_{sp}}{dt^2}r_{spe}p + \mu\left(\frac{d\phi_{sp}}{dt}\right)^2 r_{spe} = 0 \tag{2}$$

and when the particles just purely roll along the wall of the spout, the equation becomes:

$$\frac{d^2x_{sp}}{dt^2} - (5/7)\left(\frac{d^2\phi_{sp}}{dt^2}r_{spe}p + \left(\frac{d\phi_{sp}}{dt}\right)^2 x_{sp}\right) = 0 \tag{3}$$

The spout wall indicator p is equal to -1 for the left wall and +1 for the right wall. The impact of a particle on the wall follows the models for stick and sliding impact as derived by

Adam[11]. In the case of stick impact, the angle of reflection only depends on the initial particle rotation. In the case of sliding impact the angle of reflection depends on both the elastic and the friction properties of the particle and not on the initial particle rotation.

The model developed by Speelman is based on the Eqns (2) and (3) and the impact models of Adam[11]. The first part of the simulation work was the calculation of particle trajectories for many initial conditions (imaginary coefficient of friction and restitution and initial particle rotation). The simulation results were compared with trajectory data for two fertilizers, obtained from analyses of high speed films. Simulation and measurement results were compared with respect to the discharge velocity, the duration of stay in the spout, and for the particles that met these two parameters, also with the angle of dispatch β, see also *Fig. 3*. For the uncoated chilisaltpeter granules good agreement was found for the values $\omega_1 =$ -4000 rad/s, $\mu^* = 0.2$, and $\varepsilon^* = 0.4$ and for the coated ammonium nitrate prills good agreement was found for $\mu^* = 0.1$ and $\varepsilon^* = 0.7$. Due to the low value of the imaginary coefficient of friction, the initial rotation of the particle was found to be unimportant.

A second part of the simulation work was the study of the effect of design variables on the motion of particles. The most important results and conclusions from Speelman's[9] work are:

(a) spout length (l_{sp})
An increase of the spout length does not result a priori in a higher discharge velocity due to the possible interception of particles by the spout wall. It was assumed that this also depends on the sorting-in process and the flow properties of the particles. It was found that an increase of the spout length creates possibilities for an increase of the discharge velocity of the particles of about 0.5 - 1.0 m/s for each 0.04 m increase of the spout length.

(b) spout angle (γ)
The spout angle appeared to have a very small effect on the discharge velocity. The effect on the dispatch angle was larger but there was no particular tendency.

(c) rotary frequency (ω_d)
An increase of the rotary frequency resulted in a mean increase of the discharge velocity of about 2 m/s for each increment of 60 rev/min. For the shortest spout length (0.63 m) the mean angle of dispatch decreased and for the longest spout length (0.75 m) the mean angle of dispatch increased. However, the latter was due to the presence of two extreme values.

(d) crank - connecting rod ratio (C)
An increase in ratio resulted in an increase of the oscillation angle and in higher maximum and mean values of the angular velocity of the spout. The discharge velocity of the particles increased by about 3 - 4 m/s for each increment of C by 0.075 (about 4.7° increment of the maximum oscillation angle). The effect on the mean angle of dispatch did not show a uniform tendency and the variations were considerable. The practical consequence of this is that the bow at the end of the spout must be adapted for the fertilizer type. Unwanted and unexpected variations can occur when applying one single type of bow at the end of the spout.

(e) C, ω_d, and l_{sp}
A combined increase of these three factors resulted for the highest values of ω_d (=69.12 rad/s) and C (=0.6) in an increment of the mean discharge velocity varying from 10 m/s (l_{sp} = 0.63 m) to 17 m/s (l_{sp} = 0.75 m) and an estimated increase of the throwing distance by 5.0 to 12.0 m. The effect on the mean angle of dispatch was as expected: an increase of the discharge velocity was attended by an increase of the mean angle of dispatch and an estimated increase of the spread width of about 4.4 m.

(f) accessories at the end of the spout
Analysis of the effect of the bow and the grooves at the end of the spout showed that the objective of these attributes, which is changing the flow from divergent into convergent and to transform the two peak spread pattern into a one peak spread pattern, must be obtained from the action in the vertical plane since the bow did not contribute to a more convergent character of the flow.
The velocity in the horizontal plane increased slightly and the mean angle of particle dispatch decreased which resulted in a slight increase in the spread width. The trajectories in the vertical plane showed an increase in the variation of the angle of elevation. The negative mean value indicated that a majority of the particles were directed downwards to the centre which provided the opportunity for a one peak spread pattern.
The process of dispatch was found to depend strongly on the physical properties of the fertilizer and thus on the previous character of the particle motion in the spout. Therefore, the design of the bow must be adapted and optimised for various fertilizers.

3.2. *Adjusted model*

Based on the work of Speelman[9] and Bahasoean and Brouns[10], an adapted version of their simulation models has been developed. The new model rests on the assumption that the particles do not behave individually but that they move as a kind of packet in the spout. This assumption is supported by the analysis of some high speed films that have been made to analyze the motion of the fertilizer in the spout with realistic mass flows. The model developed neglects both the rotation of particles and the rebound of particles when they impact on the opposite spout wall after crossing the spout. These effects are neglected because it is supposed that the large amount of particles that are actually in the spout (about 1000 or more) mean that both motions are almost impossible because there will be too much interaction between the particles themselves.

The bow and the grooves at the end of the spout have not been incorporated into the model. The shape of these attributes at the end of the spout is such that it is almost impossible to model. So the results discussed in the next sections apply to what happens in the spout itself.

The motion of the particles in the spout is as follows. The particles start to slide along the wall. At a certain moment the velocity of the wall decreases due to the oscillation characteristic. The particles leave the wall and start crossing the spout. They usually impact on the other spout wall when the spout is in its reverse motion. Then the particles continue to slide along the wall and either leave the spout or cross the spout again. When they cross the spout, they can either leave the spout during the crossing or impact on the opposite spout wall and slide further along this wall and leave the spout.

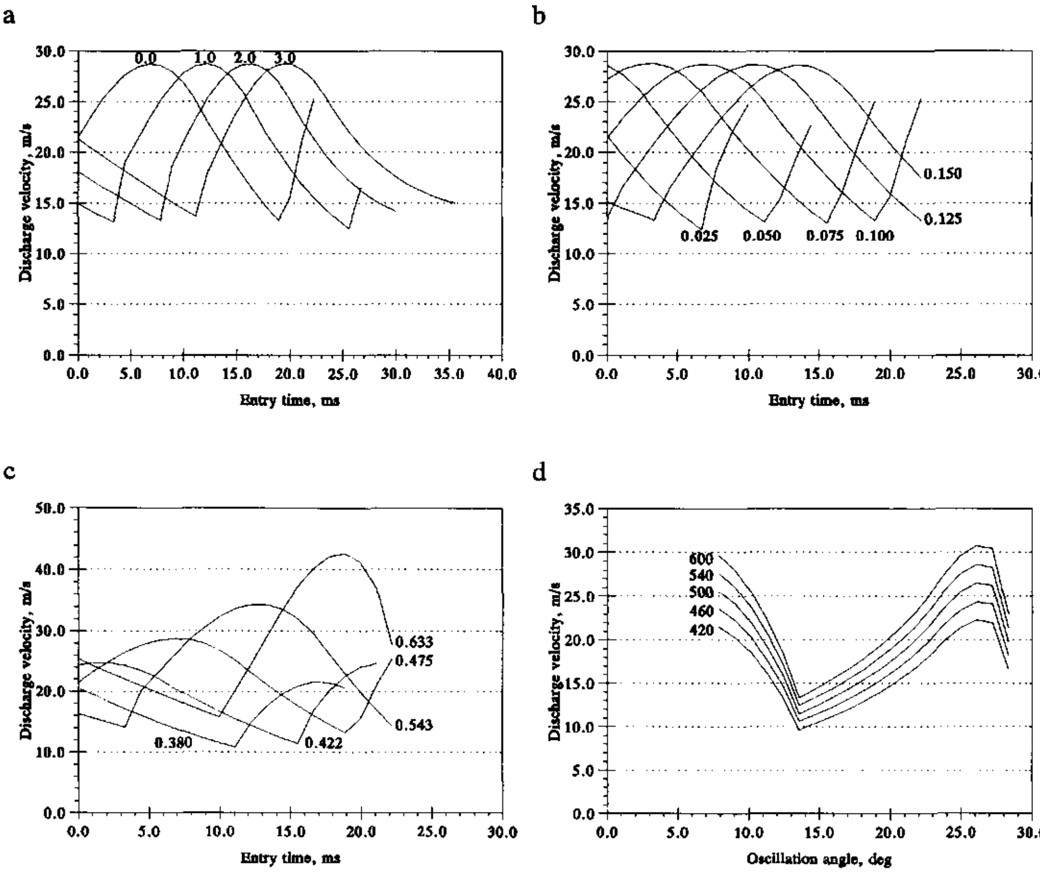
The actual motion of the particles depends very much on the time they enter the spout, i.e. the instantaneous oscillation angle of the spout, and their initial sliding velocity at the entry time.

Fig. 3 shows the most important parameters of the spout. The effects of the several factors on the motion of the particles are shown in *Fig. 4*. The curves in *Fig. 4* terminate when either one half oscillation is finished or the particle does not start the motion along the spout wall. All figures (except *4d*) use time for the X axis and not the oscillation angle of the spout since the flow of particles into the spout is constant with respect to the time and not with respect to the oscillation angle. *Fig. 4d* uses the oscillation angle since time and oscillation angle are not synchronous for different angular velocities of the driving shaft. All simulation runs contain at least the following initial conditions: $x_{sp} = 0.10$ m, $v_{xsp} = 0.0$ m/s, $\mu = 0.40$, $\rho_p = 1800$ kg/m^3, $r_p = 4.0$ mm, $q = 1.0$, $\omega_{ds} = 18\pi$ rad/s (540 rev/min), $C = 0.475$, $\gamma = -1°$(convergent), $r_{spe} = 0.08$ m and $l_{sp} = 0.63$ m.

It is not possible to derive from *Fig. 4* mean values for discharge velocities. This requires that the number of particles that start the motion at a certain time (or oscillation angle) is also known.

3.2.1. *Initial model parameters*

The model simulates the motion of the spout during one half oscillation. The spout starts at its left most position (entry time is 0.00 s and the oscillation angle is equal to the maximum oscillation angle) and moves to its most right position. Particles are entered at regular times during this motion. Calculations for the reverse spout motion are not executed since the results will be the same. The initial model parameters (oscillation angle, initial velocity and initial position) are considered to represent the sorting-in process that has been found to be very important for the further motion in the spout[9].



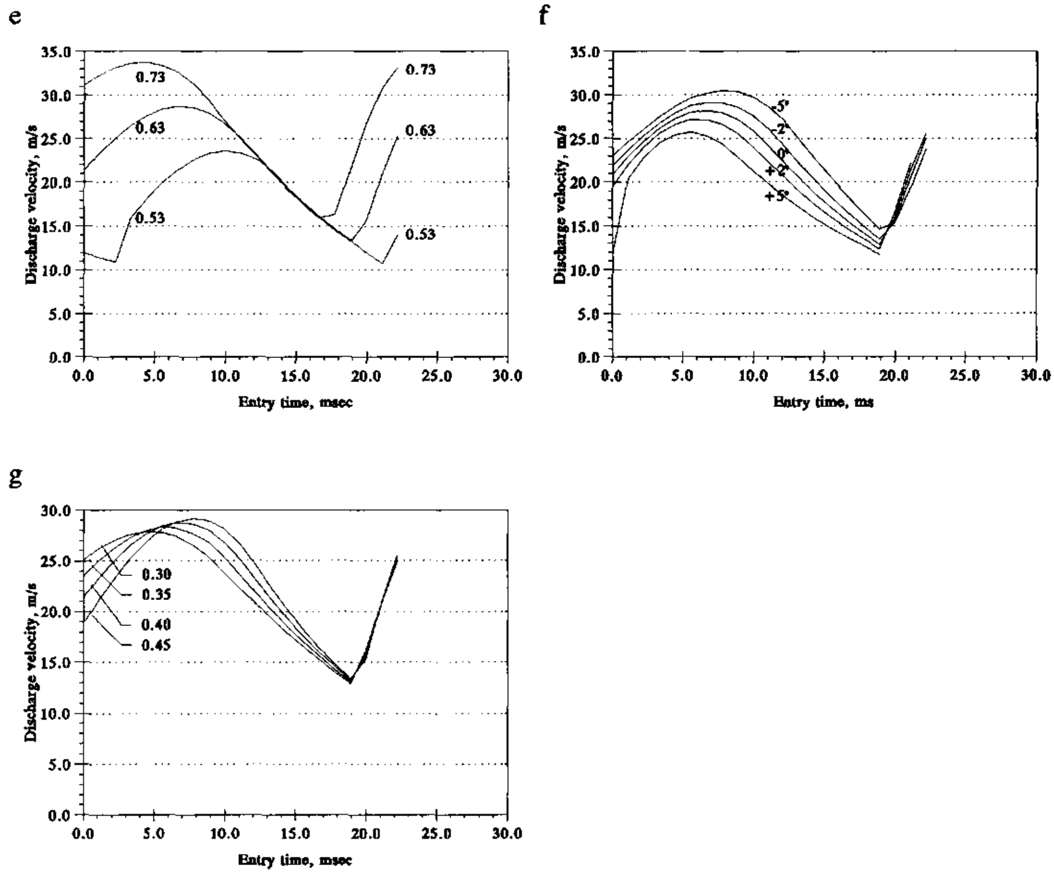


Fig. 4 Results of the simulation experiments with respect to the effects of the sorting-in process, the design parameters and the fertilizer properties on the discharge velocities. (a= initial velocity in m/s (v_{xsp}), b= initial position in m (x_{sp}), c= crank connecting rod ratio, d= angular velocity driving shaft in rev/min, e= length of the spout in m (l_{sp}), f= spout angle in degrees (γ), g= coefficient of friction)

3.2.1.1. *Entry time or oscillation angle.* The entry time can be understood as the moment a particle starts to move and determines the oscillation angle of the spout when the simulation starts (Eqn (1) and *Fig. 1*). It depends on the oscillation angle whether particles can start an outward bound motion or not. Beyond a certain angle the resulting force acting on the particles is directed inwards the spout. This means, in practice, that the particles will remain in the bowl just before the spout and under the metering device and start the motion along the spout wall when the spout starts with its reversal motion.

3.2.1.2. *Initial velocity.* The effect of the initial velocity is shown in *Fig. 4a*. It shows that the effect of the initial velocity depends on the time (or oscillation angle) when the particles start to move because this determines where the particles will start to cross the spout and contact the other spout wall and therefore the moment of discharge. The resulting discharge velocities depend on the velocities of the particles along the spout wall and the angular velocity of the spout itself at discharge time. The figure shows that a higher initial velocity does not result a priori in a higher discharge velocity when they start the motion at the same oscillation angle of the spout.

