Tarım Makinaları Bilimi Dergisi (Journal of Agricultural Machinery Science)
2011, 7 (3), 283 - 288

Design and Development of a Dense-Phase Suction Pneumatic System for Conveying Granular Materials in Agriculture

Hasan GHAFORI[1], Abbas HEMMAT[2], Ali Mohammad BORGHAEE[3], Saeid MINAEI[4]
[1] Department of Mechanical Engineering, Majlesi Branch, Islamic Azad University, Isfahan-IRAN
[2] Department of Agricultural Machinery Engineering, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, IRAN
[3] Department of Agricultural Machinery Engineering, Science and Research Branch, Islamic Azad University, Tehran-IRAN
[4] Department of Agricultural Machinery Engineering, College of Agriculture, Tarbiat modares University, Tehran-IRAN
hasangh28@gmail.com

Received (Geliş Tarihi): 09.05.2011 Accepted (Kabul Tarihi): 09.07.2011

Abstract: Dense-phase pneumatic conveying is used in many industries such as chemical, pharmaceutical and food industries due to its advantages including less dust, minimum product degradation and segregation, low specific energy consumption and low pipe wear. This is in sharp contrast to dilute-phase conveying system. In spite of these advantages, little attention has been paid to the adaptation of the dense-phase conveying system for agricultural uses. Most of the earlier researchers worked on positive pressure for dense-phase conveying in agriculture. The main objective of the research reported here was to design and develop a dense-phase suction pneumatic system for conveying corn and barley. The pneumatic conveyor system consisted of a centrifugal blower, an electric motor, a seed hopper, a rotary airlock, a rotary airlock motor, intake and discharge pipes, a separator cyclone and a discharging cyclone. The choice of power source and vacuum blower was based on the ability of the blower to provide adequate suction and discharge pressures to overcome the pressure losses in the system (including air friction losses, losses due to acceleration of the grain, lift of the grain and the grain flow). The results indicated that the pressure drop, power consumption and mechanical damage of seeds increased with air velocity. It is desirable, therefore, to work the lowest possible air velocity to keep the specific energy consumption and mechanical damage to seeds as low as possible.

Key words: Dense phase, pneumatic conveying, specific energy consumption, mechanical damage

INTRODUCTION

Application of pneumatic conveyer system is very comprehensive and wide range of powder and granular materials can be transferred by this system. In agriculture, the high volume of harvested products such as grains and rice, processed materials, animal feed pellets, chemical fertilizers, food products such as flour, sugar, tea and coffee can be transferred by this way (Mills, 2004). Performance of the pneumatic conveyors are influenced by a wide range of parameters such as material and fluid properties, the mode of conveying and conveyor physical conditions (Mills et al., 2004).

Suction-type pneumatic conveying systems are commonly used for drawing materials from multiple sources to a single point. There is little or no pressure difference across the feeding device and so multiple points feeding into a common line presents few problems but in pressure -type pneumatic conveying systems, air leakage through the feeding device can be quite significant in relation to the total air requirements for conveying. Suction-type pneumatic conveying systems are also widely used for drawing materials from open storage, where the top surface of the material is accessible. Suction systems, therefore, can be used most effectively for off-loading ships and trucks. Vacuum systems have the particular advantage that all gas leakage is inward, so that the injection of dust into the atmosphere is virtually eliminated (Mills et al., 2004).

Major researches in pneumatic conveying of agricultural materials are mostly conducted to improve the performance of agricultural machinery such as pneumatic seeder, grain combine and grain cleaning machinery. The researches are not extended extensively to material handling for grain storage, flour mills and animal feed processing in which a high volume of seed materials are transported. The main objective of this research is to design and development of a dense-phase suction pneumatic system for conveying granular materials in agriculture and to obtain the change in pressure drop, power consumption and mechanical seed damage as a function air velocity during pneumatic conveying of corn and barley through a developed suction-type pneumatic conveying system.

MATERIALS and METHOD

A pneumatic conveying system may be designed according to mathematical models, available test data or a combination of the two methods (Mills, 2004). In this research, the combination of the mathematical models and available test data was used for designing a suction-type pneumatic conveying system. Among cereals, corn and barley were chosen. Because they are the cereals with high transport volume and have different shape, prolate and oblate shaperespectively. The seeds were collected from animal feed storage silos in Isfahan, Iran.

The pneumatic conveying system consisted of a centrifugal blower, an electric motor, a seed hopper, a rotary airlock, a rotary airlock motor, intake and discharge pipes, a separator cyclone and a discharging cyclone (Figure 1).

