Air flow, temperature, and humidity patterns in a co-current spray dryer: modelling and measurements

Citation for published version (APA):
Kieviet, F. G., & Kerkhof, P. J. A. M. (1997). Air flow, temperature, and humidity patterns in a co-current spray dryer: modelling and measurements. *Drying Technology*, *15*(6-8), 1763-1773. https://doi.org/10.1080/07373939708917325

DOI:
10.1080/07373939708917325

Document status and date:
Published: 01/01/1997

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

DRYING TECHNOLOGY, 15(6–8), 1763–1773 (1997)

AIR FLOW, TEMPERATURE AND HUMIDITY PATTERNS IN A CO-CURRENT SPRAY DRYER: MODELLING AND MEASUREMENTS

F.G. Kieviet and P.J.A.M. Kerkhof
Laboratory of Separation Processes and Transport Phenomena,
Department of Chemical Engineering, Eindhoven University of Technology,
P.O.Box 513-FT, 5600 MB, Eindhoven, The Netherlands

Keywords: spray drying, computational fluid dynamics, flow, particulates

ABSTRACT

In a co-current pilot plant spray dryer measurements were done of the airflow pattern (no spray) and the temperature and humidity pattern (water spray). These patterns were simulated with a computational fluid dynamics package (FLOW3D).

The measured air velocities showed large fluctuations. The measured and predicted flow pattern showed good agreement qualitatively, but the measured profiles showed less variation than the predicted ones.

The measured temperatures and humidities showed good agreement in large areas of the dryer, but the agreement in the zone near the central axis leaves room for improvement.

INTRODUCTION

Although spray drying equipment is very bulky and expensive, the spray drying process is commonly used for drying temperature sensitive materials like food stuffs. Spray dryers have been used for nearly a century now. Still it is very difficult to model the performance of a spray dryer, especially with respect to the quality of the dried product.

The objective of this research project is to develop a model with which the product quality can be modelled. This model aims to predict the temperature and moisture of the particles being spray dried as a function of time. For this it is necessary to model the air temperature and humidity a particle experiences on its way through the drying chamber. These air temperature and humidity histories can be calculated by combining the temperature and humidity pattern at one hand, and the particle tracks at the other hand.

Since the introduction of fast computers and computational fluid dynamics (CFD) software, it is possible to predict the airflow pattern in spray dryers (e.g. Oakley et al 1988, 1991, 1994, Livesley et al 1992). Commercial CFD software is nowadays readily available and can be used by researches who are specialised in subjects other than numerical mathematics. Still, not many studies have been published that assess the validity of CFD predictions. This is probably caused by the fact that measurements in drying chambers are quite complicated due to the interfering presence of the dispersed phase.

In this paper we describe measurements and CFD simulations of the velocity, temperature and humidity patterns in a spray dryer.

Except laser Doppler anemometry (LDA) there is no technique that allows for measuring in the presence of a spray. Standard LDA equipment is not suitable for measurements in a standard spray drying chamber because the chamber is not very well optically accessible. Having not the most sophisticated LDA equipment to our disposal, we made use of hot-wire anemometry. This implied that these measurements had to be done in the absence of spray.

Measuring temperatures in an operational spray drying chamber is not as simple as inserting a thermometer into the chamber. Wet particles will deposit on the thermometer and because of the evaporation of the water, the temperature that is actually being measured will be between the wet bulb temperature and the actual air temperature. The same problems arise when measuring humidities.
Therefore, special measures have to be taken to prevent the wet particles from depositing on the measuring probe. A special device was designed to accomplish this.

In this paper we first describe the measurement of the air flow pattern after which we will describe the measurements of the temperature and humidity pattern. The airflow, temperature and humidity patterns were modelled using a CFD package. The basic principles of this model will be described; hereafter the measurements will be compared with the simulations.