3.2.1.3. *Initial position.* The initial position of the particle along the spout wall (x_{sp} when the particles enter the spout) shows a similar effect as the initial velocity does (*Fig 4b*). It affects the crossing of the spout by the particles and therefore the moment of discharge and the discharge velocity. The figure further shows that particles that start to move at the beginning of the spout encounter problems in starting the motion when the oscillation angle of the spout increases. The figure further shows that a lower or higher initial position does not result a priori in higher or lower discharge velocities.

3.2.2. *Propulsion and spout design*

3.2.2.1. *Crank - connecting rod ratio.* The parameter C affects the oscillation characteristics of the spout and therefore the motion of particles in the spout. An increase of C generally results in shorter durations of stay and larger discharge velocities but actual values depend strongly on the oscillation angle of the spout at the start of the simulation. The effects are illustrated in *Fig. 4c* and the results show that a higher value of C results in higher discharge velocities that can be reached but not, a priori, in a higher discharge velocity.

3.2.2.2. *Angular velocity driving shaft.* The results of the effect of an increase of the angular velocity of the driving shaft (*Fig. 4d*) show that a higher angular velocity results in a higher level of the discharge velocity. The actual discharge velocity depends on the oscillation angle at the start of the simulation. Further it has to be mentioned that the amount of particles in the spout varies with the angular velocity since at a higher angular velocity an oscillation will last for a shorter period of time and the total number of particles in the spout will be less.

3.2.2.3. *Spout length.* The effect of the spout length on the discharge velocities is given in *Fig. 4e*. The figure shows that an increase of the spout length does not always result in a higher discharge velocity. There is a certain trajectory where spout length does not have any effect. This trajectory corresponds with particles that cross the spout a second time and leave the spout during this crossing. For these particles the spout length does not matter within certain limits.

3.2.2.4. *Spout angle.* The spout angle determines whether the spout becomes smaller (convergent) or wider (divergent) towards the end. A spout angle that decreases from +5° to -5° results for most entry times in a larger discharge velocity (*Fig. 4f*). Only for those entry times (> 18 ms) where the particle crosses the spout twice and leaves the spout when sliding along the wall, the effects are opposite.

3.2.3. *Physical properties*

In theory the most important physical property that affects the motion of particles is the coefficient of friction. The effect of the coefficient of friction on the discharge velocity is illustrated in *Fig. 4g* and it shows that the effect depends heavily on the entry time. A higher coefficient of friction results initially in a lower velocity along the wall and a lower discharge velocity. But after a certain entry time, a higher coefficient of friction results in a higher discharge velocity. Due to the lower velocity along the wall at the start, the particles cross the spout at a more favourable position. As a consequence of this they are discharged at a time when the spout has a higher velocity. The coefficient of friction hardly affects the discharge velocities of those particles that cross the spout twice and leave the spout when sliding along the wall.

Other physical properties of fertilizer that can affect the motion of particles in the spout, like particle density and particle radius, hardly affect the motion of particles. These properties will affect the consecutive motion through the air since they affect the aerodynamic resistance of the fertilizer particles. The used model uses the aerodynamic resistance of the particles during their cross spout motion but the effects are small due to the very small distances involved.

3.3. *Discussion*

Comparing the simulation results with those obtained by Speelman[9] shows that there is a great deal of similarity between the results. Effects noticed by Speelman[9] are supported by the simulation results. The simulation work showed that the discharge velocity also depends on whether the particles are intercepted by the spout wall or not and therefore that the spout length does not affect the discharge velocity in all situations. The occurrence of a second interception by the wall depends on the length of the spout but also on the sorting-in process (initial position and initial velocity) and the motion along the spout wall (coefficient of friction).

The analysis of the effect of the entry times showed that it is very difficult for this type of spreader to find particular trends for a specific parameter since the effects largely depend on the entry times and the actual entry times and initial conditions depend on the sorting-in process. A small change in the sorting-in process, e.g. the initial velocity, can have a large impact on the discharge velocity. Other design parameters like the angular velocity of the driving shaft, can also affect the sorting-in process.

A property that is difficult to model is the mass flow. However, it may be expected that the mass flow will affect at least the sorting-in process and therefore the discharge velocities. Due to this interaction, the effect of the mass flow can depend on a specific combination of all parameters that have an effect and a small difference in these parameters can result in an opposite effect on the discharge velocity.

Comparison of the simulation results with those usually obtained and mentioned in the literature for the spinning disc type spreaders shows that the clear trends that are found for the spinning disc type spreader are not found for the reciprocating spout type spreader. The results of the reciprocating spout type fertilizer spreader are very diverse and it is almost impossible to predict the effect of the change of a certain parameter.

When both approaches (single particles and mass flows) are compared with each other it must be concluded that they do not differ in the trends but differ in the specific values that are found for durations of stay and velocities.

4. Measurements

4.1. *Materials and methods*

The measurements are executed with a normal Vicon PS-type fertilizer spreader. This spreader has a crank - connecting rod ratio equal to 0.475 The spreader is equipped with a standard spout that has a length of 0.63 m. The entrance diameter of the spout is 106 mm and then converges to 69 mm at the end.

It must be noted that the results in the next sections do not say anything about the performance of this spreader in practice since the used settings do not necessarily correspond with the settings that have to be used in practice.

The measurements are executed with calcium ammonium nitrate (CAN 27N) originated from two manufacturers (A and B). Other parameters that are varied are the metering rate, the angular velocity of the driving shaft and the use of the bow (spout with and without bow at the end). A review of the measurements is listed in Table 1. The measurements were carried out on four different days. Comparison of data between different days is restricted because no distinction can be made between the effect of a factor and the effect of the day. This applies especially to the measurements on Day 2 and 3. Table 1 also lists the number of valid particles that are detected for each measurement. This number is the number of valid particles. The actual number is higher but some selection criteria are applied to the data that do not meet some basic criteria: at a certain position behind the spreader the direction of the particle must be within certain limits.

During each measurement the velocities of the particles are detected in 20 grid lines with a distance of 0.10 m. The covered arc is equal to 210° which corresponds with a total length of the grid equal to 5.13 m (radius 1.40 m). The circumferential velocity of the frame was 0.34 m/s. Each measurement lasted about 3 minutes of which 2.5 minutes are actual measuring time.

4.2. *Experimental results*

The measurements are analyzed afterwards and relevant characteristics for each measurement are calculated. These characteristics are the mean velocity of the detected particles, the mean horizontal and vertical velocity components of the detected particles, the mean horizontal and vertical position of the detected particles at the detection moment and an imaginary projected distance.

All calculated projected distances are based on a fixed particle diameter of 3.0 mm and particles are assumed to behave as ideal spheres. The trajectories are calculated by a model based on the numerical solution of the differential equations that describe the motion of a particle through the air[1,2]. The used simulation program evaluates the value of the aerodynamic resistance coefficient (K) each integration step since a part of the trajectory can be in the transitional flow range ($1 < Re \leq 800$). A fixed diameter has been used because until now it has not been possible to get a sufficiently accurate diameter from the magnitudes of the reflection signals in the three directions[4].

The results of the measurements themselves will be described in the following sections and the results as a whole will be discussed in Section 5.

Statistical analysis has also been applied to the data. A statistical significant difference was found for some situations but the underlying trends were not always consistent. Small differences became significant rather quickly due to the large number of particles. Only using the means for the analysis of variance resulted in a very small number of the degrees of freedom for some cases which made a proper statistical analysis also difficult.

Table 1
Review of the measurements executed with the reciprocating spout fertilizer distributor. (The numbers between brackets indicate the position of the metering device of the spreader)

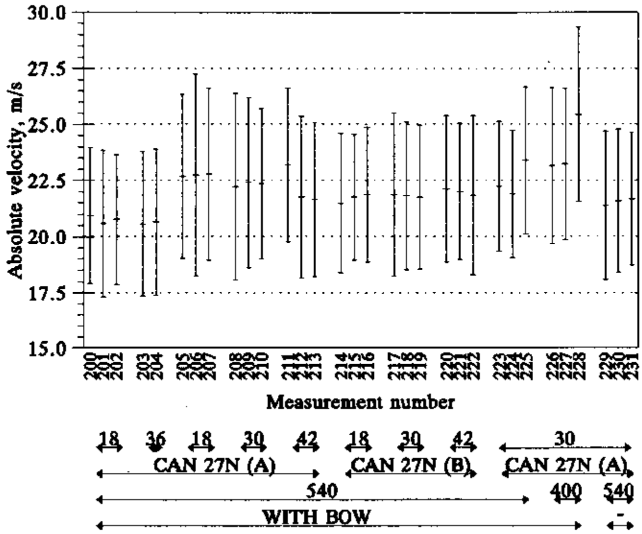
Number	Day	Fertilizer manufacturer	With / Without bow	Metering rate kg/s	Velocity p.t.o. rev/min	Number of detected particles
200	1	A	With	0.17 (18)	540	1175
201	1	A	With	0.17 (18)	540	1370
202	1	A	With	0.17 (18)	540	1262
203	1	A	With	0.57 (36)	540	2768
204	1	A	With	0.57 (36)	540	1983
205	2	A	With	0.17 (18)	540	1629
206	2	A	With	0.17 (18)	540	1429
207	2	A	With	0.17 (18)	540	1448
208	2	A	With	0.41 (30)	540	2357
209	2	A	With	0.41 (30)	540	2286
210	2	A	With	0.41 (30)	540	1826
211	2	A	With	0.74 (42)	540	2417
212	2	A	With	0.74 (42)	540	2862
213	2	A	With	0.74 (42)	540	2007
214	3	B	With	0.17 (18)	540	1540
215	3	B	With	0.17 (18)	540	1353
216	3	B	With	0.17 (18)	540	1310
217	3	B	With	0.41 (30)	540	2044
218	3	B	With	0.41 (30)	540	2108
219	3	B	With	0.41 (30)	540	2267
220	3	B	With	0.75 (42)	540	2626
221	3	B	With	0.75 (42)	540	2743
222	3	B	With	0.75 (42)	540	2879
223	4	A	With	0.42 (30)	540	2103
224	4	A	With	0.42 (30)	540	2034
225	4	A	With	0.42 (30)	540	2015
226	4	A	With	0.40 (30)	400	1023
227	4	A	With	0.40 (30)	400	983
228	4	A	With	0.40 (30)	400	1004
229	4	A	Without	0.42 (30)	540	1327
230	4	A	Without	0.42 (30)	540	1171
231	4	A	Without	0.42 (30)	540	1196

4.2.1. *Velocities*

The measured mean velocities (absolute velocity, horizontal velocity component, and vertical velocity component) are shown in *Fig. 5a-c*. The total length of the bars is equal to 2σ. The results of the mean velocities immediately show that the results are rather diverse.

The same measurements executed on Day 1 and Day 2 (200-202 and 205-207) show a difference in mean absolute velocity of about 2 m/s. This difference in absolute velocity is mainly related to a difference in the horizontal velocity component since the vertical velocity

a



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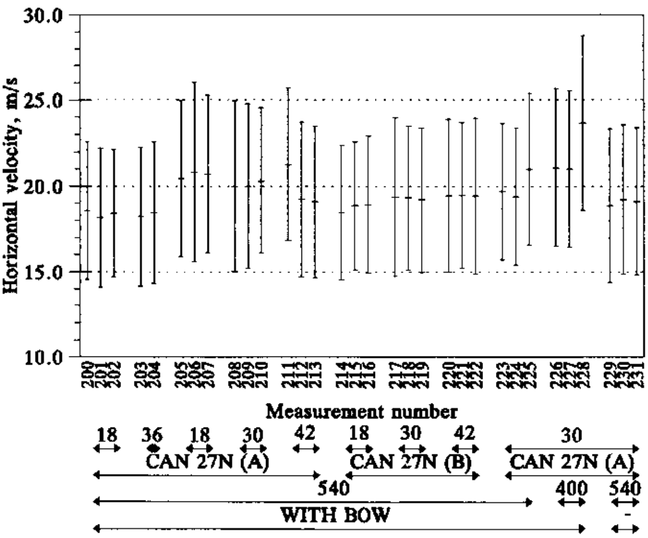

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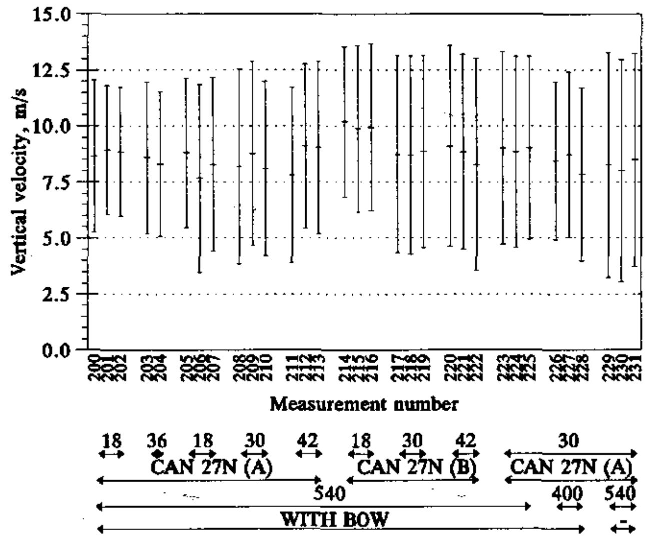

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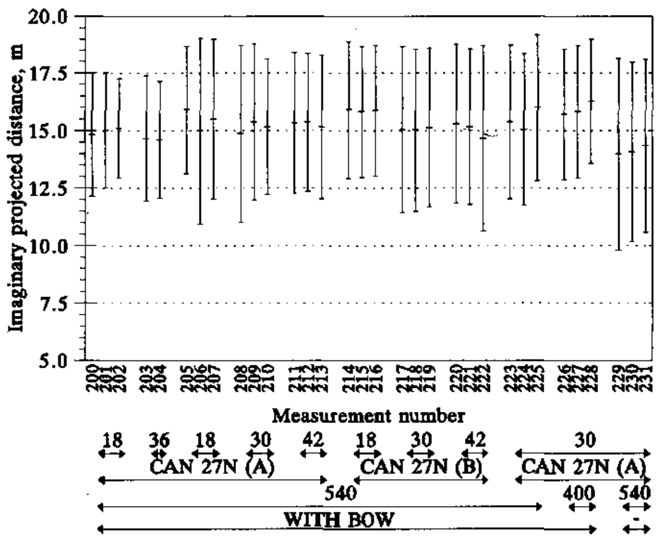


Fig. 5 Velocities (absolute, horizontal, and vertical) and imaginary projected distances. The measurement numbers refer to the numbers in Table 1. The length of the bars is equal to 2σ.

components are almost the same. Another set of comparable measurements executed on different days (208-210 versus 223-225) show a difference in absolute velocity of about 0.2 m/s, in the horizontal velocity component a difference less than 0.1 m/s and in the vertical velocity component a difference of about 0.6 m/s.

