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Original Article

The Influence of the Pipe's Material and the Mass Flow Rate on the Pressure Drop and Velocity Variation During Pneumatic Conveying of Wheat Using Computational Fluid Dynamics

Sajed Naeimi Dizajeyekan[1], Golamhossein Shahgholi[1], Adel Rezvanivande Fanayi[2*]

[1]Department of Biosystem Engineering, Faculty of Agricultural Technology and Natural Resources, University of Mohaghegh Ardabili, Iran
[2]Department of Biosystem Engineering, Urmia University, Urmia, Iran

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ABSTRACT

According to flexibility of pneumatic conveying systems with respect to other types of transmission systems, this system has wide application in industry and agriculture processes. One important application of this system is in the loading and unloading tankers and powdery bulk materials such as trucks carrying cement, plaster and sand. Conveying efficiency is associated with pressure, which increases the pressure drop in the pipe, operational efficiency will be reduced. This work presents a computational fluid dynamics (CFD) calculation to predict and evaluate the influence of the pipes type and the inlet mass flow rate on the pressure drop and velocity fields during pneumatic conveying of wheat. The numerical solutions were carried out using spreadsheet and commercial CFD code Ansys Fluent 14.5. The CFD simulations predict excellently the pressure drop and velocity field under different pipe types and inlet mass flow rate. Pressure drop were estimated to be 2780, 3120, and 3360 pa for mass flow rates of 4.33, 5.77 and 8.66 kg/s respectively in Steel pipes. Also there were 2940, 3240 and 3390 for polyethylene pipe that showed the maximum pressure drop in polyethylene pipes is higher than the steel pipes.

INTRODUCTION

Human of the first start an ongoing effort to improve his/her lives. One of the important issues is problem of transfer of different materials that have a lot of problems and a lot of money spent in this way. Human efforts were in direction to improve situation of transportation and the cost of financial and target is prevent of energy waste in this way. The concept of transmission is not modern at all and Using of this type of conveying can be track back to antiquity. For example, the Romans use the guidance pipe to transfer and save water and excretion waste, while Chinese transported natural gas through of bamboo tubes.

According to flexibility of pneumatic conveying systems with respect to other types of transmission systems, this system has wide application in industry and agriculture processes. One important application of this system is in the loading and unloading tankers and powdery bulk materials such as trucks carrying cement, plaster and sand. Conveying efficiency is associated with pressure, as the pressure drop increases in the pipe, operational efficiency will be reduced. The flow mode for a bulk solid material is largely determined by the material properties,

***Corresponding Author:** Adel Rezvanivande Fanayi, Department of Biosystem Engineering, Urmia University, Urmia, Iran

in particular those properties which involve particle/air retention and de-aeration [Hilbert, 1980]. From the engineering point of view, the bends in a pneumatic conveying pipeline are one of the major critical devices. They contribute a major part of the pressure drop (energy consumption). They are causing a great damage to the particles. They intend to wear out and they might cause blockage to the flow due to intensive build-up [Kalman, 2000].

Hilbert [1980] examined three bends: long-radius bend (LR), short-radius elbow (SR) and a blinded-tee (BT), experimentally. He found that with regards to wear; the BT is the best device, with the SR taking a close second and the long-radius sweep, third. Marcus et al. [Marcus et al. 1985] have measured the pressure loss of the three bends and found that for fine powdered materials, SR certainly appear to provide the lowest pressure loss over a wide range of mass flow ratios. Marcus et al. [1985] measured the relative abrasion resistance of 11 materials on an LR.

A comprehensive experimental study was carried out by Agarwal et al. [1985] on an LR. They have studied the acceleration length due to bends and the effects of phase density, conveying velocity and use of inserts on the wear, particle degradation and depth of penetration. Weinberger and Shu [1986] studied the effect of the curvature radius of a bend on the transition velocity (the gas velocity at which minimum pressure drop occurs). They have discovered that the transition velocity is decreasing and becomes closer to the predicted transition velocity of a horizontal pipe, as the bend curvature increases.

Recently, Bell et al. [1996] presented attrition experiments using salt in which the size distribution was measured on line. They have also shown that the air velocity has the prime effect on the attrition rate, although the loading ratio and the bend structure also have some effects. Kalman and Goder [1996] measured all four parameters for four types of bends. They conducted the experiments in a close-loop 1-in. pneumatic conveying pipeline testing sand. Aked et al. [1997] showed that even fine powders (15 μm) could be attrited significantly in certain conditions.

