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Feasibility study of the materials handling and development of a sustainable conveying system in plastics recycling and manufacture

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Abstract

The appropriate handling of materials in manufacturing is essential for the realization of reductions in direct and indirect costs. This research was carried out at a plastic manufacturing company in Zimbabwe where polymer pellets are used to produce plastic packaging. An in-depth work study was carried out at the plant followed by the feasibility, review and analysis of available and affordable conveying systems. A semi-automated pneumatic conveyor system comprising of a prime mover, feeder, and mixer was designed to replace the manual handling of materials. The analysis and eventual development of the optimal conveying system assisted the company in not only freeing up space for the uninterrupted movement of materials, but also improvements in safety and reduction in transportation and operational costs for the sustainable recycling and manufacture of plastic packaging. The research also contributed to the company's product quality and variability.

Selection and peer-review under responsibility of the scientific committee of the 16th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: Conveyor, materials handling, plastic manufacturing, recycling, sustainability

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1. Introduction

Manual handling of materials poses several problems like material contamination, in which particles like dust or leaves from the environment get mixed with the materials [1]. The contamination compromises the integrity of the products produced thus resulting in decrement of standards and quality of service of the organization. Material spillage is also common in manual handling processes at the factory. A factory would require frequent cleaning and a bigger workforce to perform housekeeping chores in an attempt to limit the hazard potential posed by spillages [2]. The pneumatic conveyor system was designed to efficiently deliver materials to the desired destination, at the desired rate, in a closed pipeline with a very close degree of accuracy. Escape of material has been vastly reduced and material contamination is also greatly reduced. Overall factory efficiency was also increased as the material flow rate was varied accordingly. When bulk amounts of material are required the system can be made to deliver material at a faster rate thus increasing reliability of the material handling process [3]. A single person can now operate the pneumatic system; thus, less manpower would be required compared to the manual method which once characterized the plant. The lifting, pushing and pulling of the 25kg or 50kg bags of raw materials has now been completely eradicated. Adoption of an auto-pneumatic system that suits the materials being transferred reduces fatigue and increases motivation and job satisfaction cascades to improved productivity. Material handling does not increase product value, but it helps in the production process thus increasing profitability by making the processes more efficient [4]. Manual handling of the polymer pellets exposes the pellets to the environment hence compromising on quality and poisonous dust is released into the environment [2]. Contaminated raw materials compromise the quality of products and dust released also causes a health hazard for the workers. The case study was carried out at a plastics manufacturing company in Zimbabwe. The operational costs at the company were very high as interpreted by the high number of overtime periods per month. The power bill was also very high per unit item produced as it stood at 0.05c/kg of product but the company wished it to be reduced by at least 50%. The costs seemed to point towards the production line which was highly manual and the material handling by humans was time consuming. A lot of wasted man hours were being lost due to exhaustion and in the long run the company faced lawsuits emanating from employees making reparation claims. The research was therefore aimed at designing a pneumatic conveying system for the sustainable recycling and manufacture of plastics through analyzing available methods of conveying, conceptualizing and selection of the most appropriate solution for the company in terms of cost, health and safety. This was then followed by the design of pneumatic system with an optimal number of bends capable of conveying plastic pellets and finally resizing of the plastic transfer systems for a safe working environment with minimal human interface.

2. Background and literature review

Manual handling of granular and powdered materials is still in common practice in manufacturing, construction, and other related industries [4] as was the case with the case study company. Usually these materials are packed in 25 kg or 50 kg bags for ease of transportation, and most industries interpret this as a limiting factor to improving the materials handling process. The manual handling of materials at the company was slow, labor intensive, and often resulted in material contamination, injury to worker or environmental pollution. Material spillage was also common with the manual handling of materials and storage of the materials in 25 kg or 50 kg bags take up a lot of space. An automatic system greatly improves on the efficiency of a plant and minimizes these challenges faced by the manual handling of materials [5]. Pneumatic conveying system are an automatic method employed for materials handling. A careful study and analysis of the material properties was undertaken in order to design the most suitable conveying system. Pneumatic systems are flexible and easy to route since they can be made to change conveying direction [6].

2.1. Classification of pneumatic conveying methods

Pneumatic conveying can be achieved by moving materials by either a vacuum system or by a pressure system [7]. Pneumatic conveying systems can be classified into two, dense phase and dilute phase where the dense phase conveys materials using high pressure low velocity air and the dilute phase conveys materials using low pressure high velocity air [8].