The logic diagram using in this research for the design of the pneumatic conveying system is presented in Figure 2. The procedure starts with the specification of the fixed parameters (material mass flow rate , conveying distance, pipeline bore and air mass flow rate). The system was designed for a capacity of 30 t/h and has a 15 m long horizontal pipe, a 10 m long vertical pipe with inside diameter of 15.25 cm and four bends. The conveying line inlet air velocity was specified from plots that were given for the various materials (Mills, 2004). The inlet air velocity of 35 m/s was selected for conveying of corn and barley seeds.

In the logic diagram, a loop was necessary after determination of solids loading ratio to check the air velocity. For such materials, the value of minimum conveying air velocity is dependent upon the value of solids loading ratio.

The fundamental step in the design of a pneumatic conveyor is estimate the pressure drop along the pipe correctly (Chand and Ghosh, 1968). Then, the choice of power source and vacuum blower was based on the ability of the blower to provide adequate suction and discharge pressures to overcome the pressure losses (air friction losses, losses due to acceleration of the grain, lift of the grain and the grain flow) in the system (Srivastava et al., 2006).

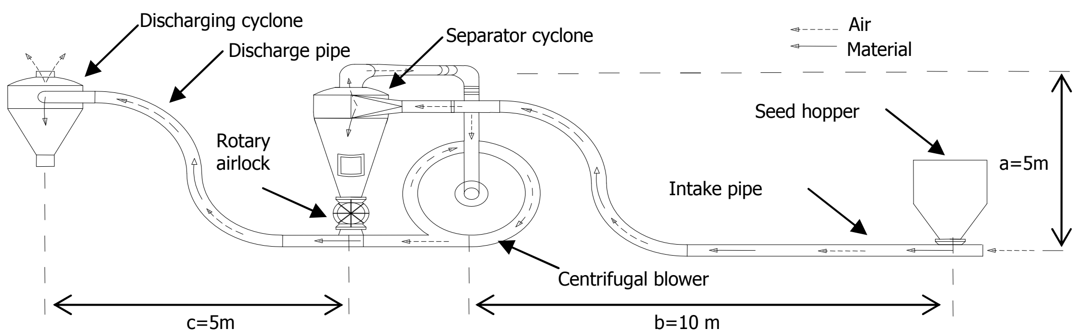

Figure 1. Layout of the pneumatic conveying system

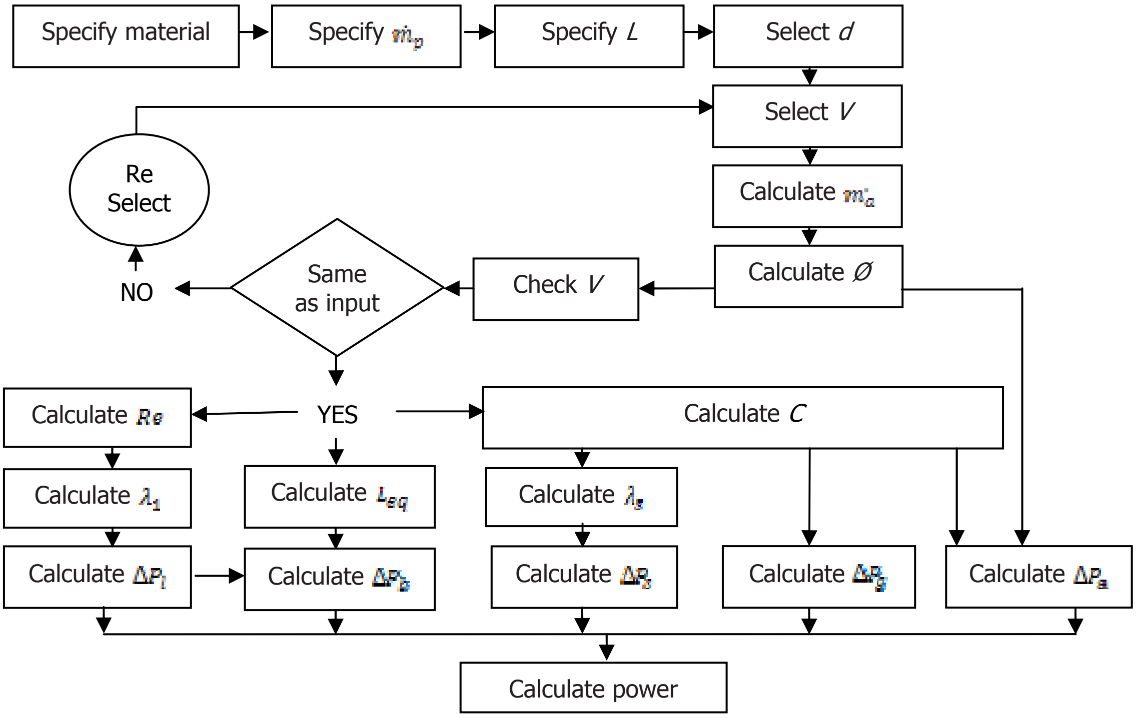

Figure 2. Logic diagram for calculating power requirement of a pneumatic conveying system

