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Selection of a mathematical model to describe solid fuel pneumatic transport to the ship boiler

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Abstract

This article presents an overview of the mathematical models applied for the description of the pneumatic transportation of grain materials. Thus the model that has been selected is best suited for the description of the pressure drop in the pneumatic transport installation of solid fuel for a ship boiler. The research conducted allows for verification of the hypothesis that the ship's motion is of minor importance and therefore it is possible at the design stage to apply the simplified model to determine the pressure losses in the installation.

Introduction

The most important and most frequently examined parameter in connection with the grain material pneumatic transportation is determination of the flow resistances in the installation which are significant regarding the selection of the appropriate flow machine. The laboratory stand, complete with the transport installation located on the movable platform that simulates the ship's rolling at sea, has been built in order to enable examination of the pressure drop in the shipboard pneumatic transport installation of solid fuel. The stand has been specified in detail in Łuszczyński & Zeńczak (Łuszczyński & Zeńczak, 2014). The examinations conducted are of active nature. A factor that interferes with the transport process in the laboratory conditions is the swinging movement of the platform. The obtained results of the experimental research will be applied for the validation of the mathematical model of the process.

Since multiphase mixture flows in pipelines are a complex phenomenon, and thus hard to define, in mathematical models several idealising assumptions and simplifications have been applied. In effect, numerous models can be found with various degrees of simplification, which are applied to describe the same process.

The goal of this paper is to present the most frequently encountered models and indicate that the model is reasonably simple, with determined accuracy, and possibly most useful for the description of the process of pressure drop in the solid fuel pneumatic transportation to the boiler during the interferences caused by the ship's movement on waves.

Analysis of the Pneumatic Transport Phenomenon

Introduction

Pneumatic transport is a particular example of the two-phase flow phenomenon. It is characterised by the fact that its continuous phase is gas while solids constitute the dispersed phase. The continuous phase is a carrier medium whose movement is caused by the pressure difference. The carrier medium employed while flowing past the interior surface of the pipeline at a specified rate produces the lift force, which transports the particles of the solid object. In pneumatic transport, as opposed to hydraulic transport, a specific feature is a substantial ratio of solid phase density to the continuous phase, i.e. in the order of 103. This means that in pneumatic transport the velocity of the fluid (gas) is larger by an order of magnitude and the solid phase participation is smaller than in hydraulic transport by a volume of an order or two of magnitude (Orzechowski, 1990). Owing to the large gas velocities, the pressure losses at the transport line unit of length are significantly greater than in the case of hydraulic transport, which is why the pneumatic transport lines do not exceed several hundreds of meters in length (Dziubiński & Prywer, 2009). While this is a limitation, it is not an obstacle in the application of such installations on board ships because they do not exceed 100 m (Schroppe & Gamble, 1981).

In marine conditions horizontal and vertical segments in the transport line occur together with elbows. In each of these segments we face somewhat different phenomena. In the case of ship's rolling on waves, the particular segments will temporarily also become the segments inclined at a certain angle which offers yet another representation of the phenomenon.

The air velocity in horizontal segments should be larger than the sedimentation rate of the particles, and in the vertical segments larger than the so called choking velocity, in the other words such velocity that is accompanied by the pressure gradient that is unable to compensate for the weight of particles resulting in them falling down. The flow then becomes the plug flow. Its equivalent in the horizontal segment is so called saltation, or in other words the formation of material clusters resembling sand dunes.

Vertical Flow

In the pneumatic transport as a rule the material concentration is of low value and the mass ratio of solids to gas is lower, ranging from 10 up to 20 (Kunii & Levenspiel, 1991).

Figure 1 shows examples of the structures of flow characterised by their dependence on the gas velocity, material condensation and diameter of particles. The solid material particle movement lifted upwards by an air jet is always locally unsettled. As shown in Figure 1 the loose groups of particles mostly move in the form of smudges, streams or layers. Our own observations at the research stand as well as references from literature indicate that at particularly larger material concentrations the particle groups flow not only upwards but also downwards.