EXPERIMENT

The spray dryer

The spray dryer in this research project is a co-current pilot-plant spray dryer manufactured by Niro Atomizer, depicted in figure 1. For the measurements of the temperature and humidity pattern in the spray drying chamber, the temperature of

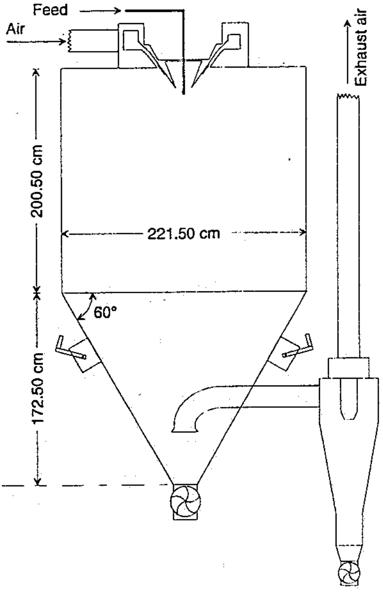

Figure 1: Geometry of the spray dryer

the drying air was 195 °C. The feed (42 kg/hr; water) is atomised using a centrifugal pressure-nozzle, producing a hollow cone spray.

The droplet size distribution of the water spray was measured by collecting droplets in silicon oil and photographing them.

For normal spray drying experiments, the drying air is fed tangentially into the air distributor. The swirl angle of the air entering the drying chamber was measured using tufts and had a value of about 5°. Because the swirl angle was not constant at every location in the air inlet annulus, the top plates of the air distributor were removed for the measurement of the air flow pattern, thus causing the swirl angle to be exactly zero.

To position a measuring probe in the spray drying chamber, a vertical arm is used that can be moved manually along the wall of the cylindrical part of the dryer. At the bottom end of the arm a horizontal arm is attached, that has a length that equals the radius of the spray dryer. On the roof of the dryer, a small motor is installed to rotate the vertical arm under PC control. In this way all radial positions can be reached.

Measurement of the air flow pattern

The airflow pattern was measured using a single normal hot-wire probe (hot film). This probe consists of a fused quartz support (diameter about 40 μm, length about

2 mm) coated with platinum. The wire is supported by two prongs. The wire is heated by an electrical current and kept at constant temperature (is equivalent to constant resistance) using an electrical circuit.

The hot-wire cannot distinguish between two opposite flow directions (the so-called forward reverse ambiguity, Lomas 1986), so in the case of flow reversals the arithmetic mean overestimates the true mean significantly. Flow reversals manifest themselves in the velocity distributions by distributions that lie against the velocity = 0 axis (appears to overlap with velocities < 0).

The bridge voltage was sampled using a 12-bits AD-converter built in a PC. The data-acquisition software converts the bridge voltage to the effective cooling velocity prior to further processing. The mean, standard deviation and the complete velocity distribution of the sampled signal were calculated.

Although the hot-wire is directional sensitive, it proved to be impossible to measure velocity directions. This was caused by flow reversals and the unstable nature of the flow. Therefore only velocity magnitudes were measured.

Measurements were done on a grid of a number of radial and axial positions. The probe was positioned in such a way that the wire and the prongs were parallel to the roof of the spray dryer. Velocity distributions were obtained from measurements over 10 minutes at a sample frequency of 200 Hz. Examples of a number of characteristic velocity distributions are depicted in figure 2. More details about these measurements can be found in Kieviet et al, K2.

The data were interpreted using the following procedure: the distributions were divided in four categories:

– Normal distributions that do not lie against the v=0 axis (e.g. distribution 30/9.7 in figure 2)

These distributions are at locations were the flow is apparently stable and where there are no flow reversals. Hence the mean velocity can be calculated from the first moment of the velocity distribution (equals the arithmetic mean of the velocities).

– Narrow distributions that lie against the v=0 axis (e.g. distribution 140/57 in figure 2)

These distributions are at locations where the flow is apparently stable, but where flow reversals occur. Calculating the mean velocity magnitude by calculating the first moment of the velocity distribution would result in a very large overestimation of the mean because flow reversals are neglected.