KEY

$\dot{m}_p$	mass flow rate of material
l	conveying distance
d	pipeline bore value
v	inlet air velocity
$\dot{m}_a$	air mass flow rate
$Ø$	solids loading ratio
C	material velocity
Re	reynolds number
λ_1	air resistance coefficient
L_{eq}	equivalent length
λ_s	materials friction coefficient
ΔP_l	pressure drop in pipes due to air flow
ΔP_b	pressure drop due to bends
ΔP_s	pressure drop due to materials friction
ΔP_g	pressure drop to lift the materials
ΔP_a	pressure drop in pipes due to accelerate of materials

The total pressure drop (ΔP) was calculated using the following equation:

$$\Delta P = \Delta P_l + \Delta P_a + \Delta P_s + \Delta P_g + \Delta P_b + \Delta P_a \qquad (1)$$

The pressure drop for air flowing in a straight pipeline was determined from Darcy's equation:

$$\Delta P_l = \lambda_l \frac{\rho}{2} v^2 \frac{L}{d} \qquad (2)$$

Where ρ is air density. For turbulent flow, the value of λ_l was calculated using the Koo equation (Srivastava et al., 2006):

$$\frac{\lambda_l}{4} = 0.0014 + 0.125\, Re^{-0.32} \qquad (3)$$

The pressure drop in pipes due to accelerate of materials was determined from Marcuse's equation (Srivastava et al., 2006):

$$\Delta P_a = Ø\, v\, \rho\, c \qquad (4)$$

The following equation was suggested by Marcuse to determine the material velocity (Srivastava et al., 2006):

$$\frac{c}{v} = 1 - 0.68\, (d_p)^{0.92} (\rho_p)^{0.5} (\rho)^{-0.2} (d)^{0.54} \qquad (5)$$

Where d_p and ρ_p are mean diameter and density of particles, respectively.

The pressure drop due to materials friction was computed using following equation which is similar to Darcy's equation:

$$\Delta P_s = \Phi_m \lambda_s \frac{\rho}{2} v^2 \frac{L}{d} \qquad (6)$$

Materials friction coefficient (λ_s) was calculated using the following equation that was suggested by Marcus (Srivastava et al., 2006):

$$\lambda_s = \frac{0.0285\sqrt{gd}}{v} \qquad (7)$$

Pressure drop to lift the materials due to elevation differences in the system and was calculated using the following equation:

$$\Delta P_g = \rho^* g \, \Delta h \qquad (8)$$

Where ρ^* is the bulk density and the following equation was used to obtain the term ρ^*:

$$\rho^* = \frac{\Phi_m v \rho}{c} \qquad (9)$$

The pressure drop for bends in the system can be expressed in term of equivalent length. The equivalent length of a bend was determined as follows:

$$L_{eq} = \frac{kD}{\lambda_f} \qquad (10)$$

Then the pressure drop in bends due to air flow and materials were calculated using the following equations:

$$\Delta P_{b,air} = \frac{\Delta P_f}{L} L_{eq} \qquad (11)$$

$$\frac{\Delta P_{b,solid}}{\rho v^2} = 0.245\left(\frac{\dot{m}}{\rho v D^2}\right)^{1.267}\left(\frac{R}{d}\right)^{-0.26} \qquad (12)$$

After determine all necessary parameters for the system, the power requirement was calculated using the following equation:

$$P = \frac{\Delta P \cdot \dot{m}_s}{\eta} \qquad (13)$$

Where η is the efficiency. The value of power requirement was calculated 35 kW.

After designing the pneumatic conveyer, all separated parts of conveyer was constructed and assembled individually on a chassis by using connecting pipes and fittings (Figure 3).

The centrifugal blower was used to deliver air through the system. The seed hopper served as a storage container for the material. The seeds to be conveyed are introduced into the system using a gate feeder under the hopper. The gate feeder was adjusted to feed seeds at constant rate. The separator cyclone was used to separate the seeds from the air. The rotary airlock was used to provide an airtight on cyclone. In the separator cyclone, the seeds fell downward and the air was exhausted out of the cyclone by the centrifugal blower.