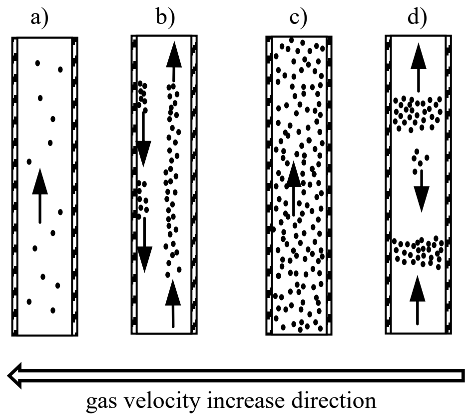

Figure 1. Structures of flow of gas/solid mixture in vertical duct: a) lifting of particles at low concentration, b) smudges, c) particle lifting in larger concentration, d) plugging (Orzechowski, 1990; Kunii & Levenspiel, 1991; Dziubiński & Prywer, 2009)

Figure 2 shows an image of the wheat grain flow structure obtained within our own means at the research stand.

Figure 2. Flow structure during vertical pneumatic transportation of wheat grains

This phenomenon occurs mostly near the pipeline wall and is caused by the friction of air and particles against the pipe wall. In effect, in the core of the duct the particles move faster than at the wall. As the air velocity decreases from the maximum value (Figure 1a), the friction reduces and thus the pressure resistances start to depend on the sum of the gas and material static height to a larger degree. Initially the joint flow resistances decrease accompanying the air velocity decrease, but after passing the characteristic bending point they start to increase again, because the concentration of the solid material increases. At that time the flow gets throttled and the aforementioned choking occurs. Figure 3 presents the typical image of pressure changes during the vertical transportation.

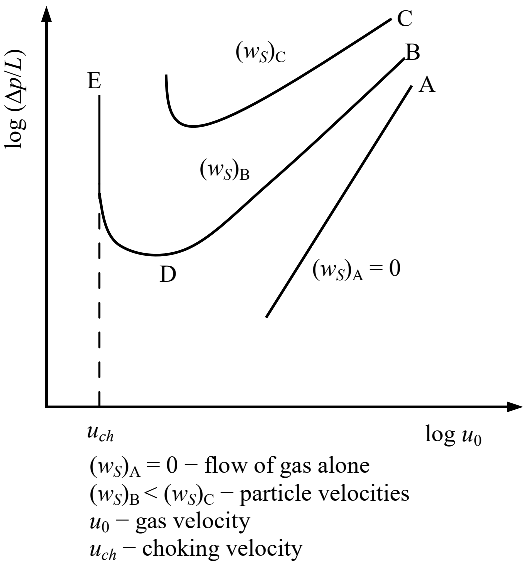

Figure 3. Picture of the changes in specific pressure losses during vertical pneumatic transport (Kunii & Levenspiel, 1991)

The phenomenon of choking itself is interesting although more attention is paid to determination of the minimum air velocities, which guarantee safe pneumatic transport.

Horizontal Flow

The picture of the flow in horizontal pipeline is more complex than in the vertical line because the movement of a single particle in the vertical duct, regardless of friction and inertia forces, depends only on the forces of gravity, displacement and resistance. In the horizontal line the particle is additionally influenced by Magnus force, related to the revolution of particles owing to the pressure gradient at the pipeline wall. This force causes lifting of the particle and momentarily keeps them suspended because in case of horizontal flow the resistance force is directed perpendicularly to the gravity force. The particles move up by jumps and fall down. The horizontal flow is possible when these forces keep the particle suspended, which is possible with an adequately large gas velocity. With the large flow rate and low concentration the particles move approximately along the straight runs which take turns in case of mutual collisions and resultantly hitting the duct wall (Orzechowski, 1990). In Figure 4 the diagram of Magnus force effect is presented in relation to the resting particle and the flow structure with large air velocity.