Because the hot-wire can not determine the sign of the velocities, the part of the velocity distribution at negative velocities is added to the positive counterpart. Assuming the true velocity distribution can be described with a normal probability function, the velocity distribution as measured with a hot-wire can be described with

$$P(U) = \frac{1}{\sigma\sqrt{2\pi}}\left[\exp\left(-\frac{(U-\mu)^2}{2\sigma^2}\right) + \exp\left(-\frac{(U+\mu)^2}{2\sigma^2}\right)\right]$$

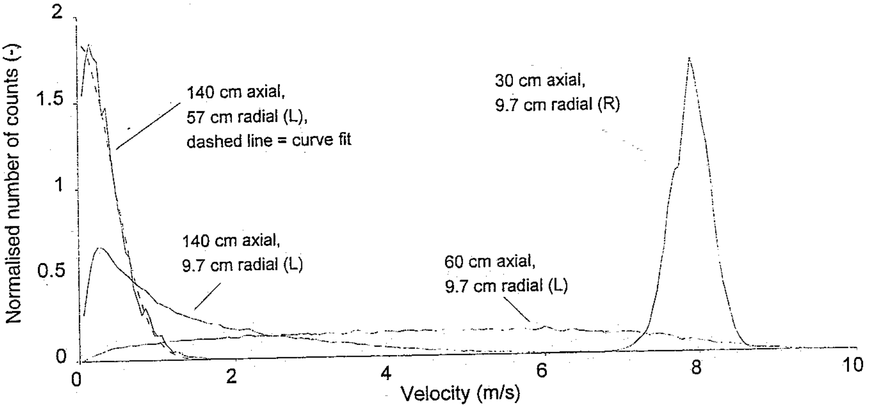

Figure 2: A number of characteristic distributions

The mean velocity can now be calculated using a non linear regression of this function to the measured normalised velocity distribution.

- Skewed distributions that lie against the v=0 axis (e.g. distribution 140/9.7 in figure 2).

These distributions consist of a large number of normal distributions. Since the velocity distributions lie against the v=0 axis, it is *impossible* to calculate a sensible mean. The only way of evaluating the velocity distribution quantitatively is to assign a velocity interval by eye.

- Wide distributions that do not lie against the v=0 axis (e.g. distribution 60/9.7 in figure 2).

It is possible to calculate a mean of this distribution by calculating the first moment. However this mean is not very reliable. Therefore we have also indicated a velocity interval for this category of distributions.

The calculated means and estimated intervals are depicted in figure 4 (a).

Measurement of the temperature and humidity pattern

Special measures had to be taken to eliminate the interfering effect of the spray on the temperature and humidity meters. After examining designs presented in literature, it was decided to develop a new device to separate droplets/particles from the air before the air reaches the temperature and humidity probe.

The design we have come up utilises the inertia of the particles. The air stream to be cleaned follows a sharp curve (180°), such that the particles cannot follow this curve. The design is depicted in figure 3. The effectiveness of the de-

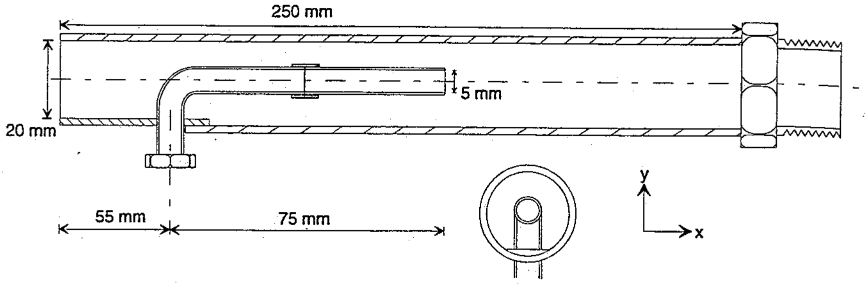

Figure 3: Geometry of the micro-separator. Please note that the scales in x- and y-direction are different.

sign was investigated using computational fluid dynamics. CFD was also used to determine the optimum flow rates in the inner and outer tube. The design is fully described in Kieviet et al. (K1).