Figure 3. Pneumatic conveyor

After design and manufacturing of the conveyer, the effect of air velocities (10, 15, 20, 25, 30, 35 and 40 ms^{-1}) on pressure drop (kPa/ m), power consumption (kW) and the percentage of seed damaged was evaluated. The pressure was measured by a pressure meter (model: Testo 512). The air velocity was measured by a velometer (model: Testo 512) installed at the inlet of the centrifugal blower (Raheman and Jindal, 2001).

To determine the conveying power consumption, voltage (V), current (I), and power factor (φ) drawn by the electric motor for the blower were measured using a voltmeter, an ampere meter and power factor meter, respectively. Power consumption was calculated using the following equation:

$$P = \sqrt{3} * V * I * \cos\varphi \qquad (14)$$

The mechanical damage was expressed in mass percentage according to following equation (Mohsenin, 1970):

$$S_d = \frac{M_d}{M_d + M_{ud}} 100 \qquad (15)$$

Where M_d and M_{ud} are damaged seeds mass and undamaged seeds mass, respectively.

RESULTS and DISCUSSION

The effect of air velocity on pressure drop is presented in Figure 4. The pressure drop for air only, increased directly with the air velocity. This is agreement with results obtained by Guner (2007). The pressure drop during the conveying seeds was first slightly decreased; then there is a turning point at which the pressure drop increased rapidly with an increase in air velocity. The lowest pressure drop for corn and barley occurred at the air velocity of 20 and 15 m/s, respectively.

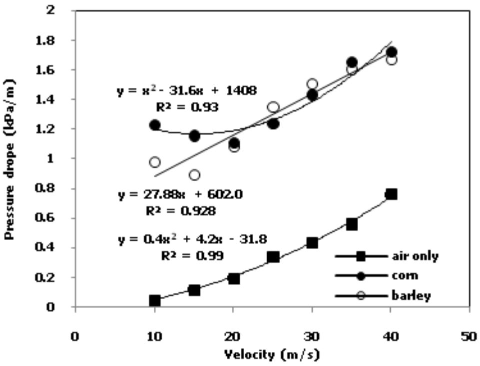

Figure 4. Effect of air velocity on the pressure drop

Our observations showed that at air velocity below the turning point, the material flow was in a dense phase and the material conveyed in a layer along the bottom of pipeline. At high air velocities (30-40 m/s), the seeds were distributed evenly and moved in suspension above the strand in the pipe and the material flow was in a dilute phase. With increasing speed from 20 to 25 m/s for corn and 15 to 20 m/s for barley there was a mixture of dense and dilute phase which is called unstable zone. Conveying state in this zone changes between the suspension flow and strand. The suspended seeds impinging the strand will slow down to the strand velocity and be expelled from the suspension. Other seeds will be knocked out from the strand and accelerated by the air to the same velocity of the air in the suspension. Similar results have been reported by Wypych and Yi (2003), Guiney el al. (2002) and Tsuji el al. (1981).

The effect of air velocity on the power consumption is shown in Figure 5. As can be seen, the power consumption for conveying seeds was at least 4 times the air only and was greatly influenced by the air velocity than the air only. This shows that most of the power consumption is due to seed moving in suspension mode. Similar results have been reported by Zhang et al. (2010). The effect of seed type on power consumption was not significant and the trend of change in power consumption for corn was similar to barley.

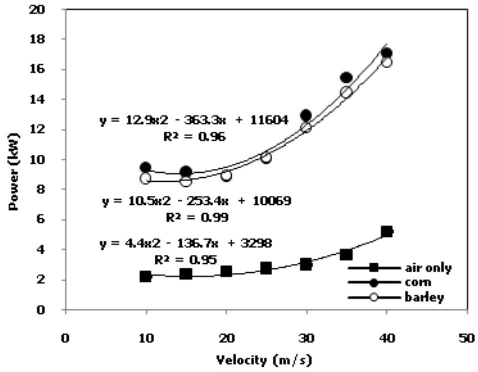

Figure 5. Effect of air velocity on the power consumption

The effect of air velocity on the mechanical damage is shown in Figure 6. The mechanical damage to the seeds increased linearly as the air velocity increased. The results are agreement with the ones obtained by Segler (1951) and Guner (2007). With an increase in air velocity from 10 to 40 m/s, the increase in mechanical damage for corn and barley varied from 4.4% and 3.1% to 10% and 6%, respectively.