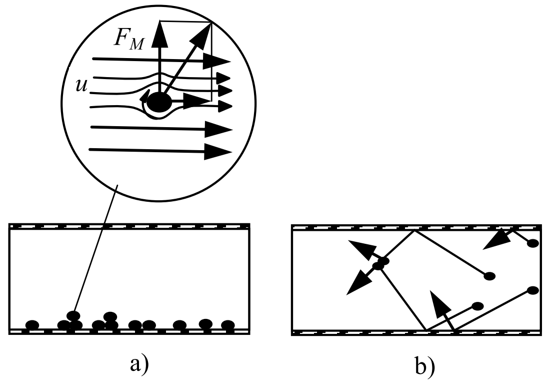

Figure 4. Diagram of Magnus force effect on resting particle (a) and the flow structure with the large air velocity (b) (Orzechowski, 1990)

While the gas flow velocity decreases, the particles start to collect in the lower part of the pipeline forming a layer that moves in a sliding motion, and which in case of continued velocity decrease forms the wandering dunes (phenomenon of saltation). Earlier small wandering waves are also formed. Similar phenomena are observed in the transport lines inclined at a certain angle to level (Kunii & Levenspiel, 1991).

Figure 5 shows the typical flow structures in horizontal pneumatic transport. On the other hand, Figure 6 shows the picture of flow structure during the horizontal pneumatic transport of wheat grains as observed at own research stand. In the pipeline lower part, the lower layer is clearly visible as it moves in a sliding manner (a) and the beginnings of saltation (b).

Figure 7 shows the picture of specific pressure changes during horizontal transport with various particle contents. Similarly as in the vertical flow it is observed that as the velocity decreases the friction decreases, thus resulting in pressure losses owing to friction, and in point D corresponding to saltation

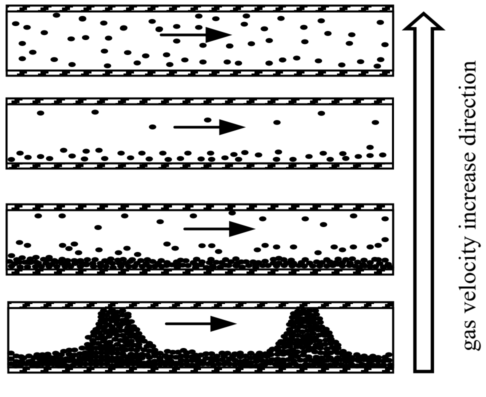

Figure 5. Flow structures in horizontal pneumatic transport (Orzechowski, 1990; Kunii & Levenspiel, 1991; Dziubiński & Prywer, 2009)

rate, the particles start to sediment in the lower part of the pipeline. In effect the duct diameter gets reduced and pressure rises abruptly as far as point E (Kunii & Levenspiel, 1991).

a)

b)

Figure 6. Image of flow structure during the horizontal pneumatic transport of wheat grains: a) layer moving by sliding b) saltation beginning

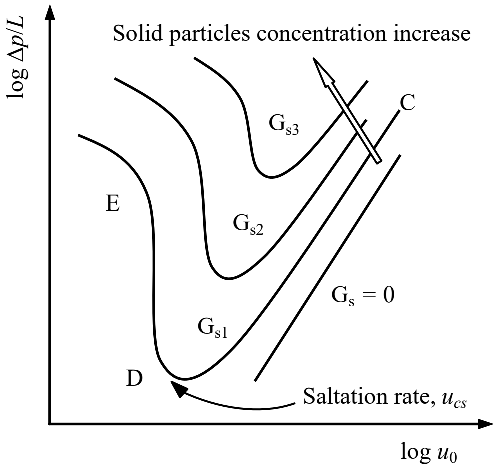

Figure 7. Specific pressure changes during horizontal transport with various particle content (Kunii & Levenspiel, 1991)

Flow in Inclined Ducts and Elbows

As already mentioned, in the pneumatic transport lines inclined at a certain angle to level, similar phenomena occur regarding the horizontal flow and they will not be further analysed in this article.

In elbows connecting various straight segments, the result of the centrifugal force is a change in the flow structure. Particles move almost along the straight-line runs, hit the elbow wall and segregate so that after collision they form a bundle of smaller diameter than the bundle consisting of the biggest elements. Just behind the elbow, in the effect of abrupt velocity reduction in that place, a significant concentration occurs. According to research, subject to the radius and diameter of the pipeline, the return to the flow conditions as they were before the elbow could occur at a maximum distance of approximately 30 diameters of the pipeline (Dziubiński & Prywer, 2009). The picture of the flow in the elbow is shown in Figure 8.