In the inner pipe a thermocouple was installed. The voltage of the thermocouple was recorded using an AD-converter built into a PC. The clean air stream was led to a dew point meter (Endress Hauser Hygrolog WMT343 & DT33) installed outside the drying chamber. This device has an air pump built in that takes care of the air flow in the inner pipe (mean velocity in the inner tube is 1.5 m/s). Special measures were taken to prevent condensation in the tubing from the spray dryer to the dew point meter. This was done by wrapping electrical heating wire and insulation around the tubing. The signal of the dew point meter was also recorded using the PC. The airflow in the outer pipe was maintained at an average velocity of 9 m/s by means of a secondary pump.

The measurements were carried out on a grid of locations in the drying chamber. At every location, the system was allowed 4 minutes to equilibrate. After this, during 3 minutes the signals of the thermocouple and dewpoint meter were recorded. The average of this signal was then taken as the value at that location.

The results are depicted in figure 5.

SIMULATION

The flow solver

We have used the flow solver FLOW3D version 3.3 by CFDS (Computational Fluid Dynamics Services, Harwell, United Kingdom). Like most CFD programs, this solver calculates an approximate solution of the turbulent flow pattern by ap-

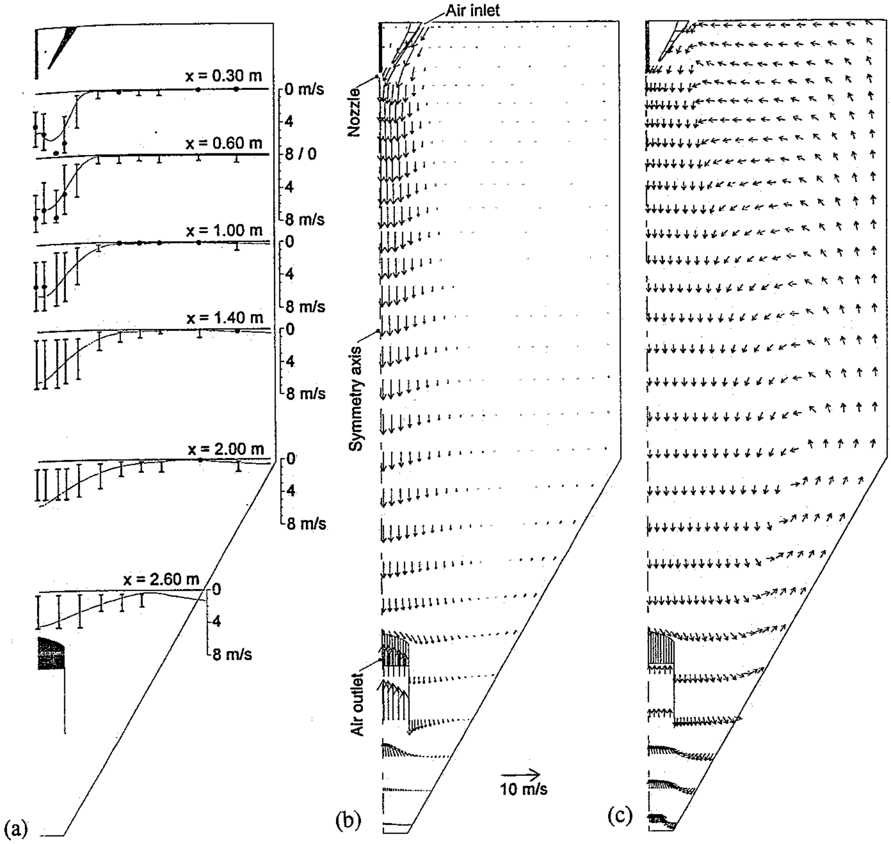

Figure 4: The measured and simulated velocity magnitudes (a), the flow pattern in vectors (b) and the flow pattern in normalised vectors (c). For ease of display, in (b) and (c) only one in four vectors is displayed. In (a) the circles denote mean values obtained either by fitting or the calculation of the first moment. The vertical lines denote intervals estimated by eye.