The particle motion in pipes, or any other wall-bounded gas—solid flow, is influenced by a number of physical phenomena, such as:

- gravitational settling in horizontal pipes;
- inertial behavior in pipe bends and branches,
- turbulent dispersion
- transverse lift forces (i.e., Magnus effect) induced by particle rotation which is mainly caused by particle—wall collisions;
- lift forces due to shear flow;
- the collision of the particles with the rough walls of the pipe;
- wall collision process for non-spherical particles
- interparticle collisions.

At higher particle mass loading also the gas flow will be considerably altered by the particles and the turbulence is modulated, i.e., enhanced or reduced depending on particle site [4].

COMPUTATIONAL FLUID DYNAMICS

Ansys Fluent is a commercially available CFD code which utilizes the finite volume method to carry out calculation. It is ideally suited for incompressible to mildly compressible flows. The conservation equation include mass, momentum and energy equations in fluid flows are expressed in terms of non-linear partial differential equations which defy simulation by analytical means. The solution of these equations has been made possible by the advert of powerful work station, opening avenues towards the calculation of complicated flow fields with relative ease [Hilbert, 1980].

The finite volume methods has been used to discretized the partial differential equations of the model using the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) method for pressure-velocity coupling and the Second order Upwind scheme to interpolate the variables on the surface of the control volume [Hilbert, 1980].

The work process in CFD and fluent schematically is shown in Figure1.

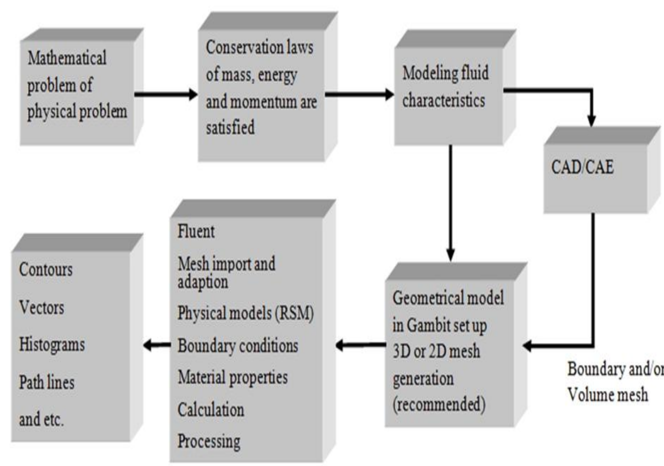


Figure1: Work process in CFD and Fluent [2]

MODEL DESCRIPTION

The model used for flow simulation solves the conservation equations for mass (or continuity) and momentum. The turbulence in the system is solved through transport equations. Navier–Stokes equations for incompressible flows along with appropriate turbulence model are adopted for flow predictions. Under steady state conditions, the equations for mass and momentum in a general form are as follows:

$$\nabla \rho v = 0, \quad (1)$$

$$\nabla\left(\rho\vec{v}\vec{v}\right) = \nabla p + \nabla.\left(\vec{\tau}\right) + \rho\vec{g} \quad (2)$$

Where P is a static pressure, $\rho\vec{g}$ is the gravitational body force $\vec{\tau}$ is the stress tensor given by

$$\vec{\tau}\mu_{effective}\left[\left(\nabla v\right) - \frac{2}{3}\nabla.\rho\vec{v}^{2}\right]$$

Where $\mu_{effective} = \mu + \mu_t$

The standard k–Ɛ model

The standard k–Ɛ model is a semi-empirical model based on model transport equations for the turbulent kinetic energy (k) and its dissipation rate (Ɛ), and is given by:

$$\frac{\partial}{\partial t}\left(\rho k\right) + \frac{\partial}{\partial x_i}\left(\rho k u_i\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right].$$

(3)

$$\frac{\partial}{\partial t}\left(\rho \varepsilon\right) + \frac{\partial}{\partial x_i}\left(\rho \varepsilon u_i\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right].$$