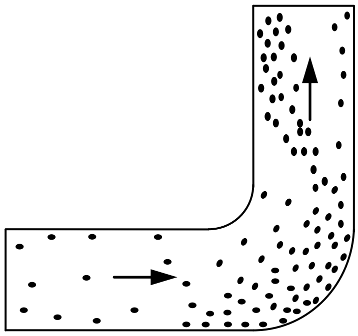

Figure 8. Solid phase flow through elbow (Dziubiński & Prywer, 2009)

The Basis of Construction of Mathematical Models Applicable in Two-Phase Flows

Mathematic modelling consists of the mathematical description of a system, process or physical phenomenon. It is a system of equations or inequalities which map the performance of a system or the course of the modelled process with specified accuracy. The mathematical models are used to conduct analyses of the performance of actual objects under the influence of various external factors. Since the changes of the phenomena observed in nature occur in time and space, they are described through the time sequences of condition variables and input variables (Tarnowski, 2004). The computer simulating models built on the basis of the mathematical model provide the possibility of simulating and observing the performance of systems both under normal operation conditions as well as in hypothetic emergency conditions without fearing their destruction.

The pneumatic models are created on the basis of the laws of physics and process observations or the observations of the performance of the examined system. The paradigms are used for that purpose, for instance the law of conservation of mass, momentum and energy and the defining equations as well as the particular models of the phenomena (Tarnowski, 2004). The starting point being the assumed search for a model that is reasonably simple in these considerations, the focus has thus been made on two-phase one-dimensional settled flows without heat and mass exchange.

A characteristic feature of the two-phase flow is the occurrence of the interface. The flow area may be regarded as an area divided by the moving boundary surface into two one-phase sub-areas. Thus the equations can be formulated for each of the phases separately as for the one-phase flow. The varied, i.e. not uniform, distribution of the dispersed phase and the moving division boundaries of shape varying in time cause it to be impossible to achieve the explicit mathematical description of these flows. This results in the necessity of looking for substitute flow models (Orzechowski, 1990; Malczewski & Piekarski, 1992; Dziubiński & Prywer, 2009).

There are two methods applicable for the description of the two-phase flow dynamics (Dziubiński & Prywer, 2009):

- phenomenological method;
- averaging method.

The phenomenological method to describe the two-phase flows does not take into account the particle or atom structure of the mixture, because it consists of the description and survey of what is given directly. Thus in this method the mixture flow is described in the macroscopic terms and refers to direct measurement of the physical figures such as: pressure, velocity/rate and temperature. The essential merits of the phenomenological description of the motion are: low degree of complexity of the calculations, universal nature of the laws and the possibility of their experimental analysing (Szargut, 2000; Wiśniewski, 2013).

In general terms, the averaging may be done in space, in time or statistically. The equations describing the two-phase dynamics, i.e. equations describing the processes in microscale inside the one-phase sub-areas, are averaged for the temporary local variables. The spatial microscale is the characteristic linear size of the irregularities, in this case the size of particles. The important advantages of averaging are: profound description of the physical laws and notions as well as the possibility of calculating the physical properties of the mixtures from the input data referring to the molecular structure and elementary particles, which in the phenomenological method should be determined empirically. If averaging by the volume is conducted simultaneously for both phases, the obtained equations are referred to as the homogenous model. In the homogenous model each of the components fills the entire volume and loses the individual traits so both phases are perfectly mixed and move with the same velocity (non-sliding model). Thus in this model the interface also disappears which presents a serious problem from the mathematical point of view. The opposite of the homogenous model is the heterogeneous model in which each phase retains its features in its separated volume which represents the component of the total volume of both phases (Orzechowski, 1990; Malczewski & Piekarski, 1992; Dziubiński & Prywer, 2009). In the modelling of flows this is referred to as flow with the division of phases. One of the features of two-phase flow thus regarded is the occurrence of different velocities of both phases. Models in which a particular stress is put not on the velocity of each phase, but on the flow velocity of one phase versus the other, belong to the class of sliding models (Dziubiński & Prywer, 2009). The following averaging methods of transport equations are commonly used (Malczewski & Piekarski, 1992):

- averaging by Euler's method;
- averaging by Lagrange's method;
- averaging by a statistical method, e.g. Boltzmann's.