proximating the time-averaged Navier-Stokes equations. In the case of FLOW3D this is done on a body fitted grid, which allows for the grid cells to be non-rectangular. The technique that is used in FLOW3D to solve the equations is finite volume. As a turbulence model, the k-ε model was used.

Two way coupling of the spray with the gas phase was accomplished as follows:

[1] The extra source terms in the Navier Stokes equations are set to zero.

[2] An approximate solution for the airflow is calculated

[3] Particles are 'injected' into the flow domain at the nozzle. The particles trajectories are calculated. At every location on the trajectory, the exchange of water vapour, momentum and enthalpy to the gas phase is calculated.

[4] The transferred water vapour, momentum and enthalpy are stored as the extra source terms in the Navier Stokes equations

[5] If the number of iterations has not been exceeded, the process restarts at step [2]. Typically ten of these outer iterations are required.

The particles trajectory are calculated by integrating the equations of motion where the forces acting on the particle include the drag, the pressure gradient force, the buoyancy force, and the added mass force. Simultaneously with the integration of the equation of motion, heat transfer and mass transfer are calculated using standard mass transfer correlations and the Antoine equation for the calculation of the vapour pressure. Further, the model incorporates heat loss through the walls and the buoyancy of the air due to temperature and humidity differences.

Simulation and results

The geometry of the spray dryer was converted to a grid of 40 by 55 cells, assuming rotational symmetry.

For the simulation of the airflow pattern *without* spray, the inlet conditions were measured using hot-wire anemometry (Kieviet et al, K2), and were found to be (U,V,W) = (6.03, –4.22, 0 m/s) where U,V,W are the velocities in x (axial), y (radial), z (tangential) directions. The turbulence intensity k and the dissipation rate ε at the inlet were found to be 0.027 m^2s^{-2} and 0.37 m^2s^{-3} respectively.

For the simulation of the airflow pattern *with* spray, the inlet velocities were calculated from the mass flow and the inlet angle of 35° and the swirl angle of 5°: (U,V,W) = (7.4, –5.2, 0.65 m/s). k and ε were set the same as for the isothermal simulation.

The spray was modelled using a Rosin-Rammler distribution with parameters with parameters $D_m = 91$ μm and q = 2.452. The velocity of the droplets were estimated based on measurements by Kerkhof et al (1974) and were set (U,V,W) = (33, 26, 0 m/s).

In figure 4 (b) and (c) the calculated flow pattern in the absence of spray is depicted. In figure 5 a number of temperature and humidity profiles is depicted.

DISCUSSION

The CFD model predicts a fast flowing core at the axis of the spray drying chamber. This is consistent with the hot-wire measurements. In that respect there is good agreement between prediction and measurement. In the measurements however, the core flattens out more rapidly than in the CFD model.