2.2. Dense phase conveying system

The dense phase conveying system uses high pressure and low air velocity for conveying materials [8]. It is most appropriate for friable, abrasive and mixed batch materials which require low conveying velocities. Reduced air velocity means the conveying process is gentler [9]. This reduces material attrition as well as equipment wear. It uses positive pressure to push materials along conveying lines as shown in Fig.1.

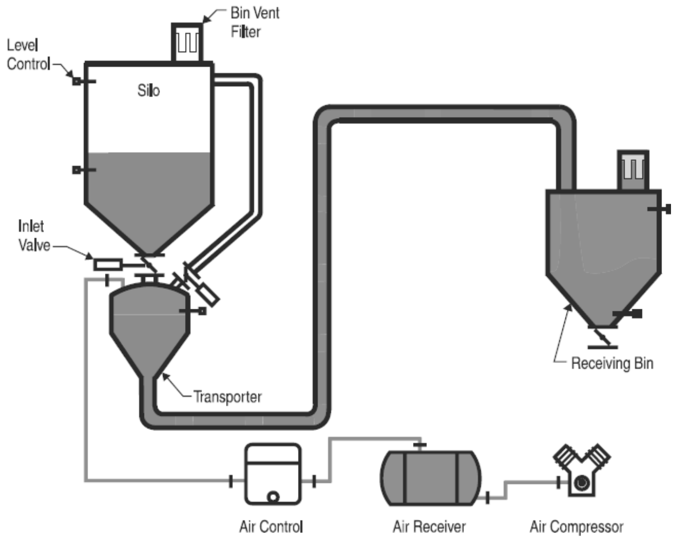

Fig. 1. Dense phase conveying system.

2.3. Dilute phase conveying system

A wide range of materials can be conveyed using the dilute phase system. This conveying method uses high air velocity at low pressure, usually under 1 bar to convey materials [8]. The conveying mode is also commonly known as suspension flow since the conveyed materials will be fully suspended in air [10]. The system has a high air to material ratio. Power requirements are high as relatively high velocities are required for conveying. It is common for conveying materials like powders and granules, and is ideal for non-fragile, non-abrasive materials which have light bulk density. The dilute phase method can use either a vacuum or pressure system [11]. When designing a pneumatic system, it is necessary to have an understanding of the material properties; cohesive materials have several problems in pipe feeding, conveying and hopper discharge [7]. The use of a blow through valve instead of a rotary valve if there are difficulties in discharging the materials is recommended. For combustible materials, polymer pellets are examples of such materials, for closed systems, either the level of oxygen in conveying air is controlled or nitrogen is used as conveying gas [12]. Damp or wet materials result in handling problems at discharge from hoppers [13]. Usually fine materials do not discharge properly from a rotary valve hence a blow-through type is used. Wet, fine materials tend to stick to the pipeline and bends, and progressively block the line. Electrostatic charge builds up is a problem when the air is humidified.

The amount of air which has to be conditioned for a dense phase system is less than in the dilute phase [8]. As a result, operating costs for air quality control will be lower for the dense phase. The entire system and conveying line network ought to be earthed. Erosive wear occurs when the hardness of the system components of the conveyed particles crush on impact. High velocities mean high wear. For a dilute phase system long life all pipe bends should be protected while screws and rotary valves should be avoided [8]. With granular materials, air may permeate through the materials in the blow tank and as a result the materials will not convey if the blow tank has no discharge valve. The discharge line may be blocked by granular materials having a high percentage of fine materials which cannot be conveyed in the dense phase. In rotary valves, shearing of granular materials should be avoided, and so a valve with an off-set inlet should be used [8]. Low melting point materials should have fewer impacts against bends and pipe walls at high velocity [8]. Dilute phase conveying results in high particle temperatures. Plastic pellets such as polyethylene are susceptible to melting when conveyed in the dilute phase. The problem can be eliminated if materials are conveyed using the low velocity, dense phase system. If the materials are to be conveyed in suspension mode, the problem may be eliminated by a roughened pipeline surface which prevents the particles from sliding. Toxic materials are handled by a vacuum system [12]. A closed system is however ideal for conveying. An open system may also be used if the conveying air is filtered before being released into the atmosphere