The measurements with fertilizer A show a small decrease of the absolute velocity with an increase of mass flow (about 0.15 m/s for 200-202 to 203-204 and about 0.5 m/s for 205-

207 to 211-213) while the measurements with fertilizer B show a small increase of about 0.3 m/s for 214-216 to 220-221. Analysis of horizontal and vertical velocity components shows that there is no clear trend. The horizontal velocity components of 214-216 are slightly smaller than those of the other groups while the vertical velocity component of 214-216 is slightly higher than those of the other groups.

Rather strange is the effect of the decrease of p.t.o.-speed from 540 (223-225) to 400 rev/min (226-228): the absolute velocity increases slightly due to an increase of the horizontal velocity component. The vertical velocity component shows a small decrease. Within 226-228 the absolute velocities and the horizontal velocity components of 228 are much higher. However, when 228 is neglected, the velocities also increase when the p.t.o.-speed decreases. Only the vertical velocity components decrease slightly.

The standard deviations of the velocities do not show very much differences. Only the standard deviations of the vertical velocity components of the measurements without bow are slightly higher than those of the other measurements.

4.2.2. *Imaginary projected distances*

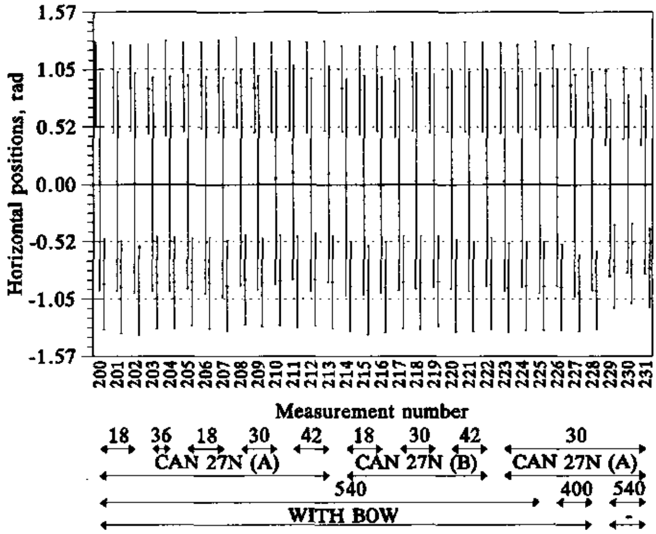
Imaginary projected distances represent the joint effect of velocity and direction. The results are given in *Fig. 5d* and show that there are only minor differences in the results. This figure, in combination with the *Figs 5a-c,* shows the effect of the vertical velocity on the projected distance very clearly. Measurements with a relative low absolute and horizontal velocity but with a relative high vertical velocity (e.g. 200-204) realize almost the same projected distance as measurements with a high absolute and horizontal velocity but with a relative low vertical velocity (especially 228).

4.2.3. *Horizontal and vertical positions*

The horizontal and vertical position of a particle is the position of a particle in the grid when it is detected. The horizontal position is expressed in radians (or degrees) and the vertical position in meters above floor level. The mean values of the measured horizontal positions are given in *Fig. 6a.* A distinction is made between the mean horizontal position of the whole pattern and the mean horizontal position of the left and right half of the pattern. The expected value of the mean horizontal position of the whole pattern is at the centre line of the spreader (parallel with the travel direction). This corresponds in the figure with the zero line. The mean values of the left and right half of the pattern indicate the width of the pattern. A small difference between left and right indicates a narrow pattern and a large difference a wider pattern. The mean horizontal positions for the left and right half of the pattern of the measurements 229-231 (without bow at the end of the spout) show a mean value for left and right which is lower than the values for all other measurements. These measurements correspond with the measurements without bow.

The mean values of the measured vertical positions are given in *Fig. 6b.* The results show a small decrease of the vertical position with an increase of the mass flow for fertilizer A. The vertical positions for the measurements with fertilizer B (214-222) are almost independent of the mass flow. Comparisons of the measurements with the high and low angular velocity of the driving shaft show a decrease of the mean vertical positions by about 0.05 m. The effect of removing the bow (measurements 229-231 versus 223-225) is a decrease of the mean vertical positions by about 0.10 m.

a



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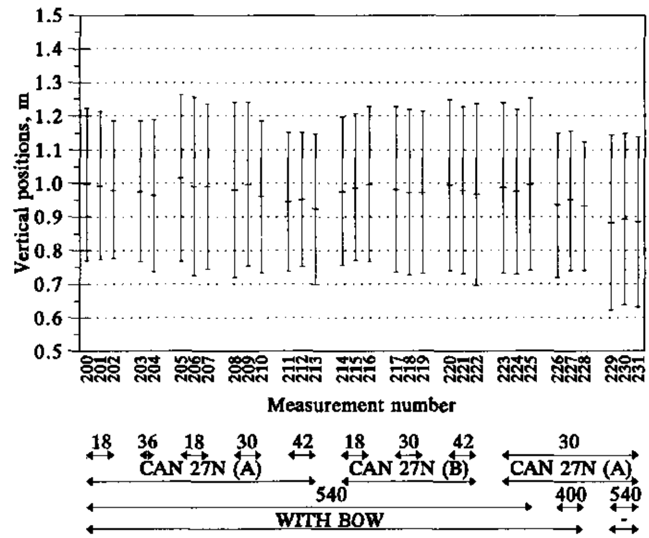

Fig. 6 Horizontal and vertical positions of the detected particles. The measurement numbers refer to the numbers in Table 1. The three lines for the horizontal positions for each measurement represent from left to right the mean horizontal position of the right half of the pattern, the mean horizontal position of the whole pattern and the mean horizontal position of the left half of the pattern. The total length of the bar is equal to 2σ.

5. Discussion

The analysis of the measurements showed that the results are rather diverse. This diversity could almost be expected in part because the simulation results also showed a large diversity.

The difference in discharge velocities between the measurements of Day 1 and Day 2 and especially the measurements 200-202 and 205-207 can possibly be explained by a difference in initial velocity or a difference in the coefficient of friction, both due to unequal environmental conditions. The environmental conditions did not affect the mass flow on both days since it was almost constant for both days. This makes the explanation that a different initial velocity, which is a derivative of the mass flow, is responsible for the difference rather unlikely. The friction measurements discussed by Hofstee[2] showed that large differences in the coefficient of friction (0.05 and sometimes more) can occur when the same measurements are repeated at other environmental conditions. When these differences are projected on the simulation results as discussed earlier, differences in discharge velocities of about 2 m/s are not unexpected.

When the results of the measurements with different fertilizer origins (measurements 205-213 and 214-222) are compared with each other, there are only small differences in measured values, i.e. there is hardly any effect of the fertilizer itself. Measurements of the coefficient of friction also showed that there were small differences in the friction values for both CAN fertilizers with respect to a nylon surface[2,12].

The effect of an increase of the mass flow is different for both CAN fertilizers. Fertilizer A showed a small decrease of discharge velocity with an increase of the mass flow and fertilizer B showed a very small increase with an increase of the mass flow.

The measurements 205 through 222 did not show very much difference in characteristic values. The differences that occurred can easily be explained by slightly different measurement conditions since the simulation results showed that a small difference in parameters can have a large influence on discharge velocities. For the reasons discussed before and the fact that the differences are that small it must be concluded that there is hardly any noticeable effect of both CAN fertilizers and mass flows on the discharge velocities.

The observation that a lower angular velocity of the driving shaft results in slightly higher discharge velocities can be explained by the expectation that the particles at this lower velocity move in a lower plane through the spout and so more particles pass just underneath the 45° bridge in the bow. The particles that just pass below get a lower vertical velocity and this will result in a lower mean vertical position. The data of measurement 228 can be seen as an extreme example of this effect.

Removal of the bow at the end of the spout results in that the pattern becomes narrower in the horizontal and the vertical plane. The differences between the left and right mean horizontal positions for the left and right half of the pattern decreases from about 1.8 rad (100°) to 1.5 rad (85°). A second effect of the bow is that it gives a significant number of the particles an additional vertical velocity resulting in a higher mean vertical position.

6. Conclusions

From the simulation and the experiments the conclusion that can be drawn that this type of spreader is very difficult to model. This is mainly due to the oscillatory behaviour of the spout which results in the fact that particles can be 'in phase' with the motion of the spout or not. If they are in phase, they cross the spout at a position that results in higher discharge velocities. If they are not, considerable decreases in discharge velocities can be noticed since the kinetic energy is absorbed. Whether particles come 'in phase' or not depends on the sorting-in process and the properties of the fertilizer. A small change of the properties of the fertilizer or the sorting-in process can be sufficient for this transition.

An improvement for the measurement setup for this type of spreader could be that the plain vertical grid, which is now laid out behind the spreader, be transferred into a spherical grid. This will reduce the number of particles that have a downward directed velocity with respect to the transducer units which cause detection problems since the transducer units are becoming 'blind' when particles pass with a vertical velocity below a certain value[3,4].

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Chapter IV-B

The spinning disc type fertilizer spreader

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Handling and Spreading of Fertilizers Part 4B: The Spinning Disc Type Fertilizer Spreader

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The motion of particles as affected by physical properties such as coefficient of friction and design of the disc including vane type, pitch angle of the vane and surface of the vane is discussed. The influence of factors that may have an effect is studied theoretically (by means of simulations) as well as experimentally (Doppler velocity meter).

When the simulation and measurement results are compared, quite a large difference is found between them. The simulation results show the very clear effect of the coefficient of friction whereas the measurements do not show this very clear effect. The measurement results further show that the increase in the mass flow results in an increase of the projected distance of about 1 m.

1. Introduction

Spinning disc type fertilizer spreaders are the most used type of fertilizer spreaders in the Netherlands and in most European countries generally. The first spinning disc type spreaders had one disc but this has changed during the past ten years in favour of spreaders with two discs. A main reason for this change was that twin disc spreaders have fewer problems with asymmetric spread patterns than single disc spreaders.

Important factors that affect the behaviour of spinning disc spreaders are the physical properties of the fertilizer since they affect the motion of particles on the disc and along the vane[1,2]. The most important property is the coefficient of friction of the fertilizer particle with respect to the vane. The spinning disc type fertilizer spreader has, from the research point of view, the 'advantage' that many parameters, such as the delivery position, the material covering the vane, and, for some discs the pitch angle, can be altered. On the other hand, from the user point of view, these 'advantages' become 'disadvantages' because the user has to control these parameters when using the fertilizer spreader, i.e. he has to adjust them to each specific fertilizer.

At the end of 1987, a research project began at the Department of Agricultural Engineering and Physics of Wageningen Agricultural University to study the influence of the physical properties of fertilizer. Within this project a new measurement method[3,4] for measuring the velocity and direction of fertilizer particles discharged by a fertilizer spreader has been developed. The measurement principle is based on the ultrasonic Doppler effect. This method has been applied to a reciprocating spout type fertilizer spreader[5] as well as a spinning disc type fertilizer spreader. The results of these measurements, together with an analysis of the particle motion of the spinning disc type spreader in general and the spreader being used in particular, are discussed in this paper.

Notation

g	gravity acceleration, m/s^2
h	height of particle on disc with respect to base level, m
r	radius (from centre to particle position on disc), m
r_c	curvature radius of a circular vane, m
r_d	radius of the disc, m
r_0	feed radius, m
$v_{p,dis}$	particle discharge velocity, m/s
$v_{p,vane}$	particle velocity along vane, m/s
v_{rad}	radial velocity, m/s
v_{tan}	tangential velocity, m/s
x	horizontal position of particle on disc, m
x_c	horizontal coordinate of the virtual centre of the circular vane, m
x_v	position along vane, m
y	vertical position of particle on disc, m
y_c	vertical coordinate of the virtual centre of the circular vane, m
X	horizontal position (travel direction), m
Y	vertical position (height above ground level), m
Z	horizontal position (perpendicular to travel direction), m
α	cone angle, rad
β	intersecting angle between vane and radial line, rad
β_0	pitch angle (intersecting angle between vane and radial line at $r = r_0$, rad
$\beta(x)$	intersecting angle between vane and radial line at radial position x, rad
$\beta(\gamma)$	intersecting angle between vane and radial line at angular position γ along the circular vane, rad
μ	coefficient of friction
μ_d	coefficient of friction between particle and disc
μ_v	coefficient of friction between particle and vane
θ	discharge angle, rad
ω_d	angular velocity disc, rad/s

2. Disc design

The important design factors of a spinning disc are the disc radius, the feed radius, the pitch angle of the vane, the cone angle of the disc and the shape of the vane (straight, curved or combinations). Several possible vane designs and relevant design parameters are listed in Table 1 and illustrated in *Fig. 1*. The instantaneous radius (r) and the length of the path along the vane (x_v) are relevant for the description of the motion along the vane.

An important factor of all designs is the intersecting angle (β) between the vane and the radial line. This angle is important since it determines how some of the forces acting on the particle have to be resolved. An intersecting angle < 0 results in a centrifugal force component perpendicular to the vane that is directed towards the vane and hence increases the friction force that has to be overcome. This angle varies for most vane designs with the radial position (*Fig. 2*). The figure shows that the intersecting angle of the forward or backward pitched straight vanes in particular, has a large variation with respect to the radial position, especially close to the centre of the disc (start of the vane). Near the edge of the disc only a small difference in intersecting angle is left. *Fig. 2* only shows the lines for the forward pitched vanes but the lines for the backward pitched vanes are similar, apart from the fact that they are mirrored in the line $\beta = 0$.

The feed radius (r_0) must have a minimum value otherwise the particles are not able to start moving (the outward directed forces are not sufficient to overcome the initial friction forces). A positive cone angle (α) results in the particles being discharged with a vertical velocity component that usually results in a larger projected distance of the particles. It can also be advantageous during top-dressing since it will reduce the height to which the spreader has to be lifted. The radius of the disc varies for most spreaders between 0.30 and 0.45 m. The rotational velocity of most discs ranges between 75 rad/s (about 720 rev/min) and 100 rad/s (about 1000 rev/min) for effective working widths ranging from 18 to 24 m.

3. Particle motion

3.1. *Description*

The motion of a particle on a spinning disc can be described by a differential equation that can be derived from the forces acting on the particle following D'Alembert's principle. The most general equation describing the motion of a particle along the vane is:

$$A \frac{d^2 x_v}{dt^2} + B \left(\frac{dx_v}{dt} \right)^2 + C\, 2\, \omega_d \frac{dx_v}{dt} + D\, \omega_d^2 r + E g = 0 \qquad (1)$$

The values for the multipliers A to E depend on the specific vane and disc design and are listed in Table 2. The relation between x_v and r can be obtained from Table 1.

Mennel and Reece[6] studied four vane designs (from a normal flat vane to a sigma section vane) with respect to the discharge direction in the vertical plane. A slot was positioned behind the disc and only particles (bearings) discharged with a vertical direction within a $\pm 3°$ zone would pass the slot. They found that only the sigma section vane resulted in more than 80% of the bearings passing the slot. Less than 30% passed the slot for the three other vane designs.

Cunningham[7] provided analytic solutions for a flat disc with forward or backward pitched vanes, a cone shaped disc with straight radial vanes, and a flat disc with a vane meeting a logarithmic spiral. Situations for which α or β are not equal to zero or where the vanes are not straight have to be solved by numerical methods since no analytical solutions exist for most situations. The advantage of a forward curved vane is that a greater acceleration and a more positive action near the centre can be developed than with forward pitched vanes.