(4)

$$G_k = -\rho u_i' u_j' \frac{\partial u_j}{\partial x_i} \quad (5)$$

In these equations, Gk represents the generation of turbulent kinetic energy due to the mean velocity gradients, C1Ɛ, C2Ɛ and C3Ɛ are constants. σk and σƐ are the turbulent Prandtl numbers for k and Ɛ, respectively. The eddy or turbulent viscosity, ηt can be computed by combining k and e as follows:

$$\mu_t = \rho C_\eta \frac{k^2}{\varepsilon} \quad (6)$$

where Cη is a constant. $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k and σ_ε were assumed to have the following values: $C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92, C_η = 0.09, σ_k = 1.0, σ_ε = 1.3.
Geometry of pipe is shown in figure 2.

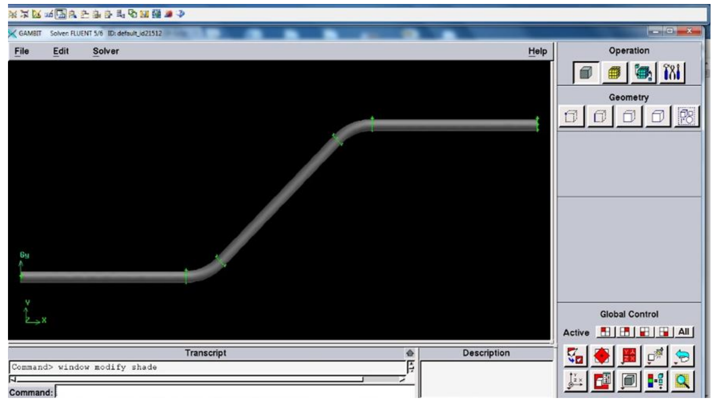


Figure2: Geometry of pipe in gambit software

THEORETICAL CALCULATIONS

To calculate the diameter of the pipe and input mass flow rate with regard to the problem assumption, the following calculations carried out.
Initially, Whet volume of 20 m^3 in 3 specified times 30, 45 and 60 minute was considered for transfer. Then with consider density of wheat in 3 states obtained.

Table 1. Computational parameters and values

Computational parameters	values
Volume of transferred wheat	$v = 20m^3$
Time	$t = 30, 45, 60\,\text{min}$
Wheat bulk density	$\rho_s = 780kg/m^3$
Wheat true density	ρ=1300 kg/m^3

$$v_s = \frac{v}{t} \quad \textbf{(7)}$$

According to equation (7) the volume of moved material per time is obtained for 30 minutes.

$$v_s = \frac{20}{30\times 60} = 0.011\ \frac{m^3}{s}$$

Then, According to equation (7) mass flow rate for example for 30 minutes was calculated and for other times can be achieved also with paste.

$$\dot{m}_s = \rho_s \times v_s \quad (8)$$

$$\dot{m}_s = \rho_s \times v_s = 8.66\ ,\ \ 5.77\ ,\ \ 4.33\ \ \text{kg/s}$$

The following calculation is performed to obtain diameter.

$$\dot{m}_a = \frac{\dot{m}_s}{\mu} = \frac{8.66}{8} = 1.08 \quad \textbf{(9)}$$

$$Q_a = \frac{\dot{m}_a}{\rho_a} \rightarrow \frac{1.08}{1.2} = 0.9 \quad (10)$$

$$v_a = \alpha_a \times v_{cv} \rightarrow 5 \times 5.5 = 27.5 m/s \quad (11)$$

$$A = \frac{Q_a}{v_a} \rightarrow \frac{0.9}{27.5} = 0.032 m^2 \rightarrow A = \frac{\pi D^2}{4} \rightarrow D = \sqrt{\frac{4A}{\pi}} \rightarrow D = 20.4 cm \quad (12)$$

$$\Delta p = \Delta p_L + \Delta p_s + \Delta p_g + \Delta p_b + \Delta p_a \quad (13)$$