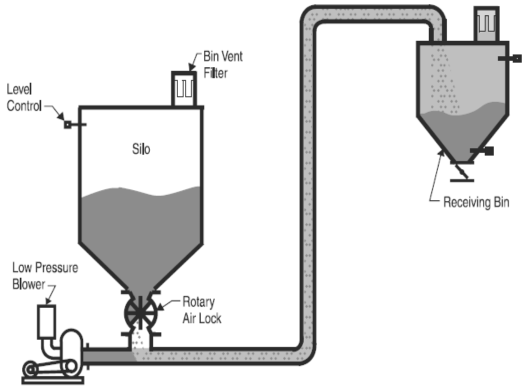

Fig. 2. Dilute phase conveying system

3. Research methodology and case study

The research covered sizing of the compressor, pipelines and various workstations as well as the elimination of possible contamination and pilferage. This involved three distinct areas of the plant i.e. primary intake, conveying and packaging for an effective and sustainable materials handling system.

3.1. Air requirements

To successfully convey materials to the desired destination it was necessary that the velocity was high enough so as to avoid saltation and choking [12]. Saltation occurs when the conveyed material gets deposited along the horizontal section of the pipeline, and choking occurs during deposition of the material at a bend of the vertical pipeline [7]. The air velocity should also not be very high as this would increase operational costs and high velocities result in increased material and pipeline wear. In order to determine the required gas velocity for conveying in the dilute phase, equation (1) was used, where μ was the phase ratio (kg of solid/kg of gas), V_s was saltation velocity, D was pipeline bore and the superficial gas velocity, U was the design conveying velocity obtained using equation (2), where FS was the factor of safety which depended on the material being conveyed and usually ranged between 1.2 – 2.0 [13]. The pressure drop in the pipeline was caused by the head loss due to elevation, solids acceleration, gas friction loss, solids friction loss, and bend/elbow or fittings. Therefore, taking design length as 40,000 mm, L_1 = 40m

$$\mu = \frac{1}{10^{\delta}}\left(\frac{V_S}{\sqrt{gD}}\right)^k \quad (1)$$

$$U = FSV_S \quad (2)$$

3.2. Secondary pipe design

Using a pipe bore D = 75mm, hence determining gas velocity using Rizk equation [13] to estimate saltation velocity, where μ = phase ratio (kg of solid/kg of gas); V_s = saltation velocity; D= pipeline bore, and the average size of polymer pellets was 4 mm, rearranging the Rizk equation (1) gives saltation velocity as equation (3):

$$Vs = \{(\sqrt{gD})(\sqrt[k]{10^{\delta}\mu})\} \quad (3)$$

Taking solids ratio, μ = 4; $Vs = \{(\sqrt{9.81 \times 0.075})(\sqrt[6.9]{10^{7.72} \times 4})\} = 13.79m/s$ and the superficial gas velocity, $U = 1.75Vs$, $U = 1.75(13.79) = 24.1m/s$, Volumetric flow rate $Q = Av$, Where A is the area; and v is velocity of the gas.

Therefore $Q = \frac{\pi D^2}{4} \times v = \frac{\pi}{4}(0.075^2) \times 24.1 = 0.1065m^3/s$

Pressure loss along a horizontal section is given by equation (4), made up of the gas acceleration, solid acceleration pressure drop, gas friction pressure drop and pressure drop due to solids friction [13].

$$\Delta P = \frac{\rho f\varepsilon Uf^2}{2} + \frac{\rho p(1-\varepsilon)U^2}{2} + \frac{2fg\rho fU^2L}{D} + \frac{2fp\rho p(1-\varepsilon)Up^2L}{D} \quad (4)$$

Therefore, total pressure loss in the horizontal pipe was the sum of the pressure drops in equation (4).

$$\Delta Ph = 438.7 + 567.45 + 3825.4 + 2191.1 = 7.023kN/m^2$$

3.3. Pressure drop for vertical section

The pressure loss along the vertical section was derived from equation (5) [4]

$$\Delta Pv = \frac{2fg\rho fU^2Lv}{D} + 0.057GLv\sqrt{\frac{g}{D}} + \rho p(1-\varepsilon)gLv + \rho f\varepsilon gLv \quad (5)$$

$$Ut = 1.74\{\frac{dp(\rho s - \rho a)g}{\rho a}\}^{0.5}$$

Therefore, the total pressure loss in vertical section:

$$\Delta Pv = 286.9 + 147.6 + 111.3 + 44.1 = 0.59\ kN/m^2$$

The total pressure drop (loss) in the bends

$$\Delta Pt = 5.9 + 0.59 + 7.023 + 0.632 = 14.145\ kN/m^2$$

3.4. Power requirements

Volumetric flow rate and delivery pressure were the main factors that influenced the power requirements of the fan or blower. An approximate of the power was obtained as follows:

$$P = 202vln\frac{p4}{p3} = 202 \times 0.1065 \times ln\frac{1.4}{1} = 7.24kW = 9.7Hp$$