Cunningham and Chao[8] described the equation for a composite vane, starting with a curved section (circular), and followed by a straight radial section. The advantage of such a vane should be that it can pick up the fertilizer flowing from the delivery opening smoothly without impact. Impact at an early stage will usually result in scattering of the particles over the disc.

Brinsfield and Hummel[9] derived a similar equation for a disc with tubes instead of vanes. The first tube region has a constant radial radius and the second tube region is radial. The advantage of this vane type is that it should also reduce the random motion inherent in most conventional distributor disc designs.

Equations for a vertical disc are given by Galili and Shteingauz[10] and Galili *et al.*[11] The vertical disc produces a linear distribution pattern instead of a horizontal circular pattern.

Table 1
Relevant design parameters for several types of spinning discs.

Vane type	Vane equation	Intersecting angle ($\beta(.)$)	Radius (r)	Path along vane (x_v)
Straight radial	$y(x) = 0$ $h(x) = 0$	0	$r_0 + x_v$	x_v
Cone shaped disc	$y(x) = 0$ $h(x) = (x - r_0)\tan\alpha \quad (x > r_0)$	0	$r_0 + x_v \cos\alpha$	x_v
Forward / backward pitched	$y(x) = -(x - r_0)\cos\beta_0 \quad (x > r_0)$ $h(x) = 0$	$\arctan\left(\frac{r_0 \sin\beta_0}{x_v + r_0 \cos\beta_0}\right)$	$\sqrt{r_0^2 + x_v^2 + 2 r_0 x_v \cos\beta_0}$	x_v
Circular	$(x - x_c)^2 + (y - y_c)^2 = r_c^2$ $h(x) = 0$	$\arctan\left(\frac{-y_{p1}\sin(-\gamma)}{x_{p1}\sin(\gamma)}\right)$ $x_{p1} = x + y\tan(\gamma - \frac{\pi}{2})$ $y_{p1} = y + x\tan(-\gamma - \frac{\pi}{2})$	$\sqrt{x^2 + y^2}$ $x = x_c - r_c \sin(\gamma - \frac{\pi}{2})$ $y = y_c + r_c \cos(\gamma - \frac{\pi}{2})$	$\Delta\gamma\, r_c$
Logarithmic spiral	$y(x) = x\tan\left(\tan\left(\beta_0 \ln\left(\frac{x}{r_0}\right)\right)\right)$ $h(x) = 0$	β_0	$\sqrt{x^2 + y^2}$ $x = x$ $y = x\tan\left(\tan\left(\beta_0 \ln\left(\frac{x}{r_0}\right)\right)\right)$	$\int_{r_0}^{x_p} \sqrt{1 + (y'(x))^2}\, dx$
Forward / backward pitched vane + cone shaped disc	$y(x) = (x - r_0)\cos\beta_0$ $h(x) = (x - r_0)\tan\alpha$	$\arctan\left(\frac{r_0 \sin\beta_0}{x_v \cos\alpha + r_0 \cos\beta_0}\right)$	$\sqrt{r_0^2 + (x_v \cos\alpha)^2 + 2 r_0 x_v \cos\alpha \cos\beta_0}$	x_v
Parabolic	$y(x) = a(x - r_0)^2 + b(x - r_0) + c$ $h(x) = 0$ $y'(x) = 2a(x - r_0) + b$	<u>$y'(x) \neq 0$:</u> $\arcsin\left(\frac{y'(x)x - y(x)}{y(x) \cdot r}\sin(\pi + \arctan(y'(x)))\right)$ <u>$y'(x) = 0$:</u> $\arcsin\left(\frac{y(x)}{r}\right)$	$\sqrt{x^2 + y^2}$ $x = x$ $y = a(x - r_0)^2 + b(x - r_0) + c$	$\int_{r_0}^{x_p} \sqrt{1 + (y'(x))^2}\, dx$

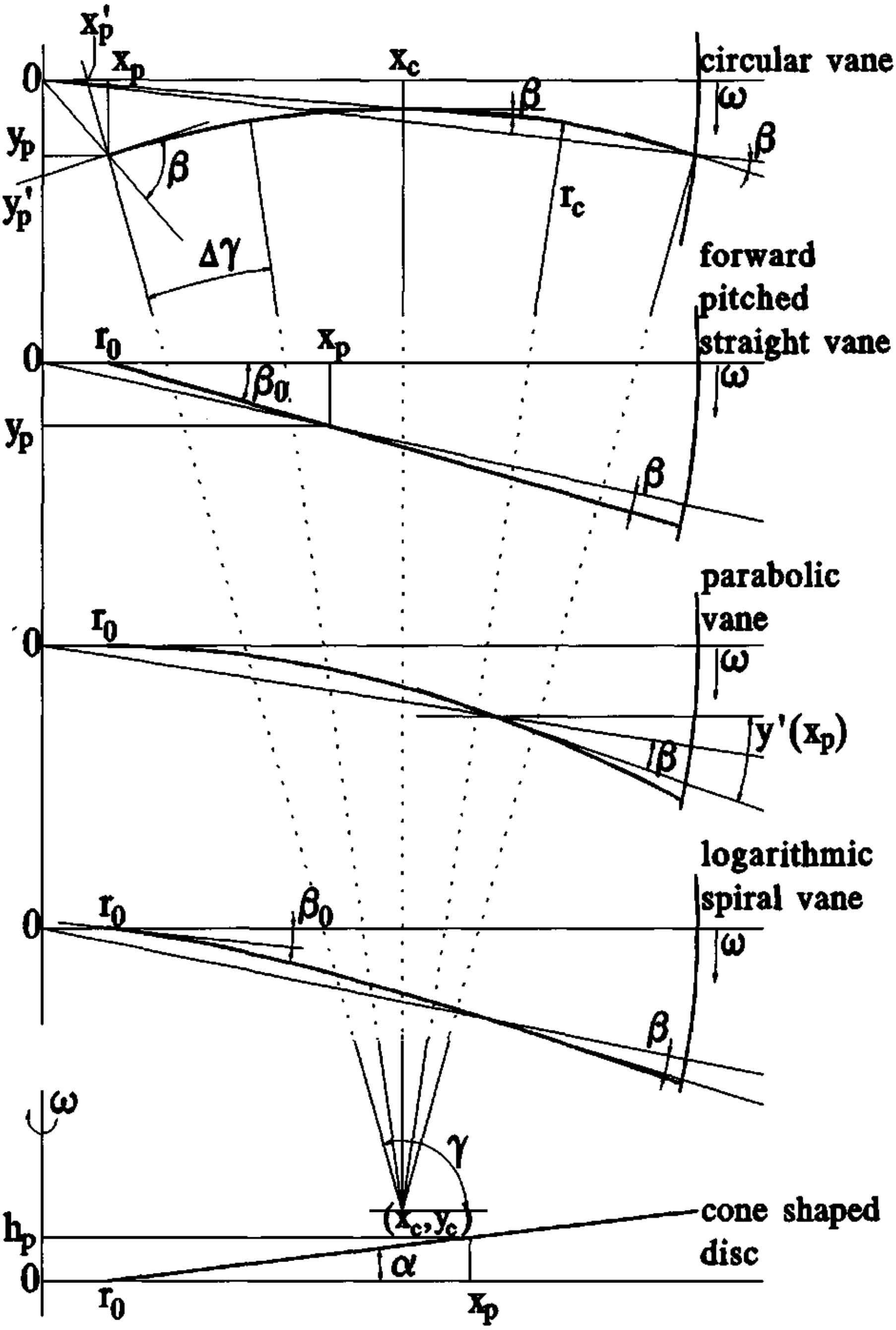


Fig. 1 Most important disc and vane designs and relevant geometric parameters. The corresponding equations are given in the Tables 1 and 2.

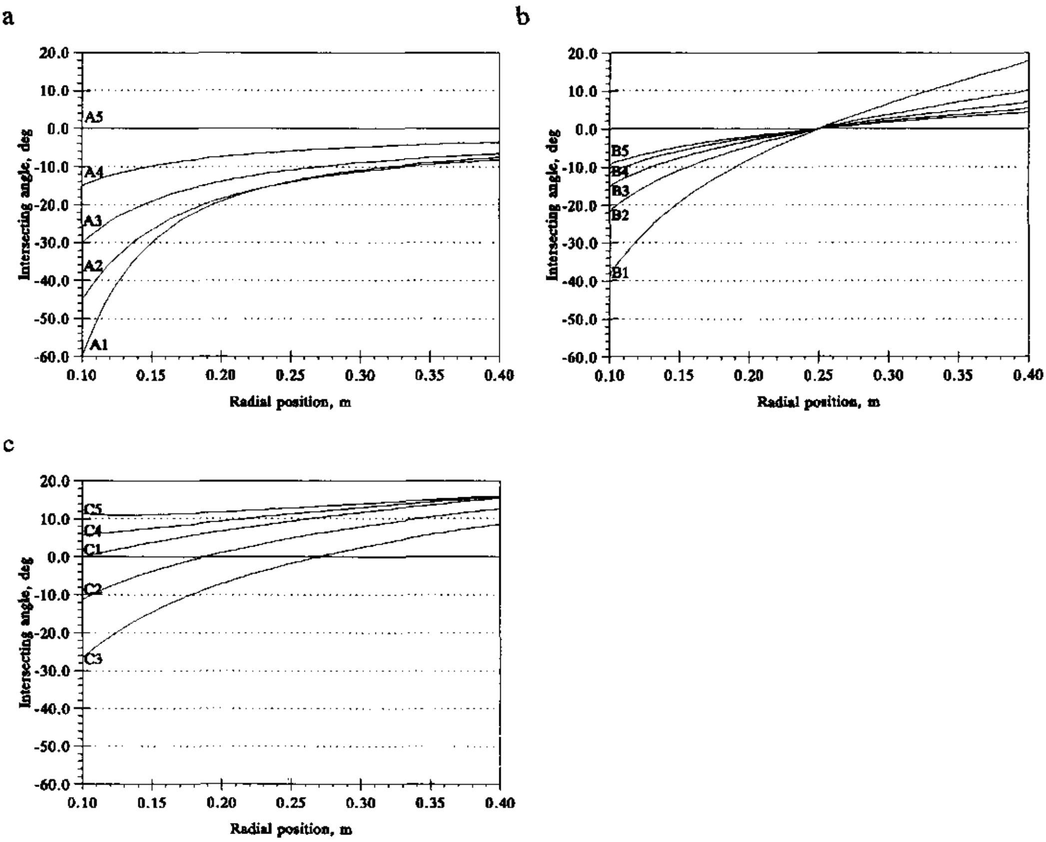


Fig. 2 Variation of the intersecting angle with respect to the radial position for several vane types.
A: forward and/or backward pitched vane; 1: β=-60°; 2: β=-45°; 3: β=-30°; 4: β=-15°; 5: β=0°
B: circular vane; 1: r_c=0.4 m; 2: r_c=0.7 m; 3: r_c=1.0 m; 4: r_c=1.3 m; 5: r_c=1.6 m
C: parabolic vane 1: a=-0.8, b=0.0, c=0.00; 2: a=-0.8, b=0.0, c=-0.02; 3: a=-0.8, b=0.0, c=-0.05; 4: a=-0.8, b=-0.1, c=0.0; 5: a=-0.8, b=-0.2, c=0.0 (see Table 1 for a, b, and c)

3.2. *Simulations*

A simulation model based on Eqn (1) has been developed to study the influence of vane design, pitch angle and coefficient of friction on the motion of particles. The model is based on single particles and does not account for the behaviour of mass flows along the vane of a spinning disc.

Table 2
Multipliers for substitution in the differential equation to describe the motion of a particle along the vane on a spinning disc.

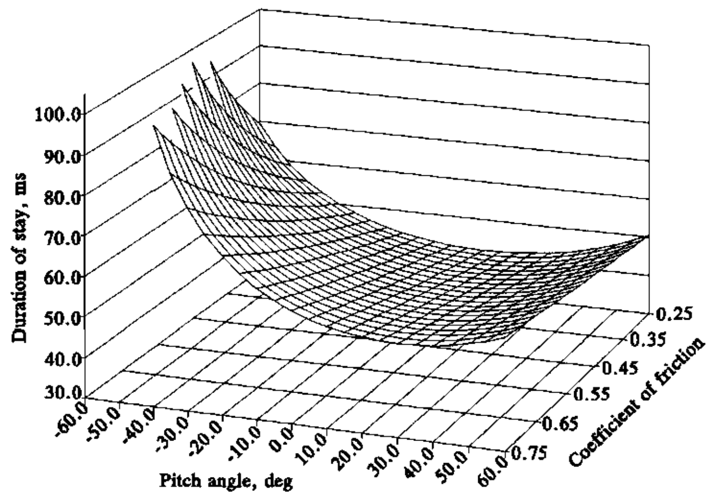
Vane type	$\frac{d^2x_v}{dt^2}$	$\left(\frac{dx_v}{dt}\right)^2$	$2\omega\frac{dx_v}{dt}$	$\omega^2 r$	g
Straight radial	1	0	μ_v	-1	μ_d
Cone shaped disc	1	0	$\mu_v \cos\alpha$	$-(\cos\alpha - \mu_d \sin\alpha)$	$\sin\alpha + \mu_d \cos\alpha$
Forward / backward pitched	1	0	μ_v	$-(\cos\beta(x) + \mu_v \sin\beta(x))$	μ_d
Circular	1	$\frac{\mu_v}{r_c}$	μ_v	$-(\cos\beta(\gamma) + \mu_v \sin\beta(\gamma))$	μ_d
Logarithmic spiral	1	$\frac{\mu_v}{r / \sin\beta_0}$	μ_v	$-(\cos\beta_0 + \mu_v \sin\beta_0)$	μ_d
Forward / backward pitched vane and cone shaped disc	1	0	$\mu_v \cos\alpha$	$-(\cos\alpha \cos\beta(x) - \sin\alpha \cos\beta(x)\, \mu_d + \ldots$ $\mu_v \sin\beta(x))$	$\sin\alpha \cos\beta(x) + \mu_v \sin\alpha \sin\beta(x) + \ldots$ $\mu_d \cos\alpha$
Parabolic	1	$\frac{\mu_v}{r_c(x_v)}$	μ_v	$-(\cos\beta(x) + \mu_v \sin\beta(x))$	μ_d

The signs of β_0, $\beta(x)$ and $\beta(\gamma)$ are such that when $\omega^2 r \sin\beta(.)$ is directed towards the vane, then $\beta(.) < 0$