The Reynolds number used for the calculation of the equation (14) was obtained:

$$R_e = \frac{\rho_a v D}{\mu} \rightarrow \frac{1.2 \times 27.5 \times 0.204}{10^{-5}} = 6.732 \times 10^5 \quad (14)$$

$$\frac{\lambda_L}{4} = 0.0014 + 0.125 R_e^{-0.32} \quad (15)$$

$$\lambda_L = (0.0014 + 0.125 \times (6.732 \times 10^5)^{-0.32}) \times 4 = 0.013$$

$$\Delta p_L = \lambda_L \frac{\rho}{2} V^2 \frac{L}{D} \quad (16)$$

$$\Delta p_L = 0.03 \times \frac{1.2}{2} \times (27.5)^2 \times \frac{3}{0.204} = 86.75 \text{ pa}$$

$$\Delta p_s = \phi_m \lambda_s \frac{\rho}{2} V^2 \frac{L}{D} \quad (17)$$

$$\lambda_s = \frac{0.0285\sqrt{gD}}{c} = \frac{0.285\sqrt{9.81 \times 0.204}}{25.69} = 1.5 \times 10^{-2} \quad (18)$$

$$\Delta p_s = \phi_m \lambda_s \frac{\rho}{2} V^2 \frac{L}{D} = 8.02 \times 1.5 \times 10^{-2} \times \frac{1.2}{2} \times (27.5^2) \times \frac{3}{0.204} = 800.3 \text{ Pa}$$

$$\Delta p_g = \rho^* g \Delta z \quad (19)$$

$$\frac{c}{v}=1-0.68d^{0.92}\rho_p{}^{0.5}\rho^{-0.2}D^{0.54} \tag{20}$$

$$c=1-(0.68(4.1\times10^{-3})^{0.92}\times780^{0.5}\times(1.2)^{-0.2}(0.204)^{0.54}))\times27.5=26.15$$

$$\rho^*=\frac{\phi_m v\rho}{c}=\frac{8.02\times27.5\times1.2}{26.15}=10.12\ \text{kg/m}^3$$

$$\Delta p_g=\rho^* g\Delta z=10.12\times9.81\times1=99.3\ \text{Pa}$$

$$L_{eq}=\frac{kD}{\lambda_L} \tag{21}$$

$$L_{eq}=\frac{kD}{\lambda_L}=\frac{0.9\times0.204}{0.013}=14.13\rightarrow2\times14.13=28.26\,\text{m}$$

$$\frac{86.75}{3}\times28.26=817.2Pa$$

$$\Delta p_b=\rho v^2(0.245(\frac{\dot{m}_s}{\rho vD^2})(\frac{R}{D})^{-0.26}) \tag{22}$$

$$\Delta p_b=\rho v^2(0.245(\frac{\dot{m}_s}{\rho vD^2})(\frac{R}{D})^{-0.26})=1.2\times27.5^2(0.245(\frac{8.66}{1.2\times27.5\times0.204^2})(5)^{-0.26})=1216.05$$

$$\Delta p_a=\phi_m\rho c \tag{23}$$

$$\phi_m=\frac{\dot{m}_s}{Q_a\times\rho_a}\rightarrow\frac{8.66}{0.9\times1.2}=8.02$$

$$c=26.15$$

$$\Delta p_a=8.02\times1.2\times26.15=247.23$$

$$\Delta p=\Delta p_L+\Delta p_s+\Delta p_g+\Delta p_b+\Delta p_a=86.75+817.2+800.3+99.3+1216.05+247.23=3266.83\ \text{Pa}$$

RESULT AND DISCUSSION

Figures 3 to 8 show the static pressure in 3 level of mass flow rate in steel pipe. As clear from figures static pressure increase with increasing mass flow rate.