3.5. Primary conveying pipe

Using a pipeline bore, D = 75mm, superficial gas velocity, U = 24.1m/s, air flow rate = 0.1065m3/s, Loading ratio, μ = 4, Conveying distance, L = 15m. Air flow pressure drop, using the equation (6) [13];

$$\Delta Pa = (P^2 + \frac{64fL\dot{m}RT}{\pi^2 d^5})^{0.5} - P \quad (6)$$

$$\Delta P = 0.237kN/m^2$$

Pressure drop along the horizontal section, using equation (4) was obtained as 3.262kN/m^2. Hence the total pressure drop in horizontal, vertical, bends and air pressure drop.

$$\Delta P = 3.262 + 0.59 + 0.237 + 2.95 = 7.04kN/m^2$$

Secondary power requirements = 1.34 HP, Design specifications for primary pipeline:

Bore = 75mm, Thickness = 3.5mm, Outside diameter = 82mm, Allowable tensile stress = 17.5kN/m^2

For mass that the material hopper can accommodate, the relationship between mass and volume is given by formula ($m=\rho v$) = 59.17kg, hence the design capacity of the hopper, m1 thus is m = 59.17kg/1.2=49.3kg

3.6. Control of vacuum motor

To determine the mass of materials required for each machine to run for 30 minutes:

$$m_2 = \frac{30mins}{1440mins} \times 350kg = 7.3kg$$

Applying a factor of safety of 1.2, m_2=7.3kg×1.2=8.75kg. Therefore, the vacuum motor would be started when material in hopper falls below 8.75kg. Pressure loss across 4 bends = 1×7.5×0.136=1.02 kN/m^2. Tertiary pipeline design specifications: Bore = 40mm, system pressure drop = 1.655N/m^2, Power requirements = 1.34 HP.

4. Results

The ultimate design produced optimum pipeline specifications of the primary and secondary sections of the plant including air requirements. This section summarizes the results obtained in these categories.

4.1. Pipeline specifications

Total secondary length conveying pipeline, L_1 = 40m. The unit feeder which was modelled using Solid Works is shown in Fig. 3(a) together with the orientation of all the components of the elements in the primary pipeline while Fig. 3(b) shows the orientation of the primary pipeline. The primary pipeline design specifications used in the design were derived from Section 3.5 as follows:

Bore = 75mm, Thickness = 3.5mm, Outside diameter = 82mm, Allowable tensile stress = 17.5kN/m2

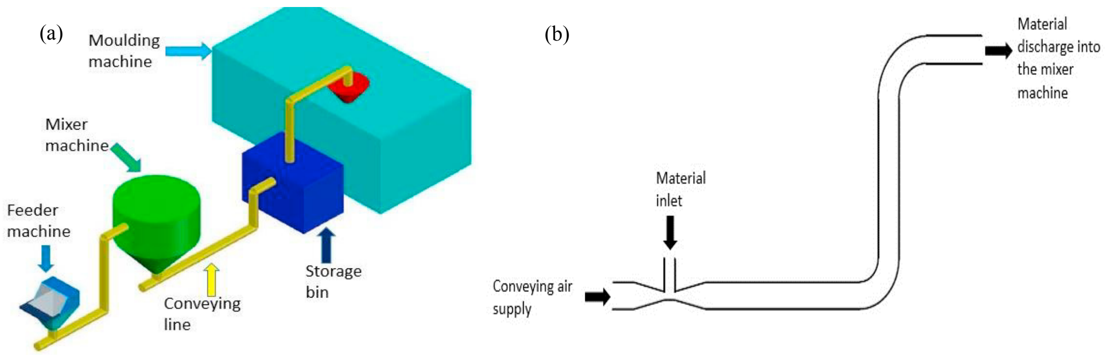

Fig. 3. (a) Unit Feeder orientation; (b) Primary conveying pipeline orientation

4.2. Primary pipe air requirements

The variation in material composition that can be handled was increased due to the mixer machine installed. There were several types of mixer machines on the market and the choice depended on the type of the material to be handled. Fig. 4 shows a screw mixer machine which was also modelled in Solid Works and installed for the pneumatic conveying system, with the following design specifications and output parameters:

Flow rate = 0.1065m3/s, superficial gas velocity = 24.1m/s, Saltation velocity = 13.79m/s, System pressure drop = 7.04kN/m2 and primary pipe power requirements = 9.7HP

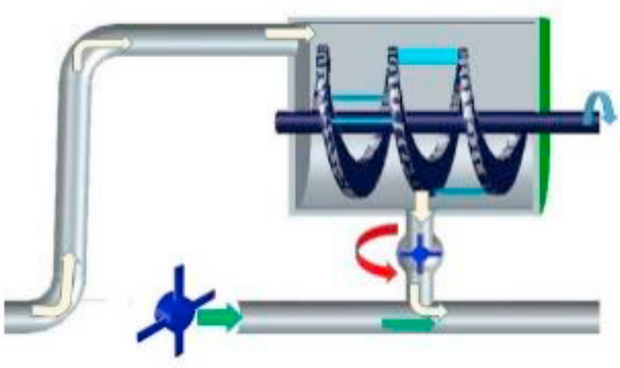

Fig. 4. Screw type mixer machine chosen and installed

5. Discussion and recommendations

Material from storage to the feeder machine was collected in the mixer machine. The mixer machine achieved mixing by rotating the screw rotor. After thorough mixing, the mixed material was then fed into the conveying pipeline. Material in the feeder machine flowed into the conveying line, then the pressurized air from the blower pushed the material along the conveying line to the desired destination. The feeding device shown in fig. 5 was partially installed and tested, the results of which showed some improvements in productivity and quality of products shown by the reduction in personnel working overtime and significant reductions in returns as previously observed. In addition to showing the cost reduction to the waste plastic conveying system, some innovative processes were incorporated into the new design in order to improve plant flexibility and agility. The innovations could improve the company’s bottom line by increasing the number of products.

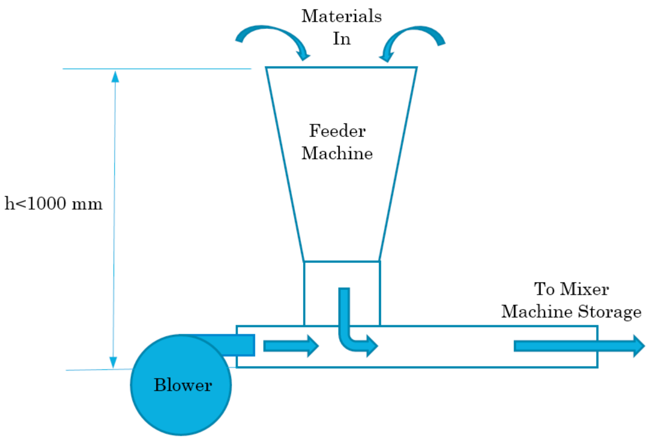

Fig. 5. Simple feeder machine

Pneumatic conveying systems are flexible as they can be easily made to go around existing factory equipment and layout through the use of appropriately designed bends. In addition, bends also provide the means of change of direction of the pipeline. Since the installation, a year ago, no significant breakdowns were reported. However, there were a few cases of clogging that were reported, an issue of which has been recommended for further research and solving. The cost per kg of products now range from 0.02 – 0.03c/kg from the original 0.05c/kg. Further improvements in throughput can be realized by automating the pneumatic conveyor in order to reduce the operational costs. The overall contribution of this work was developing an affordable and sustainable conveying system for the company.

6. Conclusions

A properly designed conveying system results in minimal power requirements, bend attrition and human involvement. The number of bends or elbows in the system were also minimized since significant pressure drops occurred across bends. Other alternative elbows such as diverter valves, feeders and mixer machines were recommended as possibilities for further improvements. Optimal combination can be derived from interchanging the combinations and recording and documenting their effectiveness. The designed optimal pneumatic conveying system resulted in the reduction of cost per kg of products from 0.05c/kg to between 0.02 – 0.03c/kg and also enabled the company to reduce the amount of overtime as well as freed up space for a safe working environment. The reductions in costs per kg of products and free movement of materials also had a net effect of reducing operational and transportation costs for the sustainable recycling and manufacture of plastic packaging. The improvements realized by this research were spelt out and enhanced the designs to limit pollution and pilferage of materials being transferred.

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