3.2.1. *Particle motion*

The combined effect of the coefficient of friction and the pitch angle of straight vanes on the motion of a particle on a flat spinning disc ($\alpha = 0$) is illustrated in *Figs 3a-d*. *Fig. 3a* shows that a change in the pitch angle (β_0) from -60° to +60° first results in a relatively strong decrease in the duration of stay on the disc to a minimum value of just beyond 0° and that this is followed by a small increase towards +60°. The figure further shows that discs with vanes with a positive pitch angle (backward pitched) are less sensitive to the influence of the coefficient of friction than discs with vanes with a negative pitch angle (forward

a



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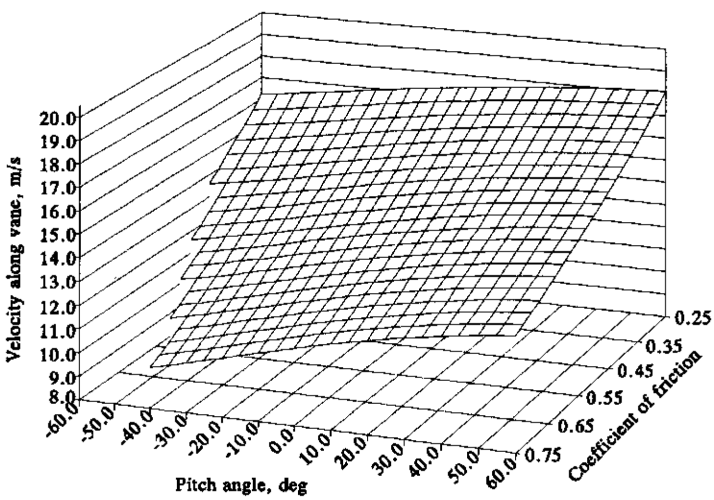

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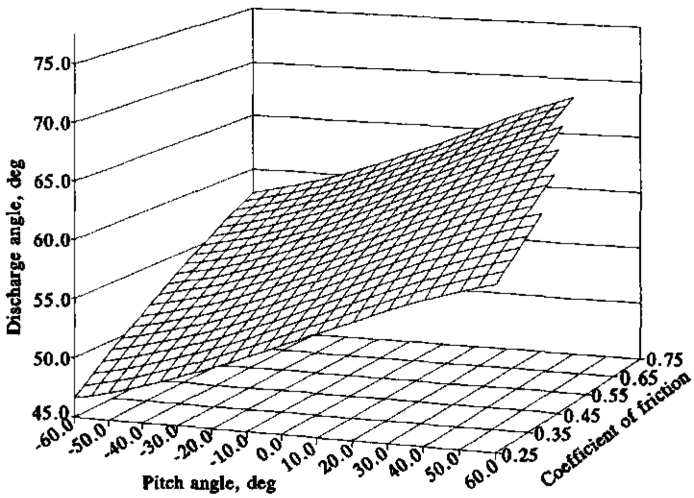


d

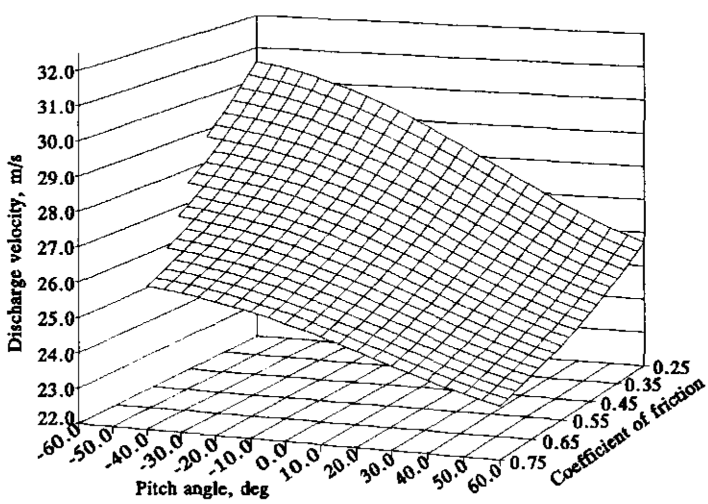


Fig. 3 Effect of pitch angle (β_0) and coefficient of friction (μ_v) on the duration of stay (a), the velocity along the vane (b), the discharge angle (c), and the discharge velocity (d). ($\omega_d = 18\pi$ rad/s, $r_0 = 0.10$ m, $r_d = 0.40$ m)
The discharge direction (θ) is equal to the angle between the radial velocity vector and the discharge velocity vector ($\arctan\theta = v_{rad}/v_{tan}$).

pitched). Beyond the duration of stay, which determines the place where the particle will leave the disc, the velocity along the vane and the actual discharge velocity are also important. *Figs 3b* and *3c* show that the velocity of the particle along the vane increases with an increase of the pitch angle but the actual discharge velocity decreases with an increase of pitch angle. The latter is due to the existence of a tangential velocity component of the velocity along the vane just opposite to the tangential velocity of the tip of the vane. *Fig 3d* finally shows the effect on the discharge angle of the coefficient of friction and the pitch angle. The discharge angle increases with an increase of the coefficient of friction and a decrease of the pitch angle.

The particle motion along a circular vane has been compared to the motion of a particle along forward or backward pitched and straight radial vanes. The circular vane approximated the vane of the fertilizer spreader used in the experiments (see Section 4.1) as far as possible. The dimensions of the disc with straight vanes agreed with the dimensions of the disc with the circular vane.

Comparison of the vane types (Table 3) showed that the duration of stay of a particle along a circular vane was somewhat lower than those along a forward pitched vane but higher than those along a straight radial or backward pitched vane. The velocity along the vane was just higher than the velocity of a particle along a forward pitched vane but lower than along a straight radial and a backward pitched vane. The actual discharge velocity of the circular vane was almost equal to the discharge velocity corresponding to a straight radial vane. This velocity is lower than the resulting velocity of a forward pitched vane and higher than the discharge velocity of a backward pitched vane. The discharge angle of the circular vane was found about 2° higher than that of a straight radial vane, about 3° lower than that of a forward pitched vane and about 7° higher than that of a backward pitched vane.

Table 3
Influence of vane design and coefficient of friction on discharge parameters.

Vane design	Property	Coefficient of friction					
		0.25	0.35	0.45	0.55	0.65	0.75
Circular vane	t, msec	48.484	53.641	59.641	66.641	74.850	84.572
	$v_{p,vane}$, m/s	16.099	14.473	13.059	11.837	10.784	9.873
	$v_{p,dis}$, m/s	27.713	26.747	25.961	25.325	24.812	24.397
	θ, deg	54.52	57.27	59.83	62.16	64.26	66.15
Straight radial vane β_0 = -40°	t, msec	50.502	56.360	63.377	71.549	82.212	95.166
	$v_{p,vane}$, m/s	15.999	14.295	12.786	11.461	10.304	9.294
	$v_{p,dis}$, m/s	29.296	28.171	27.226	26.439	25.787	25.249
	θ, deg	57.47	60.02	62.46	64.73	66.83	68.75
Straight radial vane β_0 = 0°	t, msec	40.351	42.821	45.489	48.353	51.408	54.643
	$v_{p,vane}$, m/s	16.827	15.366	14.047	12.866	11.816	10.885
	$v_{p,dis}$, m/s	27.628	26.763	26.028	25.411	24.895	24.467
	θ, deg	52.48	54.96	57.34	59.58	61.67	63.58
Straight radial vane β_0 = +40°	t, msec	42.729	44.146	45.640	47.200	48.813	50.466
	$v_{p,vane}$, m/s	17.367	16.093	14.940	13.903	12.974	12.145
	$v_{p,dis}$, m/s	25.480	24.826	24.276	23.819	23.440	23.129
	θ, deg	47.84	50.33	52.70	54.92	56.970	58.86

3.2.2. *Spread pattern*

Besides an effect on the motion of the particles, as discussed in the previous section, the ultimate effect on the spread pattern is also very important. *Fig. 4* shows the effect of the pitch angle and the coefficient of friction on the impact position on the ground because of the influence on the motion along the vane. The calculations are based on an initial height of 0.75 m above ground level and particles with a diameter of 3.0 mm. The particles were considered as ideal spheres. Similar patterns result when another particle diameter is used.

The figure shows very clear that the relation between coefficient of friction and impact position largely depends on the pitch angle of the vane. The most left point for each pitch angle corresponds with $\mu = 0.25$ and each consecutive point in clockwise direction with an increment of μ with 0.025 up to $\mu = 0.75$. A forward pitched vane ($\beta < 0$) is very sensitive to the coefficient of friction and a backward pitched vane is much less sensitive to the coefficient of friction. The figure also shows very clearly the counter-clockwise shift of the pattern up to a pitch angle of about 20°, followed by a clockwise shift when the pitch angle increases further.

An analysis of the resulting projected distances shows that the projected distance decreases when the coefficient of friction increases. The decrease depends on the pitch angle and becomes smaller when the pitch angle increases (from 9.34 m to 8.32 m for β_0 = -30° and from 8.27 m to 7.66 m for β_0 = 60°).

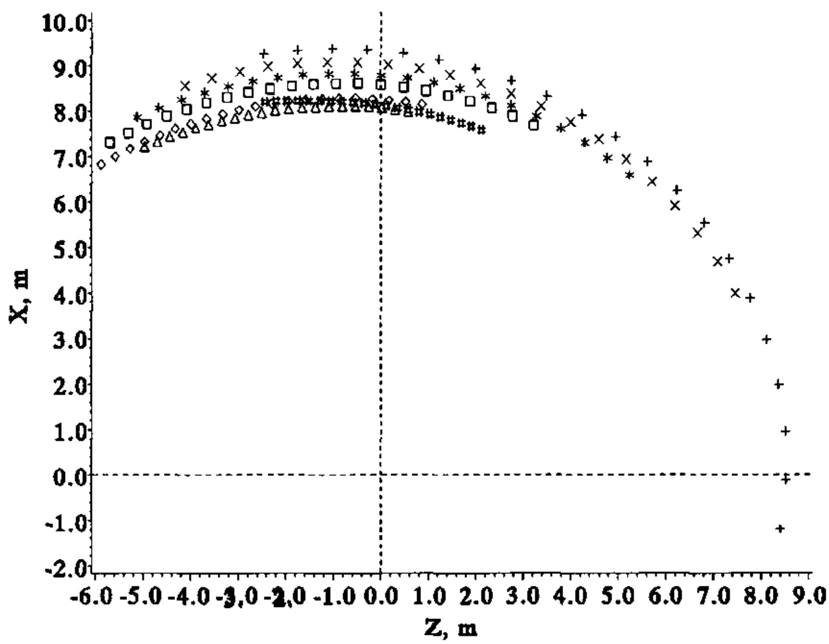


Fig. 4 Effect of coefficient of friction and pitch angle on the impact position of the particles on the ground for selected pitch angles.
(ω_d = 18π rad/s, r_0 = 0.10 m, r_d = 0.40 m)
The points correspond in clockwise direction with increasing values of the coefficient of friction, starting with μ = 0.25 and a step size of 0.025.
*+: β=-30°; x: β=-20°; *: β=-10°; □: β=0°; ◇: β=20°; Δ: β=40°; #: β=60°*

4. Experiments

4.1. *Materials and methods*

The measurements are executed with a Vicon BS-type fertilizer spreader. This spreader has two discs, each equipped with six large vanes and two very small vanes *(Fig. 5)*. The rotational velocity of the discs can be changed by interchanging gear wheels. During the measurements, the gear ratio was such that 540 rev/min of the p.t.o. corresponded with 540 rev/min of the disc. In practice this ratio belongs to an effective spread width of 12 m. This velocity has been chosen since the current measurement setup has limitations with respect to the maximum velocity that the particles may have. Particles with a velocity higher than about 30 m/s cannot be detected[4].

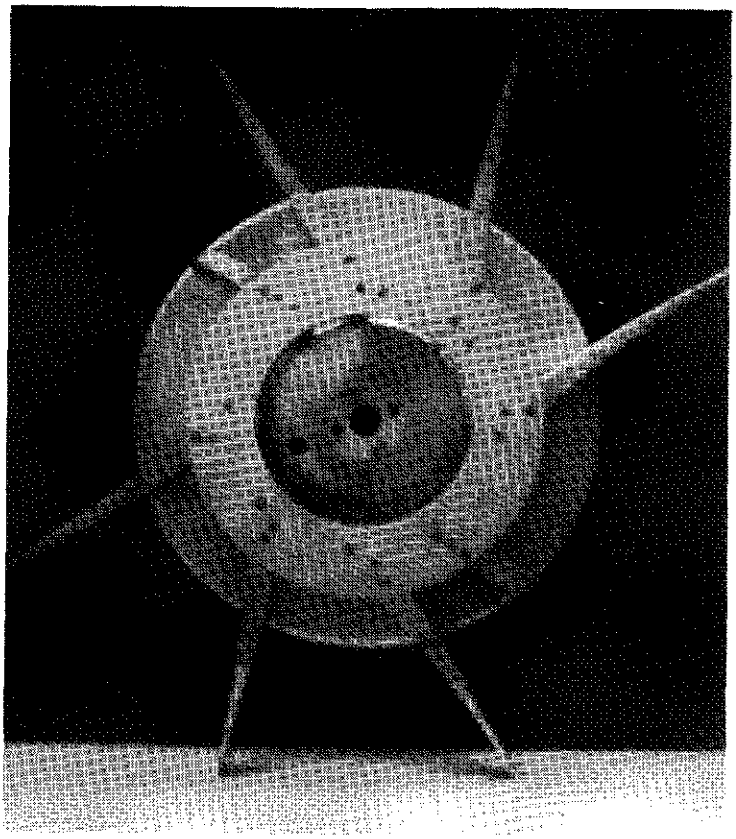


Fig. 5 Left disc of a VICON BS-type fertilizer spreader. The rotational direction of this disc is clockwise.

It is possible to change the angular position of the delivery opening of the spreader over an angle of 39.4°. The arc length of the opening is 105 mm at a radius of 93 mm. The correct position depends on the fertilizer and the mass flow[12]. The basic position and the size of the opening depend on the desired effective working width. The distance between the floor level and the bottom of the vane was 0.78 m.

It should be noted that the results discussed in the next sections say nothing about the performance of this spreader in practice. Many settings have been changed for research purposes and these settings do not necessarily correspond to the proper settings for actual spreading.

The measuring procedure is almost similar to the procedure used for measurements with the reciprocating spout type spreader[5]. The procedure differs in that the particles are detected in a grid of 16 lines instead of 20 lines. The radius of the arc that the transducer units make has been increased to 1.90 m but the circumferential velocity remained the same. Further, the distance between the grid lines has been reduced to 0.05 m. So, the total height covered is 0.80 m.

The measurements are executed with three fertilizers, CAN 27N (obtained from two different manufacturers, A and B) and NPK 17-17-17 (obtained from manufacturer A). Other factors varied were the size of the mass flow, the angular position of the delivery opening, and the surface material of the vane. The latter was varied by sticking a thin nylon plate with a size equal to the vane surface, on the vanes. The coefficient of friction of the used fertilizers has been measured with the rotating plate measuring device[2]. The values for the coefficient of friction with respect to a stainless steel and a nylon surface are listed in Table 4. For practical reasons it was not possible to use exactly the same surfaces in the friction measurements and the spreading experiments.