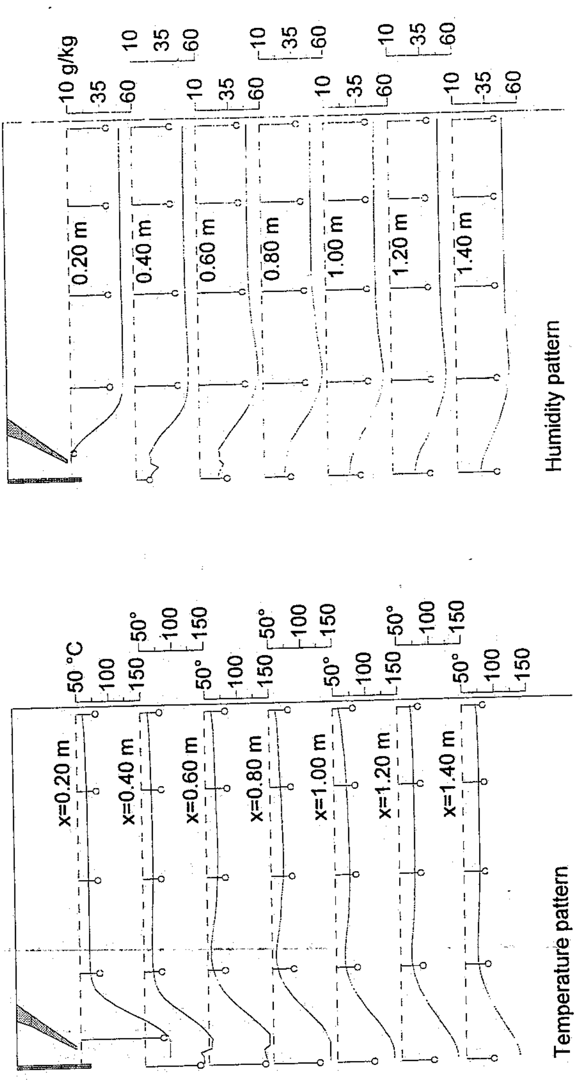

Figure 5: Measured (circles) and simulated (curved lines) temperature and humidity profiles.

Further, the hot-wire measurements show that the airflow has an unstable nature. One of the basic assumptions in the CFD model is however that the airflow can be described using the *time-averaged* Navier-Stokes equations. Large eddies are not taken into consideration at all. The use of large-eddy simulations appear to be a promising development in this context, but with today's computers it is not yet feasible to model unstable flows.

Regarding the humidity and temperature pattern, the CFD model predicts less mixing than the measurements: here too the core flattens out less than in the measurements. This may be caused by the unstable nature of the flow.

CONCLUSION

There is good qualitative agreement between measurements and predictions. The quantitative discrepancies leave room for improvement. Probably this could be obtained by taking the unstable nature of the flow into account, which is unfortunately not yet feasible with today's knowledge and computer power.

ACKNOWLEDGEMENTS

This research is part of the project Modelling Quality in Spray Drying and was sponsored by the Unilever Research Laboratory Vlaardingen.

LITERATURE CITED

Kerkhof, P.J.A.M. and Schoeber W.J.A.H., 1974, Theoretical modelling of the drying behaviour of droplets in spray dryers, In: Advances in preconcentration and dehydration of foods, Ed: Spicer, A., Applied Science, London, 349–397

Kieviet, F.G., Van Raaij, J. and Kerkhof, P.J.A.M., A device for measuring temperature and humidity in a spray drying chamber, Accepted for publication in Trans.IChemE, (K1)

Kieviet, F.G., Van Raaij, J., De Moor, P.P.E.A. and Kerkhof, P.J.A.M., Measurement and modelling of the air flow pattern in a pilot-plant spray dryer, Accepted for publication in Trans.IChemE, (K2)

Livesley, D.M., Oakley D.E., Gillespie, R.F., Elhaus, B., Ranpuria, C.K., Taylor, T., Wood, W., Yeoman, M.L., 1992, Development and validation of a computational model for spray-gas mixing in spray driers, *Drying '92,* 407–416

Lomas, C.G., 1986, Fundamentals of hot-wire anemometry, Cambridge University Press

Oakley, D., Bahu, R., Reay, D., 1988, The aerodynamics of co-current spray dryers, *Proc. 6th Int. Drying Symposium,* Versailles

Oakley, D., Bahu, R.E., 1991, Spray/gas mixing behaviour within spray dryers, *Drying '91,* 303–313

Oakley, D., 1994, Scale-up of spray dryers with the aid of computational fluid dynamics, *Drying Technology,* 12: 217–233