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Exergy Analysis of the Air Evacuation Process From the Pressure Accumulator of the Pneumatic Pulsator System

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Pulsators utilize energy of compressed air in order to destruct adverse phenomena in loose materials and make the outlets of silos permeable. The most important parameter of the pulsator is a force which can be transmitted onto the loose material bed. This impact force is related to the pressure difference but this relation is not obvious. This paper proposes a methodology for calculating an irreversibility of a high speed gas conversion with transient airflow conditions taken into account. The aim of this work is to deliver values of energy which is available for conversion to the impact force in order to adverse phenomenon could be destroyed in a silo. The exergy analysis delivers results which make it possible to determine the efficiency of the pneumatic pulsator system.
By using mean values of flow parameters such as temperature, pressure, velocity and density, the exergy analysis has been carried out. It has been assumed that the flow does not influence the environmental parameters.
The most important period of the process is observed during the first 25 ms from the start. In order to calculate energy and exergy, the corresponding fluxes are integrated in time and the total values are delivered: energy equals 682.9 kJ, and exergy is 605.2 kJ. The irreversibility of the process is, therefore, 77.7 kJ. This loss occurs in one work cycle of pulsator. The modern pulsators are designed for 1 million and more work cycles. It is easy to calculate that the irreversibility of the gas conversion during the air evacuation can reach values of over 77.7 GJ.

1. Introduction

Energy efficiency in industrial facilities is in focus because of raising cost of energy sources. Growing social consciousness and accessibility of methods for effective utilization of energy sources caused that the energy efficiency calculations are applied in the fields which have been neglected so far. This is the reason why the systems for making clear of cloggings in loose material silos have been focused on. The paper considers the energy efficiency in a pneumatic pulsator system which utilizes a pneumatic impact for making clear the outlets of loose material silos in which adverse phenomena can cause stoppages of bulk transportation. Because of the impact, they are sometimes named as air cannons or air blasters. The equipment is used in heavy industry and the energy, which is accumulated with compressed air in a pressure accumulator, has not been a subject of studies probably for the sake of too little amount of energy related to the energy used for facility functioning. Figure 1 shows exemplary location of a pneumatic pulsator unit on the walls of a loose material silo. The pneumatic pulsator unit consists of three basis parts: a pressure accumulator, a head and an outlet nozzle. The energy is accumulated in the pressure accumulator and is released during the operating of the pulsator. The work performed by air, as a final effect, destroys the adverse structures in a loose material bed. The design of the pulsator and working principles were wider described by Urbaniec et al. (2009) where a design component was emphasised. Wernik and Wołosz (2012) reported flow phenomena during the airflow though the head of the pulsator.

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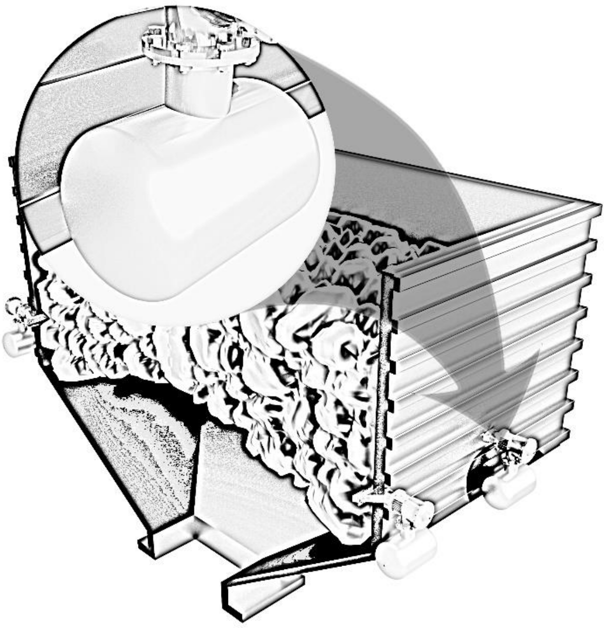