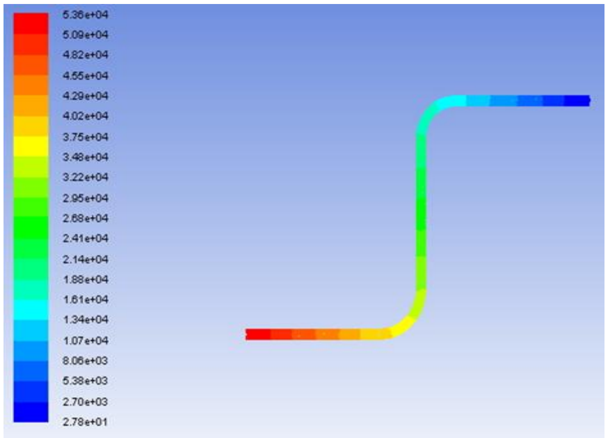


Figure 3: Contour of static pressure in 4.33 kg/s mass flow rate in steel pipe

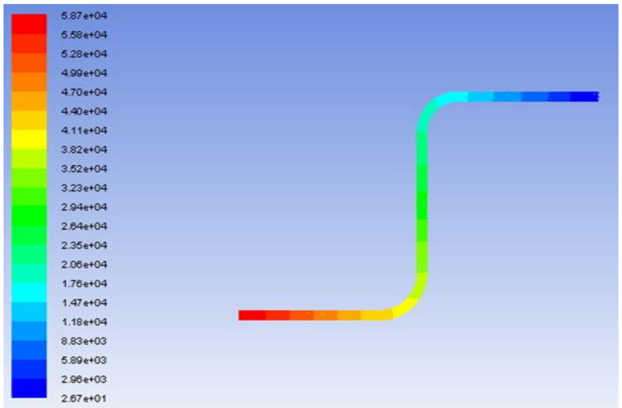
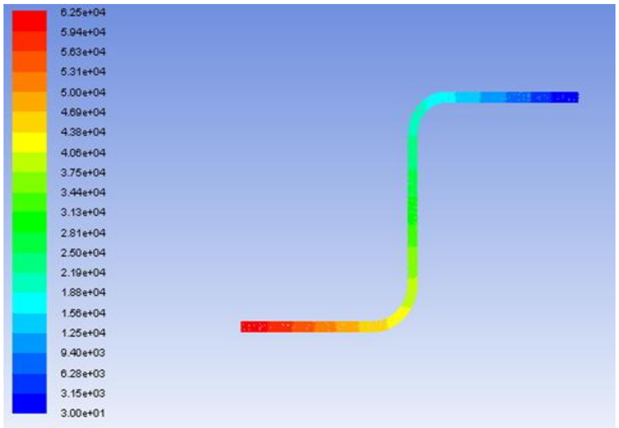


Figure 4: Contour of static pressure in 4.33 kg/s mass flow rate in polyethylene pipe



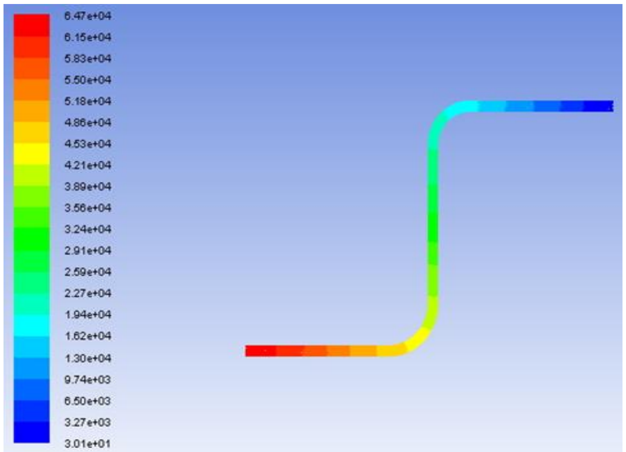


Figure 6: Contour of static pressure in 5.77 kg/s mass flow rate in polyethylene pipe

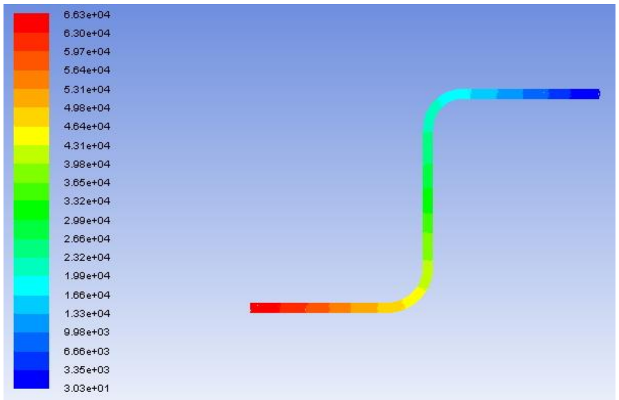
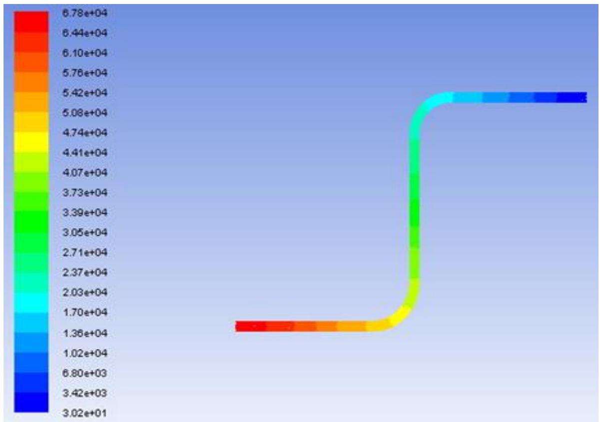