While applying Euler's method (local analysis), the movements of subsequent elements of the two-phase mixture are examined as they move through the fixed point of defined coordinates. By averaging the chosen flow parameter in Euler's method the control surface is introduced, i.e. confined or an open immobile surface is established by the same fixed points in space. In Euler's method the averaging applies to a given figure, e.g. pressure, velocity/rate, temperature in time or on surface or by volume. Thus the essence of the method is the averaging in time of the variable figure observed in a given point of space (Jeżowiecka-Kabsch & Szewczyk, 2001).

Lagrange's method (Lagrangian analysis) is applied less often. By its application the selected mixture flow parameters are examined, e.g. velocity, individually for each element of the mixture moving in space, by averaging them in time. At a given time, the coordinates of the given mixture element will be dependent on the initial coordinates and time. Having the trajectory equations at disposal we can determine e.g. the average velocity of given element of the mixture (Jeżowiecka-Kabsch & Szewczyk, 2001).

In Boltzmann's method, also referred to as LBM or Lattice Boltzmann Method, the discrete variables determining the particle velocities are substituted by seven continuous variables interpreted as probabilities that the particles follow in the direction determined on the lattice. Knowing these functions we can determine the macroscopic flow parameters such as the local velocity and density of fluid. The essence of Boltzmann's method is the simple algorithm (a kind of cellular automaton) where the evolution of the distribution function is completed in two steps: shift and collision (Matyka, Koza & Mirosław, 2016).

In these examinations owing to their specific nature, typical for the technical issues, it is proposed to adopt the method to calculate the pressure drop on the basis of the one-dimensional non-sliding model.

Homogenous Model

As already mentioned, the basic assumptions in the homogenous model are equal velocities of flow for both phases and their homogenous blending. In the one-dimensional model the changes being undergone are considered only in the direction of the z axis. Therefore in the mathematical notation, instead of partial derivatives, there will be complete derivatives to aid further simplification. Basic equations describing the model are the mass conservation equation and the momentum conservation equation which allows for determination of the flow resistances.

The mass conservation equation (flow continuity)

$$\dot{m} = \rho\, u\, A = \text{idem} \qquad (1)$$

where:

$\dot{m}$ – two-phase mixture mass flow;

ρ – mixture density (determined according to mass participation);

A – sectional area of duct/pipeline cross-section;

u – mixture velocity.

The momentum conservation equation (movement equation) consists of the balance of forces acting on an isolated element (layer) of the flowing

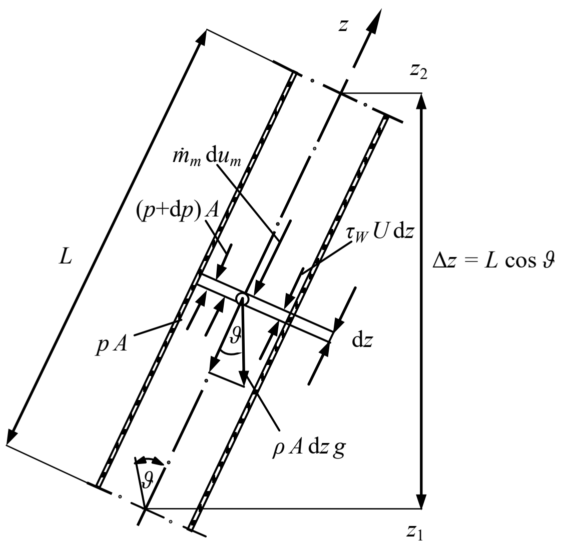

Figure 9. Forces acting on isolated element of mixture (Dziubiński & Prywer, 2009)

mixture. The forces acting on the isolated element of mixture are shown in Figure 9.

$$pA - (p + \mathrm{d}\,p)A = \tau_W U\, \mathrm{d}\,z + \dot{m}\, \mathrm{d}\,u + \rho A\, \mathrm{d}\,zg \cos\vartheta \qquad (2)$$

where:

τ_w – average contact tension on duct/pipeline wall;

p – pressure;

U – perimeter of duct/pipeline cross section (moist perimeter).