Figure 1: Exemplary location of the pneumatic pulsator unit on the silo walls

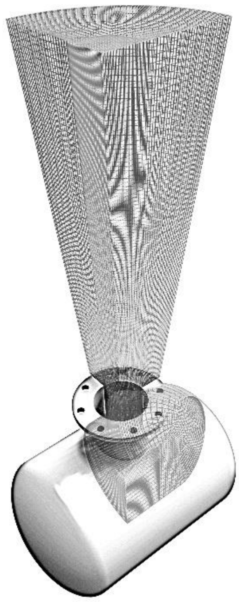

Figure 2: Pressure accumulator with structural mesh of the numerical model

Unknown energy characteristic of the air compressed in the pressure accumulator was the motivation for the present study to be undertaken. Investigation of the air outflow from the pressure accumulator has been carried out by Wołosz and Wernik (2015a), however, the amount of energy which is accumulated in pressure accumulator was not determined in the results of the study. The works on the energy calculation during the air evacuation of the pressure accumulator have been undertaken by the same authors in the same year (Wołosz and Wernik, 2015b). There has been an initial energy analysis carried out by Wołosz and Wernik (2016) however, an object being investigated was the nozzle of the pulsator. During the aforementioned studies, it has been concluded that the amount of energy which can be converted into work is a significant parameter of the operation of the pulsator. The phenomena which occur during the pulsator functioning have a thermodynamic and transient character. In order to determine the amount of work which can be obtained from the energy accumulated, the issue of exergy has been used which is strictly related to irreversibility of thermodynamic gas conversion. This paper proposes a methodology for calculating the irreversible losses during a high speed gas conversion with transient conditions taken into account. The aim of this work is to deliver values of energy which can be converted into the work, thus, into the impact force in order to adverse phenomenon could be destroyed in a silo. The exergy analysis delivers results which make it possible to determine the reference values of energy. The obtained values shall be used in future studies in order to predict the efficiency of the complete pneumatic pulsator system and its elements as well.

2. Numerical model

The numerical model utilized in flow calculation is based on the actual design of the pressure accumulator which is applied in the industrial pneumatic pulsator system. It is a vessel of a volume of 0.115 m^3 and is connected to the head of the pulsator with a flange of nominal diameter of 150 mm. On the geometry of the accumulator, there is a structural mesh applied which is shown in the Figure 2. The calculation area of continuum considers a quarter of the vessel volume and a part of the surrounding environment. The quarter could be taken into account provided that the geometry of the vessel and predicted flow phenomena are symmetrical along the two main symmetry planes. For predicting the reference value of energy, there are no additional equipment applied and the study can be regarded as an air evacuation of the pressure accumulator. In other words, the only energy losses, proposed in the numerical model, come from the gas conversions.

There are vector fields of velocity as well as scalar fields of pressure and temperature determined during the numerical simulation. For the simulation, there is a finite volume method used which utilizes equations of conservation laws. The equation of mass conservation laws for a transient compressible flow is as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

where ρ - density [kg/m^3], t - time [s], $\mathbf{u}$ - velocity [m/s].
The momentum conservation law describes effects of deformation of the element of the fluid under the influence of the viscous stress. The law is presented with the following equation:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) - \nabla \cdot \mu \nabla \mathbf{u} = -\nabla p, \tag{2}$$

where μ - dynamic viscosity [Pa·s], and p - pressure [Pa],
The gas conversion mean the change of the internal energy of the gas which must be balanced in entire system. The energy conservation law is mathematically presented by energy equation as follows:

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho \mathbf{u} e) - \nabla \cdot \left(\frac{k}{C_v}\right) \nabla e = p \nabla \cdot \mathbf{u}. \tag{3}$$

where e - internal energy of the gas [J/kg], k - thermal conductivity [W/(m·K)], C_v - specific heat at constant volume [J/(kg·K)].
Eq(3) does not include some viscous terms because of a fast-changing characteristic of phenomena.
In order to the temperature field determining, the aforementioned equations Eq(1)-Eq(3) must be complemented by using equations of: internal energy, ideal gas, and heat conduction (Fourier's law) as presented below:

$$e = C_v T, \tag{4}$$

$$R = C_p - C_v = p / (\rho T), \tag{5}$$

$$\mathbf{q} = -k \nabla T. \tag{6}$$

where R - gas constant of air [J/(kg·K)], C_p - specific heat at constant pressure [J/(kg·K)], T - temperature [K], $\mathbf{q}$ – heat flux [W/m^2].
Aforementioned equations are solved by using finite volume method which is utilized in OpenFOAM® toolbox. All of the continuous quantities are discretized by using Gauss linear scheme.
Air pressure is 0.6 MPa at time 0 s and there is a free gas outflow to the environment afterwards. The environmental pressure is set to 0.1 MPa, near to barometric pressure. Initial temperature is set to 300 K. The boundary conditions for temperature and velocity are the Neumann type, i.e. gradients of respective quantities are equal to zero. The boundary condition for pressure is a Robin mixed type. Values of outlet terms are calculated with assumption of far field being placed in some distance from the outlet.