Figure 7: Contour of static pressure in 8.66 kg/s mass flow rate in polyethylene pipe



Pressure drop has a critical issue in material conveying that play a very important role in flow field analyses. Figure9 and figure 10 shows pressure drop in 3 level of mass flow rate in steel and polyethylene pipes.

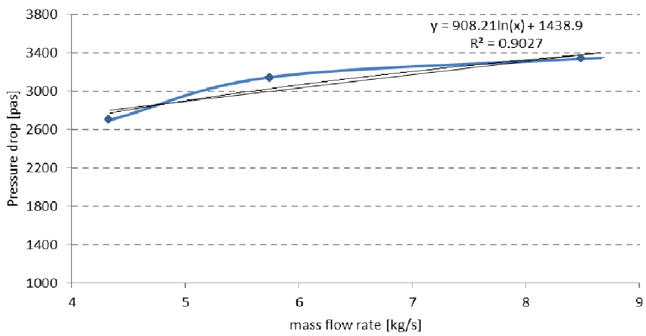


Figure 9: Pressure drop in 4.33, 5.77 and 8.66 (kg/s)mass flow rate in steel pipe

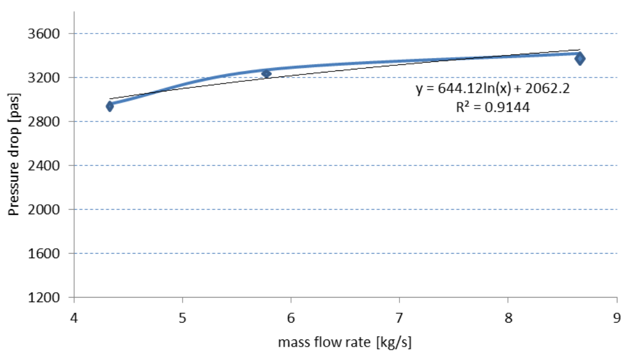


Figure 10: Pressure drop in 4.33, 5.77 and 8.66 (kg/s)mass flow rate in polyethylene pipe

Following the comparison of pressure drop and velocity field (Axial, Radial and tangential velocity in steel and polyethylene pipes are shown in figure 11 to 14. Figure shown that these values are more in polyethylene types that it may be due to higher interface of wheat and internal wall in polyethylene types.

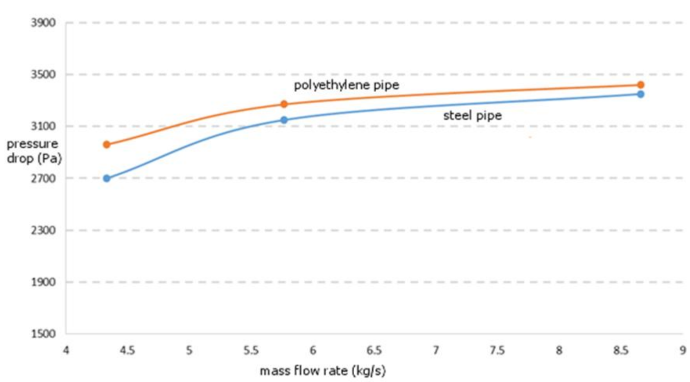


Figure 11: Pressure drop in 4.33, 5.77 and 8.66 (kg/s) mass flow rate in steel and polyethylene pipes