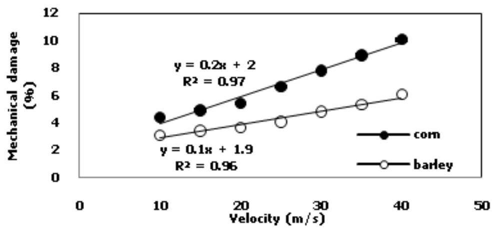

Figure 6. Effect of air velocity on mechanical damage

Then the air velocity must therefore be regarded as a most critical factor in determining whether damage will occur or not. It is desirable, therefore, to work the lowest possible air velocity to keep the mechanical damage as low as possible if we are conveying the seed used for planting. But the danger of blockage should be taken into consideration because the blockages can occur when the energy of air flow is insufficient to keep up the conveying process.

CONCLUSIONS

The results of this research can be summarized as follows:

- The designed and constructed pneumatic conveying system consisted of a centrifugal blower, an electric motor, a seed hopper, seed pipe with 15 m long and 15.25 cm inside diameter, a rotary airlock, a rotary airlock motor, intake and discharge pipes, a separator cyclone and a discharging cyclone
- The results indicated that there was a quadratic relation between the pressure drop as well as power consumption with the air velocity for corn seeds. The power consumption during the conveying seeds were first slightly decreased, then there was a turning point at which the pressure drop and power consumption increased rapidly with an increase in air velocity.
- Mechanical damage of seeds increased linearly as the air velocity increased. With an increase in air velocity from 10 to 40 m/s, the increase in mechanical damage for corn and barley varied from 4.4% and 3.1% to 10% and 6%, respectively.
- At the air velocity below the turning point, the material flow was in a dense phase and the material conveyed in a layer along the bottom of pipeline. At high air velocities (30-40 m/s), the seeds were distributed evenly and moved in suspension above the strand in the pipe and the material flow was in a dilute phase. With increasing speed from 20 to 25 m/s for corn and 15 to 20 m/s for barley there was a mixture of dense and dilute phase which is called unstable zone.
- The air velocity is an important critical factor in determining the power consumption and mechanical damage. Therefore, for reducing the power consumption and mechanical damage to the seeds, the air velocity in the developed pneumatic conveying must be decreased as long as the conveying capacity of the system is acceptable.

REFERENCES

Chand P. and D. P. Ghosh, 1968. Critical analysis under pneumatic conveyance of solids. Journal of Agricultural Engineering Research, 13(1): 36–43.

Guiney P., R. Pan. and J. A. Chambers, 2002. Scale-up technology in low-velocity slug-flow pneumatic conveying. Powder Technology, 122: 34-45.

Guner M., 2007. Pneumatic conveying characteristics of some agricultural seeds. Journal of Food Engineering, 80: 904–913.

Mills D., M. G. Jones, V. K. Agarwal, 2004. Types of Pneumatic Conveying Systems. Chap.1, pp.1-26. In: *Handbook of Pneumatic Conveying Engineering*. Scitech Book News. UK.

Mills D., 2004. Design procedures. Chap.15, pp.355-384. In: *Pneumatic Conveying Design Guide, Second Edition.* Butterworths. UK.

Mohsenin N. N., 1970. *Physical Properties of Plant and Animal Materials, First edition.* Gordon and Breach Science Publishers, NY.

Raheman H. and V. K. Jindal, 2001. PSressure drop gradient and solid friction factor in horizontal pneumatic conveying of agricultural grains. Applied Engineering in Agriculture, 17(5): 649–656.

Segler G., 1951. Pneumatic grain conveying with special reference to agricultural application. Published by Prof. Dr. _Ing. G. Segler, Braunschweig, Germany.

Srivastava A. K., C. E. Goering, R. P. Rohrbach and D. R. Buckmaster, 2006. *Engineering Principles of Agricultural Machines.* ASABE Press, Detroit, MI, USA.

Tsuji Y. and Y. Morikawa,1982. Flow pattern and pressure fluctuation in air solid two-phase flow in a pipe at low air velocities. Multiphase Flow, 8(4): 329–341.

Wypych P., and J. Yi, 2003. Minimum transport boundary for horizontal dense-phase pneumatic conveying of granular materials. Powder Technology, 129: 111–121

Zhang Ch. X., Y. Zhang, D. McGlinchey, Y. Du, X. Wei, L. Ma and Ch. Sh. Guan, 2010. Experimental and numerical study on power consumptions in a double-tube-socket pneumatic conveying system. Powder Technology, 204: 268–272.