Table 4
Values for the coefficient of friction of the four fertilizers and the two structural surfaces used in the experiments. (A and B identify different manufacturers; A1 and A2 indicate two different production batches)

	Velocity range							
	1.0 - 6.0 m/s		6.0 - 11.0 m/s		11.0 - 16.0 m/s		16.0 - 21.0 m/s	
Surface / Fertilizer	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev
Stainless steel:								
CAN 27N (A1)	0.437	0.0591	0.421	0.0612	0.398	0.0567	0.395	0.0361
CAN 27N (A2)	0.432	0.0513	0.427	0.0363	0.416	0.0493	0.382	0.0479
CAN 27N (B)	0.451	0.0553	0.446	0.0839	0.428	0.0618	0.405	0.0486
NPK 17-17-17 (A)	0.439	0.0905	0.447	0.0832	0.438	0.0603	0.419	0.0415
Nylon:								
CAN 27N (A1)	0.350	0.0343	0.289	0.0345	0.271	0.0219	0.254	0.0171
CAN 27N (A2)	0.354	0.0355	0.305	0.0354	0.274	0.0157	0.245	0.0190
CAN 27N (B)	0.322	0.0369	0.282	0.0295	0.259	0.0159	0.231	0.0095
NPK 17-17-17 (A)	0.383	0.0521	0.400	0.0324	0.360	0.0242	0.308	0.0267

A review of the measurements is given in Table 5. The numbers in the first column identify the measurements and are used to refer to the measurements. The results of the measurements are analyzed with respect to the mean discharge velocity, the mean horizontal and vertical velocity components, the mean imaginary projected distance and the horizontal and vertical positions where the particles were detected. The projected distance expresses the joint effect of velocity and direction. The detected horizontal positions provide information

Table 5
Review of the measurements executed with the spinning disc fertilizer distributor. (Fertilizer: 1 = CAN 27N (A), 2 = NPK 17-17-17 (A), 11 = CAN 27N (B); Vane surface: 1 = stainless steel, 4 = nylon; Metering rate: The numbers between the brackets indicate the position of the metering device)

Number	Day	Fertilizer	Vane surface	Disc	Angular position metering device	Metering rate, kg/s	Number of detected particles
403	1	11	1	Both	K+	0.30 (8)	630
404	1	11	1	Both	K+	0.30 (8)	553
405	1	11	1	Both	K+	0.30 (8)	549
406	1	11	1	Both	M+	0.30 (8)	593
407	1	11	1	Both	M+	0.30 (8)	697
408	1	11	1	Both	M+	0.30 (8)	744
409	1	11	1	Both	I+	0.30 (8)	988
410	1	11	1	Both	I+	0.30 (8)	698
411	1	11	1	Both	I+	0.30 (8)	692
412	1	11	1	Both	K+	0.60 (12)	1016
413	1	11	1	Both	K+	0.60 (12)	853
414	1	11	1	Both	K+	0.60 (12)	1118
415	1	11	1	Right	K+	0.30 (8)	522
416	1	11	1	Left	K+	0.30 (8)	501
417	2	1	1	Both	K+	0.30 (8)	126
418	2	1	1	Both	K+	0.30 (8)	109
419	2	1	1	Both	K+	0.60 (12)	229
420	2	1	1	Both	K+	0.60 (12)	223
421	4	2	1	Both	K+	1.00 (18)	652
422	4	2	1	Both	K+	1.00 (18)	559
424	2	2	1	Both	K+	0.39 (11)	214
424	2	2	1	Both	K+	0.39 (11)	121
425	4	1	4	Both	K+	0.30 (8)	220
426	4	1	4	Both	K+	0.30 (8)	156
427	4	1	4	Both	K+	0.60 (12)	411
428	4	1	4	Both	K+	0.60 (12)	369
429	3	2	4	Both	K+	1.00 (18)	767
430	3	2	4	Both	K+	1.00 (18)	746
431	3	2	4	Both	K+	0.39 (11)	210
432	3	2	4	Both	K+	0.39 (11)	222

about the symmetry of the pattern and the discharge position of the particles. The pattern has also been divided into a left and a right half. The dividing line between left and right corresponds to the centre of the spreader. The mean horizontal position of the detected particles per half (first order moment) has also been calculated. The angular differences between these two centres provide information about the change of the discharge positions. The vertical positions provide information about the discharge directions of the particles in the vertical plane.The results of the measurements are described in the next sections and are discussed in Section 5.

4.2. *Mass flow*

The effect of the change of the mass flow on the motion of particles was studied for all three fertilizers used. The adjustment of the mass flow to a certain value was difficult since there was a very large difference between the values from the adjusting table[12] and the actual realized values. The mass flow was determined by weighing the mass of fertilizer in the spreader before and after the test and measuring the time during which the fertilizer was spread. The intended mass flow settings were 0.42 kg/s (settings 8 (CAN) and 11 (NPK)) and 0.83 kg/s (settings 12 (CAN) and 18 (NPK)). The values listed in Table 5 show that the realized mass flows do not meet the intended settings exactly.

It is almost impossible to model the particle interactions when they move along the vane. Therefore the simulation experiments discussed in Section 3.2 rest on that the mass flow does not affect the motion of the particles. One of the objectives of measuring the effects of the mass flow on the motion of the particles is to determine to what extent the existing theoretical models are valid while the effect of the mass flow is neglected.

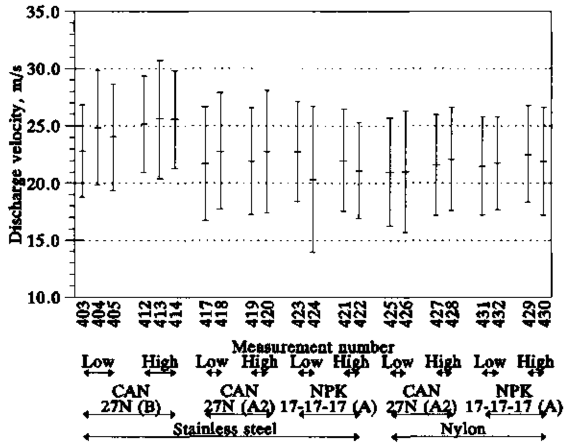
4.2.1. *Velocities and projected distances*

The results of the measurements are summarized in the *Figs 6a-e*. Comparisons of the velocities show that an increase of the mass flow results in a small increase of the discharge velocity (0.5 to 1.0 m/s) for CAN 27N (B) in combination with stainless steel (403-405 and 412-414) and CAN 27N (A2) and NPK 17-17-17 (A) in combination with nylon (425-426 and 427-428; 431-432 and 429-430). The other fertilizer surface combinations do not show an effect of mass flow on the discharge velocity.

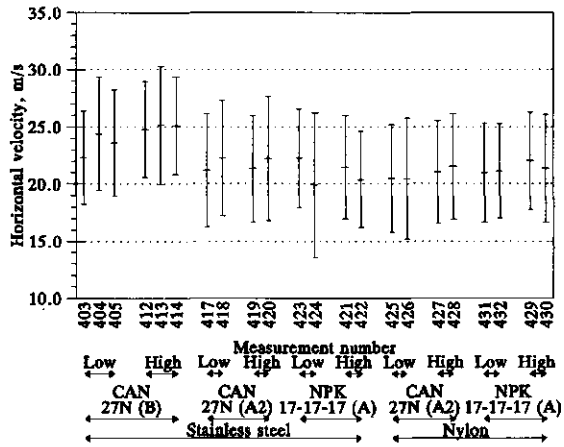
The horizontal velocity components show a similar effect of mass flow as mass flow had on the discharge velocities. The vertical velocity components are relatively small and therefore their contribution to the discharge velocity remains small. The vertical velocity components show an increase with an increase of the mass flow for almost all combinations, except for NPK 17-17-17 (A) in combination with the nylon surface (431-432 and 429-430).

When we look at the vertical directions, we see that an increase of the mass flow results in a small increase of about 0.02 rad or 1° of the vertical discharge direction. The combined effect of direction and velocity on the projected distances is an increase of about 0.5 to 1.0 m for almost all combinations.

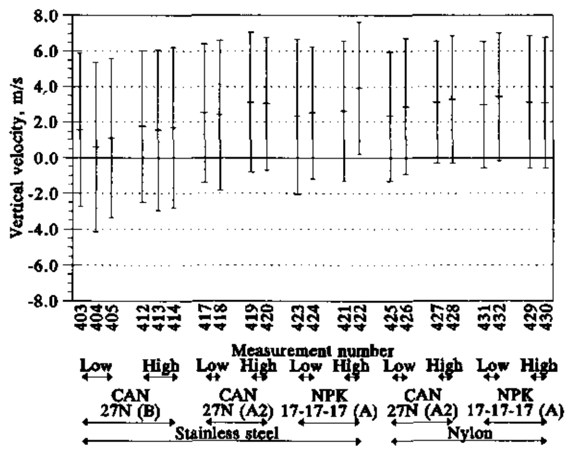
Analysis of variance techniques are used to analyze the measurement results statistically. Analyses of the measurements 403-405 and 412-414 with respect to the effect of the mass flow on the velocities, directions and projected distances show that the discharge velocity (critical level 0.064), the horizontal velocity component (critical level 0.065) and the projected distance (critical level 0.001) are significantly affected by the mass flow. The vertical velocity component and the vertical direction are not significantly affected by the mass flow (critical levels > 0.100). The main effects (mass flow, fertilizer and vane surface) a


35.0
30.0
25.0
20.0
15.0
10.0
Discharge velocity, m/s
Measurement number
Low High Low High Low High Low High Low High
CAN 27N (B)
CAN 27N (A2)
NPK 17-17-17 (A)
CAN 27N (A2)
NPK 17-17-17 (A)
Stainless steel
Nylon

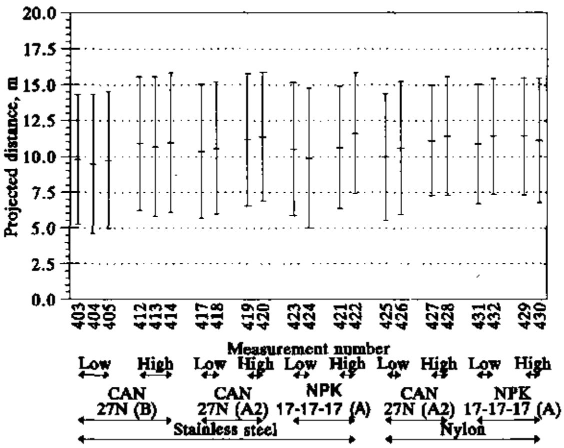
b


35.0
30.0
25.0
20.0
15.0
10.0
Horizontal velocity, m/s
Measurement number
Low High Low High Low High Low High Low High
CAN 27N (B)
CAN 27N (A2)
NPK 17-17-17 (A)
CAN 27N (A2)
NPK 17-17-17 (A)
Stainless steel
Nylon

c


8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Vertical velocity, m/s
Measurement number
Low High Low High Low High Low High Low High
CAN 27N (B)
CAN 27N (A2)
NPK 17-17-17 (A)
CAN 27N (A2)
NPK 17-17-17 (A)
Stainless steel
Nylon

d



e

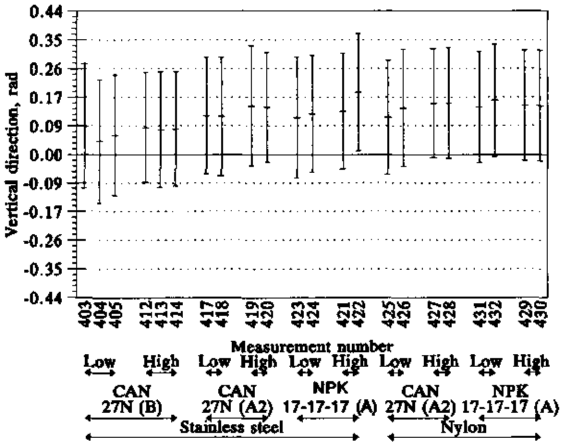


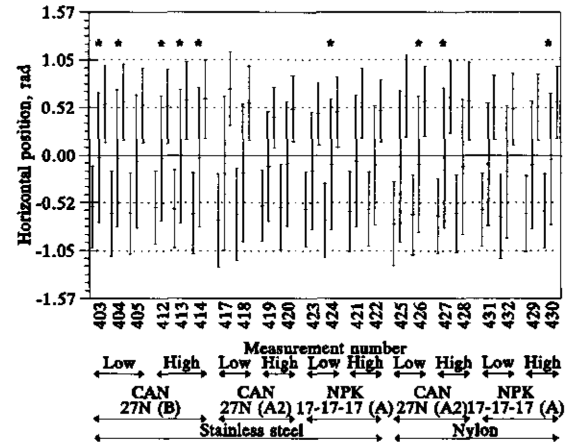
Fig. 6 Mean discharge velocities (absolute (a), horizontal (b), and vertical (c)), projected distances (d), and mean vertical directions (e) of the detected fertilizer particles. The length of the bars is equal to 2σ.

and the interaction effects do not have a significant effect on the discharge velocities and the horizontal velocity components of the measurements 417 up to and including 432. The effect of mass flow on the vertical velocity components is significant (critical level 0.029). All the other effects are not significant. The analysis further shows that the mass flow has a significant effect (critical level 0.0263) on the vertical directions (the joint result of horizontal and vertical velocity components). Analysis of the projected distances shows that only the effect of the mass flow on the projected distance is significant (critical level 0.006). None of the other effects, including the interaction effects, are significant (critical levels > 0.100).

4.2.2. *Positions*

The results of the measurements with respect to the horizontal and vertical positions are summarized in *Fig. 7*. All measurements show that the mean value for the horizontal position is less than zero. The deviation from zero is so small for some measurements that it can be considered to be equal to zero. Those measurements for which the mean can be considered equal to zero according a T-test with a critical level of 0.05 are marked with an asterisk in

a



b

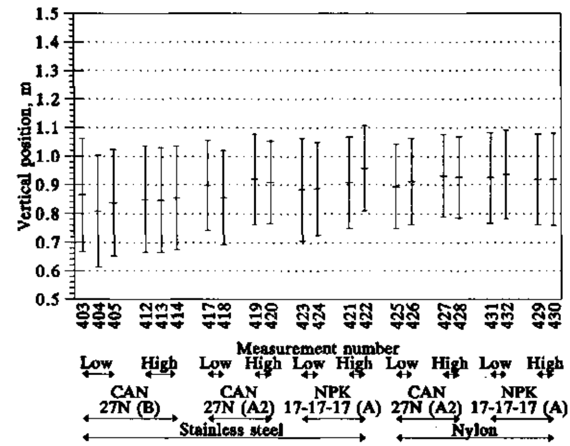


Fig. 7 Mean horizontal (a) and vertical (b) positions of the detected fertilizer particles. The measurement numbers refer to the numbers in Table 5. The length of all bars is equal to 2σ.
The three bars for each measurement in the figure for the horizontal position (a) are from left to right the mean horizontal position for the left half of the pattern, the whole pattern and the right half of the pattern. The asterisks in the figure with the horizontal positions indicate the measurements for which the mean horizontal position can be considered equal to 0 (T-test with a critical level of 0.05).