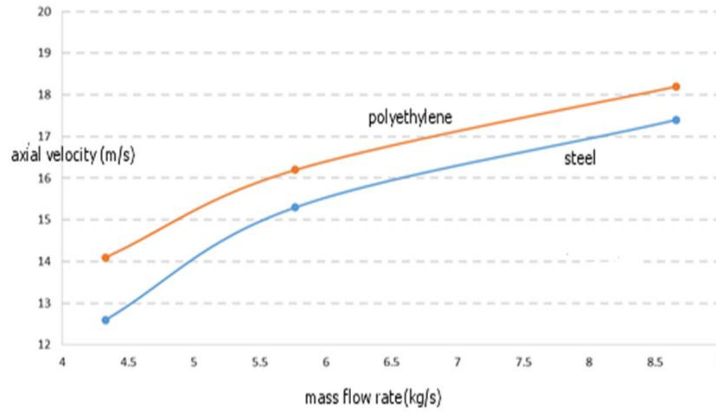


Figure 12: Axial velocity in 4.33, 5.77 and 8.66 (kg/s) mass flow rate in steel and polyethylene pipes

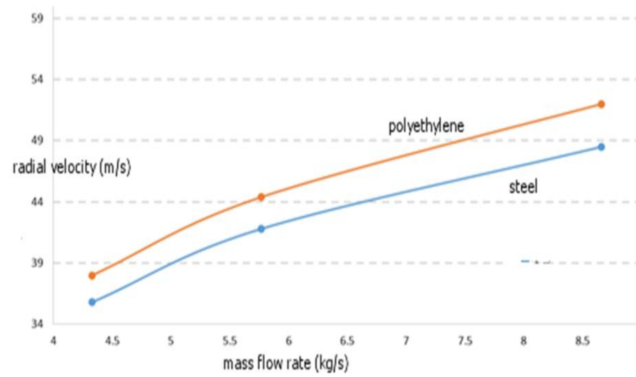


Figure 13: Radial velocity in 4.33, 5.77 and 8.66 (kg/s) mass flow rate in steel and polyethylene pipes

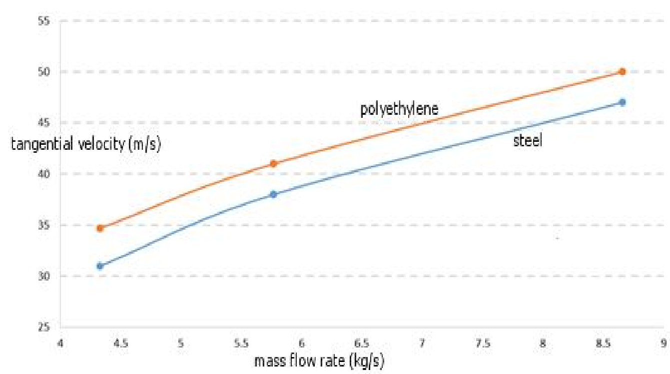


Figure 14: Tangential velocity in 4.33, 5.77 and 8.66 (kg/s) mass flow rate in steel and polyethylene pipes

CONCLUSION

Computational Fluid Dynamics and Turbulence model can predict flow field in inside the tubes as well. Contours showed good results in terms of compliance on simulations performed with interactions inside the pipe.

The results showed that by increasing the mass flow rate in the range of (4.33, 5.77 and 8.66 kg/s), pressure drop increased in the pipe and this increment in polyethylene pipe was higher. All velocity including Axial velocity, Radial velocity and Tangential velocity was obtained higher in polyethylene pipe in compare of steel pipe.

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Nomenclature

v	Velocity
t	Time
ρ_s	Wheat density
$\dot{m}_s$	Wheat mass flow rate
$\dot{m}_a$	Air mass flow rate
Q_a	Air volume flow rate
ρ	Air density
α_α	Ratio of increase in air velocity
v_{cv}	Critical velocity
A	Area
D	Pipe diameter
Δp	Total pressure drop
Δp_L	Pressure drop in pipes only for air
Δp_s	Pressure drop because of material friction
Δp_g	The pressure drop due to the lifting of materials
Δp_b	Pressure on the bends
Δp_a	Falling due to particle acceleration
R_e	Reynolds number
λ_L	Air drag coefficient
L	Pipe length
ϕ_m	Mass flow ratio
c	Solids velocity
λ_s	Wheat friction factor
g	gravity

ρ^*	wheat Bulk density during transfer
Δz	Height up desired
L_{eq}	Equivalent length for each bend
k	Loss coefficient in connections
$\frac{R}{D}$	Bend radius ratio to pipe diameter