Terms on the left side of the equation (2) represent the pressure forces while on the right side: friction force against the wall, force of inertia of lift and component of gravity force at the axis z accordingly.

Upon dividing the equation (2) by $A\mathrm{d}z$ and after transformation we obtain the equation representing the pressure drop along the duct/pipeline (Orzechowski, 1990; Zarzycki, Orzechowski & Prywer, 2001; Dziubiński & Prywer, 2009):

$$-\frac{\mathrm{d}\,p}{\mathrm{d}\,z} = \frac{U}{A}\tau_w + \frac{\dot{m}}{A}\frac{\mathrm{d}\,u}{\mathrm{d}\,z} + \rho\, g \cos\vartheta \qquad (3)$$

The terms on the right side of equation (3) stand for:

$\frac{\mathrm{d}\,p_f}{\mathrm{d}\,z} = -\frac{U}{A}\tau_w$ – pressure gradient caused by friction of mixture against duct wall;

$\frac{\mathrm{d}\,p_a}{\mathrm{d}\,z} = -\frac{\dot{m}}{A}\frac{\mathrm{d}\,u}{\mathrm{d}\,z}$ – pressure gradient caused by mixture acceleration;

$\frac{\mathrm{d}\,p_h}{\mathrm{d}\,z} = -\rho\, g \cos\vartheta$ – pressure gradient resulting from the force of gravity.

The pressure gradient caused by the mixture acceleration in the case of a fixed duct/pipeline diameter is often disregarded (Dziubiński & Prywer, 2009). Thus the most significant gradient will result from the pressure losses caused by mixture friction against the duct/piping wall which would always occur. On the other hand, the gravity force component will only cause losses in the vertical or inclined segments. It is also worth noting that with the angles $\vartheta > 90$ the pressure loss component will be negative.

The relation between the contact tension τ_w and the pressure loss in the duct/pipeline of the length L and hydraulic diameter d_h is as follows (Orzechowski, 1990; Zarzycki, Orzechowski & Prywer, 2001; Dziubiński & Prywer, 2009):

$$\Delta p_f = 4\frac{L}{d_h}\tau_w \qquad (4)$$

After comparing the equation (4) to the Darcy's-Weisbach's model, i.e.:

$$\Delta p_f = \lambda \frac{L}{d_h} \rho \frac{u^2}{2} \quad (5)$$

determining τ_w, pressure gradient caused by friction can be put down as:

$$\frac{\mathrm{d}\, p_f}{\mathrm{d}\, z} = -\frac{U}{A} \cdot \frac{1}{4} \lambda \rho \frac{u^2}{2} \quad (6)$$

where: λ – friction factor.

Thus finally considering that $d_h = 4A/U$ and disregarding the pressure gradient caused by mixture acceleration upon substituting in (3) the relation for the pressure drop takes the following form:

$$-\frac{\mathrm{d}\, p}{\mathrm{d}\, z} = \lambda \frac{\rho u^2}{2 d_h} + \rho g \cos \vartheta \quad (7)$$

Conclusions

The homogenous model can be particularly useful during research studies where the movement of individual particles in two-phase mixture is not analysed, and the most vital parameter which shall be determined is the value of mixture resistances. For the analysis the parameter averaged values are used which simplifies the complexity of the model itself and the calculations. The presented model is suitable most of all to determine the pressure losses in the established conditions of navigation such as, e.g. permanent ship's list, trim by the head or by the stern. In the conditions of continuous rolling it will also be necessary to consider the forces of inertia conditioned by the angular accelerations. The conducted experimental research aims to check how significant the changes in the flow resistances are during the ship's rolling in relation to sailing in calm sea. They will allow also for verification of the hypothesis that this movement is of minor significance and at the design stage it is possible to apply the aforementioned simplified model.

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