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \frac{\partial \phi}{\partial \mathbf{n}} = \frac{\mathbf{u}}{l_\infty} (\phi_\infty - \phi), \tag{7}$$

where ϕ is general variable (e.g. pressure, temperature), ϕ_∞ is value in far field, $\mathbf{n}$ – vector normal to the boundary, l_∞ - distance between boundary and far field. The boundary condition can be regarded as possibility to minimize number of cells in numerical simulations. The values obtained by using this condition are "transferred" into the environment of the pressure accumulator. Furthermore, it does not allow shock waves to be reflected back to the considered area what Neumann type boundary condition makes possible.
The governing equations of the laws of conservation have delivered results which have been validated by using data reported in literature. The validating case considered an outflow from an open end and it has been chosen in order to fulfil both conditions simultaneously: outflow to atmosphere and transient analysis The study chosen for validation was reported by Honma et al. (2003).
Except validation of the results, there have also been performed a grid convergence test and an error estimation which show correctness of the numerical model (Jasak and Gosman, 2003).

3. Energy and Exergy Analysis

Energy accumulated in air included in the pressure accumulator can be converted to work according to the First Law of Thermodynamics. In order to balance the energy, there has to be a balance boundary applied. The walls of the accumulator are impermeable by assumption, thus the gas is released from the vessel though the outlet flange only. Therefore, the balance boundary for energy and exergy calculations are the walls of the vessel and the cross-section of the outlet flange. The calculations for energy and exergy are carried out for transient and compressible phenomenon. There are also assumed a lack of chemical reactions and additional heat sources.

The calculations have been based on results of numerical simulations. By using mean values of flow parameters such as temperature, pressure, velocity and density, the energy and exergy analysis is carried out. It has been assumed that the flow does not influence the environmental parameters.

3.1 Energy calculation

Amount of energy accumulated with mass of the gas in the pressure accumulator can be determined by using the First Law of Thermodynamics. Integral form of the Law is presented be Eq(8) and it describes how the energy is changing in time considering the changes inside the volume of gas V and the changes across the balance boundary A.

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\partial}{\partial t}\int_V \rho\left(e + \frac{1}{2}\mathbf{u}\cdot\mathbf{u}\right)\mathrm{d}V + \oint_A \rho\left(e + \frac{1}{2}\mathbf{u}\cdot\mathbf{u}\right)\mathbf{u}\cdot\mathbf{n}\mathrm{d}A \tag{8}$$

where E is energy [J], V – volume [m^3], A – boundary area [m^2].
There are isentropic gas conversion and absence of internal heat sources assumed (no chemical reactions) in supersonic airflow consideration. Thus:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \oint_A \rho\left(e + \frac{1}{2}\mathbf{u}\cdot\mathbf{u}\right)\mathbf{u}\cdot\mathbf{n}\mathrm{d}A \tag{9}$$

There are mean values used for energy analysis. They are calculated as area averages of respective quantities obtained in the boundary area. On that conditions, the First Law of Thermodynamics is as follows:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \Phi_m\left(e + \frac{u_n^2}{2}\right) \tag{10}$$

where Φ_m - mean mass flux [kg/s], u_n - mean normal velocity [m/s].

3.2 Exergy calculation

The evacuating gas does not perform work. But the aim of the exergy analysis is to calculate how much work could be performed by using the gas compressed inside the pressure accumulator. The exergy analysis comes strictly form the Second Law of Thermodynamics. Every increment of entropy of a gas means a loss in an irreversibility of a thermodynamic process. The energy which is included in the compressed air can be utilized to destruct the adverse phenomena of the loose material bed but not losslessly. The quality of the energy is characterised by the exergy. The higher values of exergy are gained, the higher quality of the accumulated energy is. The exergy is strictly connected with the environment of investigated object and is always considered with reference to it.
Specific exergy consists of the following parts: kinetic, potential, physical, chemical, and nuclear (Szargut, 2005). They are strictly taken from the forms of energy. With this taken into account we could write as follows:

$$b = \frac{u^2}{2} + gz + b_{ph} + b_{ch} + b_{nu} \tag{11}$$

Kinetic and potential parts of exergy should be taken into account only if the pressure accumulator would move relatively to the environment. There are neither chemical nor nuclear reactions, therefore $b_{ch} = 0$ & $b_{nu} = 0$. Thus, the only part of exergy which is to be taken into account is the physical one. This part is divided into pressure and temperature exergy. Combining this with equation of state Eq(5) we get:

$$b_{ph} = b_{ph_T} + b_{ph_p}$$

$$\begin{aligned} b_{ph_T} &= \left(\Delta h_{p_0} - T_0\Delta s_{p_0}\right)\Big|_{T_0}^{T} = C_p\left(T - T_0 - T_0\ln\frac{T}{T_0}\right) \\ b_{ph_p} &= \left(\Delta h - T_0\Delta s\right)_{T=const}\Big|_{p_0}^{p} = RT_0\ln\frac{p}{p_0} \end{aligned} \tag{12}$$

,

$$b_{ph} = C_p\left(T - T_0 - T_0\ln\frac{T}{T_0}\right) + RT_0\ln\frac{p}{p_0}. \tag{13}$$

where h is specific enthalpy [J/kg], s – specific entropy [J/(kg·K)], and index 0 refers to the environment.
Values of pressure and temperature are area averaged the same as for the calculation of energy.
Eq(13) describes physical exergy of the system for steady-state problems. It is more convenient for the present study if the exergy flux will be used. The exergy flux is a product of specific exergy and mass flux as follows:

$$\frac{dB_{ph}}{dt} = \Phi_m b_{ph}. \tag{14}$$

4. Results and Discussion

Results obtained by using relations presented in Section 3 are changing in time, and therefore, it is useful to show them by using time plot as shown in Figure 3. The results of energy flux have been obtained by using Eq(10) and exergy flux – by using Eq(14).