Fig. 7a. A systematic deviation from 0 must be due to the spreader or the adjustment of the spreader since it indicates that the left and the right disc show a different type of behaviour.

The results of the measurements further show that there is almost no noticeable difference in the mean values for the left and the right half of the pattern for the fertilizers CAN 27N (B) (403-405 and 412-414) and NPK 17-17-17 (A) (423-424 and 421-422) in combination with the stainless steel surface and for NPK 17-17-17 (A) (431-432 and 429-430) in combination with the nylon surface. The results for the CAN 27N (A2) fertilizer (417-418 and 419-420) show that the mass flow has a greater effect on the difference between the centres of the left and right half of the pattern for the stainless steel surface. This difference decreases from about 76° to 59° for the stainless steel surface. The effect for the nylon surface in combination with CAN 27N (A2) (425-426 and 427-428), where the decrease is about 3°, is much smaller. However, analysis of variance of these differences for the measurements 417 up to and including 432 shows that only the fertilizer effect and the interaction effect between fertilizer and mass flow incline to be significant (critical levels were respectively 0.075 and 0.054). Analysis of variance with respect to the effect of the mass flow on the difference between the centres of the left and right half of the patterns shows that the effect of the mass flow is not significant (critical level 0.897).

The mean vertical positions show a small increase (about 0.02 m) in the vertical position as an effect of the mass flow for most of the measurements. Analysis of variance of these differences shows that for the measurements 403-405 and 412-414 there is no significant difference between the mean vertical positions (critical level 0.463). Similar analysis for the measurements 417 up to and including 432 shows that the increase, as an effect of the mass flow, is significant (critical level 0.022). The increase is accompanied by a small decrease of the standard deviation (about 0.01 m), i.e. the variation in the vertical discharge angles becomes smaller.

4.3. *Angular position delivery opening*

A feature of the VICON BS fertilizer spreader is the opportunity to vary the angular position of the delivery opening. Rotating the delivery opening is necessary to compensate for differences in the coefficient of friction and other factors that may affect the motion of particles along the vane. It can also be used to make the spread pattern wider, especially for fertilizers with a high aerodynamic resistance coefficient. The angular position has been varied by rotating the opening with respect to the initial position (K+, measurements 403-405) by about 4° in a direction equal to the rotational direction of the vane (I+, measurements 409-411) and in a direction opposite to the rotational direction of the vane (M+, measurements 406-408). The initial setting was obtained from the operator's manual[12] and was based on the desired mass flow and the fertilizer used.

Based on these settings and with the assumption that the motion of the particles along the vane does not depend on the position of the opening of the metering device, the rotating of the opening from I+ to M+ (opposite to the rotational direction of the disc) must result in a decrease in the angular distance between the centres of the left and right half of the pattern. The decrease is expected to be equal to twice the rotation of the opening.

A summary of the results of these measurements is given Table 6 and Table 7. The data show that a rotation of the delivery opening opposite to the rotational direction of the disc results, as predicted, in a decrease of the angular difference between the centres of the left and right half of the patterns. The difference between the steps is about 5 to 6°, which is somewhat less than the expected values (8°).

Table 6
Measurement results with different settings of the angular position of the metering device.

Measurement number	N	Delivery position	Vertical direction, rad		Velocity, m/s		Projected distance, m		Discharge position, rad			
			Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.	T	Pr > T
409	988	I+	0.0867	0.1832	24.81	4.502	10.84	4.742	0.0477	0.8319	1.80	0.0720
410	698	I+	0.0865	0.1790	24.53	4.361	10.76	4.814	-0.0181	0.7227	-0.66	0.5086
411	692	I+	0.0780	0.1852	25.20	4.631	10.83	5.042	0.0196	0.7397	0.70	0.4856
403	630	K+	0.0856	0.1901	22.80	4.037	9.78	4.531	-0.0267	0.7136	-0.94	0.3475
404	553	K+	0.0403	0.1885	24.85	5.027	9.47	4.846	-0.0368	0.7560	-1.14	0.2529
405	549	K+	0.0589	0.1838	24.04	4.675	9.75	4.788	-0.0674	0.7333	-2.15	0.0318
406	593	M+	0.1152	0.1830	23.14	4.134	11.03	4.606	-0.0711	0.6673	-2.59	0.0097
407	697	M+	0.0650	0.1897	24.13	4.745	10.03	4.990	-0.0385	0.6919	-1.47	0.1418
408	744	M+	0.0798	0.1814	24.72	4.648	10.65	4.723	-0.0784	0.6581	-3.25	0.0012
F			1.40		1.35		11.38					
Pr > F			0.3180		0.3286		0.0091					

Table 7
Measurement results with different settings of the angular position of the metering device.

Measurement Number	Left / Right	Mass flow kg/s	Delivery position	N	Discharge position, rad		Difference L <> R			
					Mean	St.Dev.	Mean, rad	Mean, deg	Mean, rad	Mean, deg
409	Left	0.30	I+	482	-0.6637	0.4489	1.3890	79.6		
	Right			506	0.7253	0.4663				
410	Left	0.30	I+	352	-0.6162	0.3953	1.2066	69.1	1.2662	72.5
	Right			346	0.5904	0.3999				
411	Left	0.30	I+	357	-0.5627	0.4179	1.2029	68.9		
	Right			335	0.6402	0.4440				
403	Left	0.30	K+	328	-0.5683	0.4471	1.1298	64.7		
	Right			302	0.5615	0.4245				
404	Left	0.30	K+	281	-0.6385	0.4680	1.2232	70.1	1.1805	67.6
	Right			272	0.5848	0.4181				
405	Left	0.30	K+	285	-0.6389	0.4453	1.1886	68.1		
	Right			264	0.5497	0.4122				
406	Left	0.30	M+	322	-0.5552	0.4364	1.0595	60.7		
	Right			271	0.5041	0.3717				
407	Left	0.30	M+	360	-0.5698	0.4388	1.0988	63.0	1.0728	61.5
	Right			337	0.5290	0.4005				
408	Left	0.30	M+	384	-0.5914	0.3952	1.0602	60.7		
	Right			360	0.4688	0.3846				

Analysis of vertical directions, velocities, and projected distances shows that there are some small differences between the values. Statistical analysis of the values shows that only the projected distances are significantly different for the different angular positions. However, the trend in the data does not coincide with the trend in the angular positions.

Analysis of the means of the horizontal positions for the whole pattern shows that the pattern remains almost symmetric. Three out of nine measurements show a significant (critical level 0.05) asymmetry. The maximum deviation is about 0.08 rad (4.6°).

4.4. *Coefficient of friction*

The coefficient of friction has a considerable influence on the motion of particles according to the model as discussed in Section 3.2. Values for the coefficient of friction depend on the fertilizer - structural surface combination[2]. Coefficients of friction have been varied by changing the fertilizer and the vane surface material. The results of the measurements are shown in the *Figs 6* and *7*. Values for the coefficients of friction of the fertilizers in combination with the two surfaces are given in Table 4

4.4.1. *Fertilizer*

The measured discharge velocities for the different fertilizers show that the discharge velocities for CAN 27N (B) (403-405 and 412-414) are about 2 to 3 m/s higher than for the other fertilizers (417-432). There are small differences between CAN 27N (A2) and NPK 17-17-17 (B), both for the stainless steel surface and the nylon surface. The higher discharge velocities for CAN 27N (B) go together with a smaller mean vertical direction. The standard deviations of the mean vertical directions do not show much difference, i.e. the spread in that direction is about equal. The joint effect of velocity and direction is that the mean projected distance of CAN 27N (B) is less than the mean projected distance of the other fertilizers.

Comparison of the angular differences between the horizontal centres of the left and right half of the patterns show that for the low mass flow and the stainless steel surface (417-418) the angle between the centres of CAN 27N (A2) is about 0.175 rad or 10° higher than for the other two fertilizers (403-405 and 423-424). The high mass flow in combination with the stainless steel surface (419-420 versus 412-414 and 421-422) show an opposite effect (the angle is about 0.175 rad or 10° less). The nylon surface shows a similar effect for both mass flows. The angular difference is about 0.175 rad or 10° less for the low mass flow and the angular difference decreases to about 0.087 rad or 5° for the high mass flow for NPK 17-17-17 (A). The effect of the mass flow is almost negligable for CAN 27N (B) and NPK 17-17-17 (A) in combination with the stainless steel surface (403-405 and 412-414) and NPK 17-17-17 (A) in combination with the nylon surface (431-432 and 429-430).

Analysis of variance, as discussed in Section 4.2, shows that the effect of the fertilizer on the velocities is not significant. Only the effect of the fertilizer on the difference between the centres of the left and right half of the patterns inclines to be significant (critical level 0.075).

4.4.2. *Vane surface*

Comparison of the results with respect to the vane surface shows that there are almost no differences between the two surfaces for the two fertilizers. The only main difference found is the large difference in the effect of the mass flow on the angle between the centres of the left and right half of the pattern for CAN 27N (A2). The large angular difference when the stainless steel surface is used, is reduced to a small angular difference with the nylon surface. The trends in the angular differences remain the same.

Analysis of variance of the results of the measurements 417 up to and including 432 shows that the vane surface does not have a significant effect on the velocities (discharge velocity, horizontal velocity component and vertical velocity component), the projected distances, and the differences between the left and right half of the pattern. Only the effect of the vane surface on the mean vertical position inclines to be significant (critical level 0.081).

5. Discussion

The measurement results with respect to the effect of the size of the mass flow showed that an increase of the mass flow resulted in a small increase of the projected distance for almost all measurements. This agrees with the observations of Mijnders[13] who mentioned that an increase in the mass flow resulted in a larger spread width. However, from the measurements it is not clear whether this increase is due to a higher discharge velocity or to a small increase of the vertical direction (i.e. the ratio between vertical and horizontal velocity component). The measurements 403-405 and 412-414 showed a significant effect of mass flow on discharge velocity and the horizontal velocity component and the measurements 417 up to and including 432 showed a significant effect of mass flow on the vertical velocity component. The expected effect on the spread pattern is that the pattern will become wider when the mass flow is increased. Therefore, it may be necessary to rotate the delivery opening opposite to the rotational direction of the disc in order to maintain the spread width. This was also proposed earlier by Dobler and Flatow[14]. On the other hand, some of the experiments showed that an increase of the mass flow resulted in a shift of the pattern towards the centre. This can also compensate for the increase of the spread width by an increase of the mass flow. The required action depends on which of the two (opposite) effects is the strongest.

The measurements where the angular position of the metering device was changed showed that this resulted in a corresponding change of the differences between the centres of the left and right half of the patterns.

The results of the measurements as presented in Section 4.4 showed that it is very difficult to prove the effect of the coefficient of friction on the motion of particles. A change of fertilizer as well as a change of the vane surface did not show a significant effect on the motion of the particles. Measurements of the coefficients of friction (Table 4) showed a difference of about 0.15 to 0.20 between the values for the coefficient of friction of a stainless steel and a nylon surface. According to the model, as discussed in Section 3, a decrease of the coefficient of friction should result in a higher velocity along the vane and hence in a higher discharge velocity. The higher velocity along the vane should also result in an earlier discharge of the particles and this should show smaller differences between the centres of the left and right half of the patterns. Neither the higher velocities (nylon versus stainless steel surface) nor the decrease of the difference between the centres of the left and right half of the pattern can be found in the results of the measurements. However, this does not mean that effects on the spread pattern are either absent or very small, because small differences at the measurement positions can produce larger differences in the spread pattern. A difference of 1° in discharge direction in the horizontal plane, and hence a difference in the mean horizontal position, results in a deviation of about 1.7 cm per meter distance. A second effect that plays a role is the aerodynamic resistance coefficient of the fertilizers. The two fertilizers CAN and NPK 17-17-17 have an expected difference in throwing distance of about 0.6 m ($v_{p,dis}$ = 25.0 m/s, α = 5°, q = 0.95 (CAN) or 0.80 (NPK)).

The vertical discharge directions of the particles showed a similar effect to that noted by Mennel and Reece[6]. They found that less than 30% of the particles passed a specific slot. Projection of their slot size to the measurement setup results in a slot height of about 0.15 m (about three horizontal grid lines). Analysis of the results show a mean vertical discharge angle of about 6° and a standard deviation of about 10°. The vertical discharge angle has a considerable effect on the spread width that can be realized. The measurement results showed that in most cases a relatively high value of the discharge angle in the vertical plane is accompanied by a relatively large projected distance, even when the discharge velocity is lower.

6. Conclusions

From the measurement results presented and discussed earlier it must be concluded that it is difficult to prove the effects of the coefficient of friction and the size of the mass flow on the motion of the particles.

The effect of the coefficient of friction on the motion of the particles did not agree with the results of the simulations based on the differential equations for the description of the particle motion. The two possible explanations are:

(a) the existing theoretical models, based on the assumption that particles can behave individually along the vane and/or over the disc, are not valid for situations with mass flows on a real scale. At least the mass flows effects, which depend on the fertilizer surface lining combination, have to be incorporated in such models;

(b) the values for the coefficient of friction as measured with the rotating plate device do not reflect the values for the coefficient of friction that have to be used to describe the motion of mass flows along vanes. One of the most important reasons for this can be the wear of the particle during measurement because of the duration of the measurement is much longer than the duration of stay on the disc or along the vane.

Another indication for the limited value of the theoretical single particle models is that they do not account for discharge angles in the vertical plane unless there is a cone angle $\alpha > 0$.

The effect of the mass flow on the motion of particles is small but an increase of the mass flow resulted in an increase of the projected distance of the particle, which agrees with observations that an increase of the mass flow resulted in a larger spread width. The measurements did not make clear whether this increase was due to higher velocities in the horizontal direction or to a slightly higher velocity in the vertical direction.

The measurements where the effect of the rotation of the angular position of the delivery opening was studied showed that the rotation resulted in a corresponding rotation of the centres of the left and right half of the patterns.

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Chapter V

Interpretation of findings and conclusions

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Handling and Spreading of Fertilizers Part 5: Interpretation of Findings and Conclusions

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The results of the research project 'Physical properties of fertilizer in relation to handling and spreading of fertilizer' are analyzed as a whole. Discussed are the measurements of the physical properties, the developed Doppler velocity meter, and the experimental results obtained with the Doppler velocity meter. A series of verification experiments is also discussed. Finally the relation between physical properties of fertilizer and the spreading of fertilizer is discussed.

1. Measurement of physical properties of fertilizer

According to the theory, which is mainly based on models, the two most important physical properties of fertilizer in relation to the motion of fertilizer particles are the coefficient of friction (motion in or on the distributing device) and the aerodynamic resistance (motion through the air). Two other properties that are also important in relation to fertilizer spreading are the particle size distribution and the flow properties. The particle size itself affects the aerodynamic resistance of the fertilizer particles. The flow properties, which were not a subject of study in this research project, are very important in metering of the fertilizer. The flow of fertilizers through an orifice depends on the size and shape of the orifice, the fertilizer itself (fertilizer type, particle size and particle size distribution) and environmental conditions (air temperature and air relative humidity). Air relative humidity in particular is an important factor since fertilizers are salts that start to absorb water when the air relative humidity raises above a certain level (critical relative humidity).