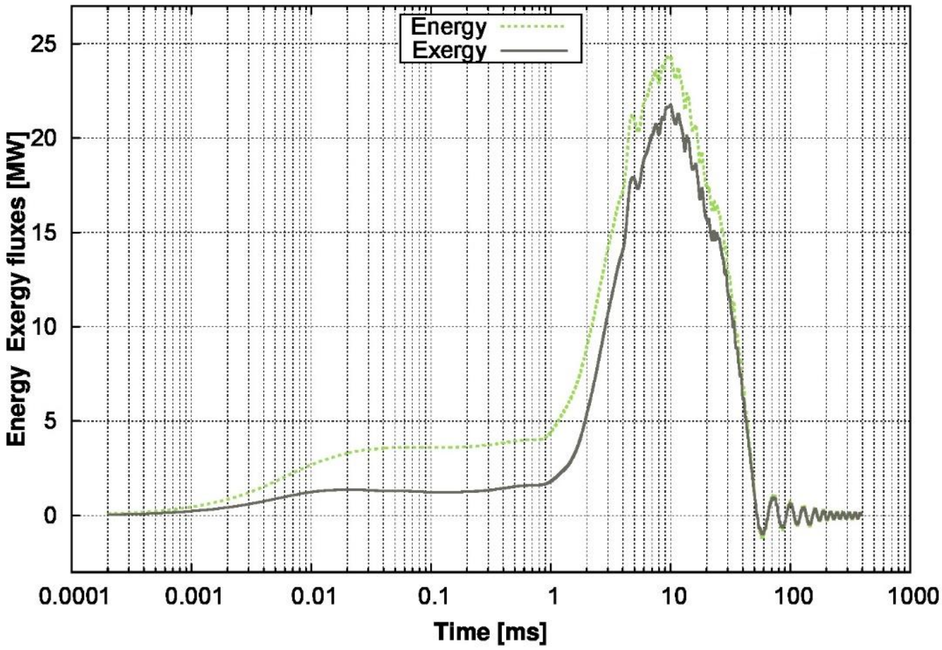

Figure 3: Values of energy and exergy fluxes and their time relation

In order to deliver total values of energy and exergy, the results of respective fluxes must be integrated in time according to the following relations:

$$E = \int_{t_0}^{t} \left(\frac{dE}{dt}\right) dt = \sum \left(\frac{dE}{dt}\right) \cdot \Delta t, \tag{15}$$

$$B_{ph} = \int_{t_0}^{t} \left(\frac{dB_{ph}}{dt}\right) dt = \sum \left(\frac{dB_{ph}}{dt}\right) \cdot \Delta t, \tag{16}$$

where Δt is simulation time step. In present study the time step has been set to 10^{-5} s.
The most important period of the process is observed during the first 25 ms from the start, which is why the plot is drawn in semi-logarithmic scale. The total values of quantities integrated by using Eq(15) and Eq(16) are: energy 682.9 kJ, exergy 605.2 kJ. The irreversibility of the process is the difference between both results and it equals 77.7 kJ. This loss occurs in one work cycle of pulsator. The modern pulsators are designed for 1 million and more work cycles. It is easy to calculate that the irreversibility of the gas conversion during the air evacuation can reach values of over 77.7 GJ.

5. Concluding remarks

Present study shows results of energy and exergy analyses in order to obtain a reference value of energy which can be converted into an impact force during pneumatic pulsator functioning. There has been a methodology developed which make it possible to calculate energy and exergy with transient airflow conditions.

There has been shown that there is a noticeable difference between energy and exergy fluxes. The air evacuation from the pressure accumulator is a gas conversion in critical conditions, therefore, a normal shock is created. These conditions produce energy losses if the irreversibility of gas conversion only is taken into account. The exergy is a maximal work which can be transferred to the impact force, therefore, it can be regarded as a reference value for efficiency of the pneumatic pulsator system. The results of the analyses show that 11.4 % of energy is wasted to the irreversibility. But this value doesn't show the rest of losses during the pneumatic pulsator system functioning, which is why the further analyses will be carried out.

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