The spreading process is influenced by the physical properties because to their influence on the motion of the particles. Improvements in the fertilizer spreading process requires that it should be possible to adjust the fertilizer spreader to the properties of the fertilizer. It is necessary, therefore, that standardized physical property data become available and that fertilizer spreaders can be adjusted according to these data. The standardization of the measuring procedures is the first necessary step. Of the four important properties mentioned before, only the measurement of the particle size distribution is standardized to a certain extent and described by ISO[1,2] or ASTM[3] standards. Not precisely defined are the number of sieves that must be placed on the sieve shaker (7 or 10), the shaking duration, and the shaking intensity. An analysis by Arts and Everts[4] showed that all three parameters affected the resulting particle size distribution.

The aerodynamic resistance of fertilizer particles can be calculated when the apparent density and the diameter coefficient are known. The apparent density can be measured with a pycnometer. The diameter coefficient q is introduced in this research. A procedure for the measurement of the diameter coefficient is described in Chapter 2 of this thesis. The advantage of the diameter coefficient with respect to the aerodynamic resistance coefficient K is that the diameter coefficient does not depend on the particle size but only depends on the fertilizer type. Consequently the diameter coefficient can be considered a physical property of a fertilizer that represents the shape in relation to the aerodynamic resistance of a particle.

The coefficient of friction of fertilizer particles is difficult to measure. The measurements described in Chapter 2 showed the possible interaction with environmental conditions. A repetition of the measurements in a climate-controlled room showed that the differences between the consecutive series became much smaller[5]. From this it can be concluded that friction measurements should be executed at prescribed environmental conditions (air temperature and air relative humidity). A second problem is to measure using conditions that occur in the fertilizer spreader. Fertilizer particles are accelerated from 0 to 10 m/s or more in less than 0.05 seconds. The friction device used in the experiments and described in Chapter 2 can operate at these high velocities but is not able to realize the high velocity increase that occurs in reality. The fertilizer particles stay much longer on the friction device and therefore are exposed to more wear than is the case in an actual fertilizer spreader.

From the measurements executed with the spinning disc type fertilizer spreader some doubts arose as to whether the measured values for the coefficient of friction were representative for the conditions in the distributor device. Existing theoretical models, based on the single particle approach, show the effect of the coefficient of friction on the motion of particles in or on the distributor device and therefore on the spread pattern clearly. The executed friction measurements showed a large difference between the values for the stainless steel and nylon surfaces. In the spreader experiments, according to the existing theoretical models, this should result in corresponding differences in characteristic values such as discharge velocity and mean horizontal position of the detected particles for the left and right half of the pattern. However, these differences were not found in the results of the spreader experiments on the scale that was expected.

Standardization of the measurement of the flow parameters requires at least a standardization of the shape and size of the orifice. Furthermore the measurements must be executed at prescribed environmental conditions. Proper adjustment of the fertilizer spreader with respect to the flow is very important because it becomes increasingly important that actual fertilizer levels do not deviate too much from the desired levels. Until now practice shows that deviations of 30% and more are not unusual. Accurate metering during fertilizer spreading can be much improved when dynamic weighing of the fertilizer in the hopper is implemented, allowing the flow rate to be adjusted while spreading. This implies that a standardized value for the flow rate is only necessary for the initial phase when no weighing data are available.

2. Doppler velocity meter

Analysis of the performance of the developed Doppler velocity meter showed that the device can measure the velocity of passing particles with an error of less than about 10%. The analysis also showed that the measurement of the size of the particles was not possible with a high enough accuracy. The measurements showed that a larger mean particle diameter (screen size) resulted in a larger mean measured particle diameter. However, the variations were so large that it was not possible to make an accurate size estimation based on the measured amplitudes of the reflected signals. The main reason for this was that the frequency response of the ultrasonic transducers is not flat in the frequency band used. This causes a particle size and particle velocity dependency on the amplitudes of the received reflected signals.

An accurate value of the particle diameter is necessary for the calculation of the spread pattern from the particle trajectories. The particle trajectory is described by a set of two or three differential equations which require knowledge of position and velocity (both outputs from the Doppler velocity meter) as initial values and the aerodynamic resistance coefficient as parameter. The latter is particle size and fertilizer type dependant. A fixed particle diameter of 3.0 mm has been used in the spread pattern calculations instead of the estimated particle diameters.

A disadvantage of the current measuring procedure is that a long processing time is required for the calculation of the velocity of the detected particles. This can be improved when parallel processing of the signals and hardware signal processing with dedicated processors instead of the current software signal processing are used.

At this moment a feasibility study has been started aimed at assessing whether it is possible to use the Doppler velocity meter for measuring spread patterns instead of using the conventional methods with a row of collecting trays. The main subjects of this study are selection of ultrasonic transducers with a more appropriate frequency response, design of the hardware signal processing, the accurate measurement of the particle size, and the calculation of the real spread pattern. If the feasibility study shows that this may be possible, the Doppler velocity meter could be used for the biannual testing of fertilizer spreaders. This testing will be implemented in The Netherlands by 1995.

3. Experimental results

3.1. *Reciprocating spout type fertilizer spreader*

The experiments with the reciprocating spout type spreader showed diverse results. Simulation results showed that a small change of initial parameters like initial velocity and initial position can result in large deviations in discharge velocity. It is concluded that the sorting-in process in combination with the properties of the fertilizer like coefficient of friction and flow properties are the most important factors that determine the behaviour of the spreader. Especially the rather large influence of the sorting-in process on the subsequent motion makes this spreader difficult to model. The impact of the initial parameters is large that a good estimation of the initial parameters is necessary. However, these parameters are difficult to measure because almost any change made to the metering device and the bowl below will affect the sorting-in process.

In practice these types of spreaders appear to be independent of fertilizer type as far as the motion of the particles in the spreader is concerned. Most differences found in spread patterns must be ascribed to the different aerodynamic resistance of the fertilizers. A major advantage of these spreaders is that they have a symmetric spread pattern for almost any situation. The effective spread width, however, is limited to about 14 m for normal fertilizers and a few meters less for fertilizers with a low density like urea.

3.2. *Spinning disc type fertilizer spreader*

The experiments with the spinning disc type spreader showed that an increase of the mass flow resulted into a small increase of the discharge velocity and the projected distance. The expected effect of the coefficient of friction, based on the particle motion model, was not noticed. It was expected that the use of a nylon lining on the vane surface (lower coefficient of friction) would result into a major change of the discharge velocities and discharge directions.

To verify some of the most essential findings, a series of spread tests has been executed in the spreader testing facilities of Greenland in Nieuw Vennep. The spreader was of the same type (Vicon BS) as that used in the laboratory experiments. In these spread tests the influence of the same variables (mass flow, fertilizer, and vane surface

Table 1
Summary of the spread tests with different velocities, flow rates and vane surface linings.

Metering rate		CAN 27N			NPK 20-10-10		
(Position)		Distribution			Distribution		
Flow, kg/s	Run	Left, %	Right, %	Distance, m	Left, %	Right, %	Distance, m
Stainless steel:							
(12)	1	20.6	79.4	5.04	20.3	79.7	4.46
0.25 / 0.22*	2	18.9	81.1	4.89	16.8	83.2	5.15
(21)	1	24.5	75.5	4.14	18.3	81.7	5.20
0.99 / 0.75*	2	25.8	74.2	3.84	18.6	81.4	5.09
(30)	1	26.9	73.1	3.58	19	81	5.01
1.70 / 1.41*	2	26.5	73.5	3.63	19.4	80.6	4.98
Nylon:							
(12)	1	18.0	82	4.82	15.7	84.3	5.90
0.25 / 0.15*	2	19.9	80.1	4.57	15.3	84.7	5.70
(21)	1	24.7	75.3	3.97	14.2	85.8	5.69
0.86 / 0.68*	2	24.1	75.9	4.21	15.4	84.6	5.76
(30)	1	30.7	69.3	3.11	18.7	81.3	5.05
1.59 / 1.34*	2	28.3	71.7	3.48	16.8	83.2	5.28

* first number applies to CAN 27N and second number applies to NPK 20-10-10.

lining) as in the Doppler velocity meter experiments were tested. The fertilizers were CAN 27N and NPK 20-10-10. Unfortunately it was not possible to use NPK 17-17-17 inthese tests although it had been used in the laboratory experiments. The NPK 20-10-10 has almost similar properties as NPK 17-17-17. The tested mass flows corresponded with application rates varying from about 50 (0.15 kg/s) to more than 500 kg/ha (1.70 kg/s) at a driving speed of 1.67 m/s (6 km/h) and an effective spread width of 18 m. Only one disc has been used in the spread tests because this gives the best opportunities for observing changes in the spread pattern. The results of these measurements are summarized in Table 1.

The data in the columns "left" and "right" show what proportion of the pattern is spread on the left and the right side of the centre of the trailing. The data in the column "distance" gives the distance from the centre of the trailing where the centre of the pattern (50% of the mass left and 50% of the mass right) is located.

A comparison of the results obtained with the Doppler velocity meter and the spread tests is summarized in Table 2. The data in the table shows that an increase of the mass flow in both types of experiments results in a change of the centre of the pattern towards the centre for CAN 27N. This indicates that the particles must have left the disc earlier, i.e. the particle velocity along the vane increases when the mass flow increases. The table further shows that the distribution and the distances of the measurements with the NPK 20-10-10 fertilizer are not affected by the mass flow. The effect of the nylon lining is small or absent for the CAN 27N fertilizer. In combination with the NPK 20-10-10 fertilizer and the lower mass flows the lining has a small effect on the distribution between left and right and the distances from the centre.

Table 2
Comparison of the results obtained with the Doppler velocity meter and the spread tests.

Factor	Doppler velocity meter	Spread test
Increase of mass flow	Increase of discharge velocity. Increase projected distance. Shift of the pattern towards the centre for CAN and not for NPK.	Shift of the pattern towards the centre for CAN and not for NPK.
Vane surface	Almost no difference between nylon and stainless steel for both fertilizers.	Almost no difference between both surfaces. Effects of other factors are more extremely.
Fertilizer	Shift of the pattern depends on the fertilizer vane surface lining combination (shift towards the centre for CAN; stainless steel larger than nylon; opposite shift for NPK).	NPK almost not affected by mass flow and vane surface lining. CAN affected by mass flow.

A comparison of the measurements in Table 2 shows that there is considerable similarity between the results obtained with the Doppler velocity meter and the spreader experiments. The final conclusions that can be drawn from these measurements are:

(1) The motion of particles on the disc and along the vane depends very much on the size of the mass flow. The discharge velocity increases when the mass flow increases but the size of the increase depends on the fertilizer type. A consequence of this is that

problems can occur in situations where the fertilizer is location specific applied and the amount is regulated by varying the size of the delivery opening. In these cases it is advisable to regulate the amount per area by varying the driving speed. The rotational speed of the disc must remain the same, so driving speed and p.t.o.-speed have to be independent.

(2) The existing theoretical models, which do not account for mass flow effects, have a limited value in practice. Increase of the mass flow results in an increase of the discharge velocity and a decrease of the duration of stay. When the mass flow effect is incorporated in the coefficient of friction, the value of the coefficient of friction must decrease with increasing mass flows.

(3) The values of the coefficient of friction as measured with the rotating plate device are not representative in all situations for the coefficient of friction that has to be used in the simulation models that describe the motion of particles on a spinning disc.

4. Physical properties of fertilizer and the spreading of fertilizer

The spreading of fertilizer is affected by both the properties of the fertilizer and the adjustment parameters of the fertilizer spreader. The relevant properties are as follows:

(1) particle size and particle size distribution

The size of individual particles can be characterized by the screen size and by the diameter of the equivalent sphere.

The particle size distribution of a fertilizer batch has to be described by the parameters that describe a specific distribution, which are the mean (corresponding with the d_{50} of a fertilizer batch) and the standard deviation in case of a normal distribution (no corresponding parameter). It can be worthwhile to find a distribution that better reflects the usual particle size distribution of a fertilizer batch and to define these parameters as properties of the distribution.

(2) coefficient of friction

The frictional properties depend not only on the fertilizer structural surface combination but also on the size of the mass flow. Measurements showed that the coefficient of friction is also affected by environmental conditions. So a value of the coefficient of friction has to be accompanied by parameters that indicate the mass flow effect, the specific structural surface effect and the air temperature and air relative humidity effects.

(3) aerodynamic resistance coefficient

The aerodynamic resistance coefficient K is not a good parameter representing aerodynamic resistance as a fertilizer property since K is particle size dependent. The aerodynamic resistance of a fertilizer can better be represented by the parameters apparent density and diameter coefficient in combination with the diameter of the equivalent sphere. These two parameters together can then be used to calculate K for a specific particle. K is still necessary because it is a parameter that is needed in the differential equations that describe the particle trajectories.

(4) flow

The flow of fertilizers through a metering device depends on many factors such as orifice shape and size, coefficient of internal friction, and particle size distribution. All these factors can be incorporated into one flow parameter (expressing the flow in kg/s) when a standardized orifice (shape and size) is used. Since environmental conditions also affect the flow, the parameter has to be measured at standardized air temperature

and air relative humidity conditions. Additional parameters have to reflect the air temperature and air relative humidity effects.
When, in the future, fertilizer spreaders have the opportunity of continuous weighing during spreading, the flow property becomes less important and is only necessary for the initial phase.

In the future adjustment of fertilizer spreaders could be made more easier if the current spread tables for each specific fertilizer are replaced by one main table which contains the values of the physical properties, as has been mentioned, as table entries. In this way a user could adjust his spreader for almost any fertilizer, also when the properties change over the years. The requirement is that fertilizer manufacturers make the values of the relevant properties available to the user of the fertilizer spreader and that manufacturers of fertilizer spreaders define this special adjusting table.

Fertilizer properties that do not depend on environmental conditions and/or storage and transport can already be determined by the fertilizer industry. Until now only the diameter coefficient q can be considered for this. The values of the other properties have to be accompanied by correction factors for temperature and air relative humidity. (like coefficient of friction and flow) or have to be measured (with a simple device) just before application (like particle size distribution and eventually flow).

However, the research discussed in this thesis also showed that the effect of a property such as the coefficient of friction is not as clear as it should be. This implies that the implementation of a physical property-based adjustment procedure has some restrictions.

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Curriculum vitae

Jan Willem Hofstee werd geboren op 3 mei 1961 te Ooststellingwerf. Na het behalen van het diploma Atheneum B aan het Gertrudislyceum in Roosendaal in 1979 werd aansluitend begonnen met de studie Landbouwtechniek aan de toenmalige Landbouwhogeschool in Wageningen. Het Kandidaats B diploma werd behaald in 1983 en het Doctoraaldiploma Landbouwtechniek (met lof) werd behaald in 1986. Het doctoraaldiploma omvatte de vakken Werktuigkunde, Informatica en Meet-, Regel- en Systeemtechniek.

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