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The Release of Energy from the Pressure Accumulator in the Pneumatic Pulsator

Krzysztof J. Wołosz*, Jacek Wernik

Dept. of Process Equipment, Warsaw University of Technology Plock Branch, 09-402 Plock, Jachowicza 2/4, Poland
krzysztof.wolosz@pw.plock.pl

Knowing the value of energy which is accumulated with air and released from a pressure accumulator in a pneumatic pulsator is crucial for the determining of a pulsator performance. The pulsators are used for unclogging outlets of silos in which loose materials are stored. They also prevent from phenomena such as bridging, arching, clinging, ratholing which are specific for loose material.
Results of numerical simulations were used to determine values of energy which can be released from the pressure accumulator. Supersonic airflow during sudden vessel evacuation in which air is compressed up to 6 bar was simulated by using ideal gas model.
Very rapid changes of energy can by observed within time period of 25 ms. Outlet air velocity raises from 0 m/s up to almost 350 m/s during that time. Sudden temperature drop occurs from 300 K to 180 K at the same time.
Reported in literature analytical studies and research on the gaseous vessel evacuation utilize assumptions of gas and flow models which cannot be applied in the case being investigated in this study. Wide vessel outlet cross-section relative to the vessel dimensions makes that the gas inertia and influence of the vessel environment must be taken into account. Therefore the flow cannot be treated as one-dimensional.
As a result of the investigation, we obtain reference value of energy accumulated in the pressure accumulator, furthermore, we will be able to determine the efficiency of separate elements of the pneumatic pulsator system.

1. Introduction

How much energy do we have? What is the amount of energy we can get during evacuation of the vessel filled with compressed air? These questions must be answered in order to obtain the effectiveness of energy usage. The analysis of energy which can be released from a pressure accumulator is investigated in the article. The pressure accumulator is an element of a pneumatic pulsator unit which is used as maintenance of loose and bulk material silos. Unclogging of outlets of the silos is the basic task of the pulsator. There is a system of pneumatic pulsators shown in Figure 1. Pulsators use pneumatic impact which proceeds during fast air decompression. Energy released from pressure accumulator is transferred onto the loose material bed though the head of the pulsator and is utilised for destruction of adverse structures of loose material. These structures are: ratholing, bridging, arching, and clinging. They cause delays in loose material transport and are hazardous in large silos. Further information on principles of operation can be found in publications recently committed. The basic numerical investigations were presented by Urbaniec et al. (2009) where the design and aims of study are presented. Wernik and Wołosz (2012) reported more detailed investigation with description of R&D project.
Motivation for the study was to recognize effectiveness of energy transfer in the pneumatic pulsator unit. Compressed air accumulated in a pressure accumulator is a source of energy for the pneumatic pulsator. Energy is a substance of existence. Determining of the amount of energy leads to obtaining effectiveness of particular elements of the pneumatic pulsator unit in the future. Similar study was carried out by Wołosz and Wernik (2014b) where gas conversion and energy effectiveness in an auxiliary, heat-resistant nozzle of the pneumatic pulsator unit was investigated. Airflow through the nozzle was also a subject of study

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reported by Wołosz and Wernik (2014a) although optimisation of topology with respect to pressure drop was emphasised. This paper presents study which leads to determining reference value of energy in whole pneumatic pulsator unit. This reference value will give information how much energy is lost during the airflow through the pulsator in the future studies.

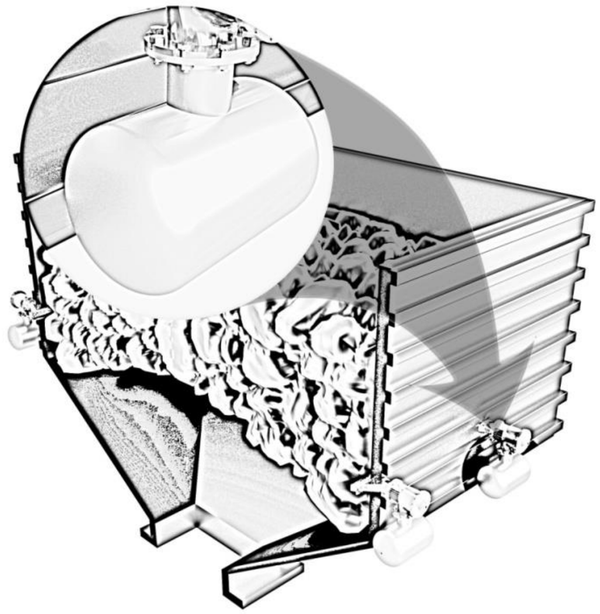

Figure 1: A silo with pneumatic pulsator system and zoom on investigated object

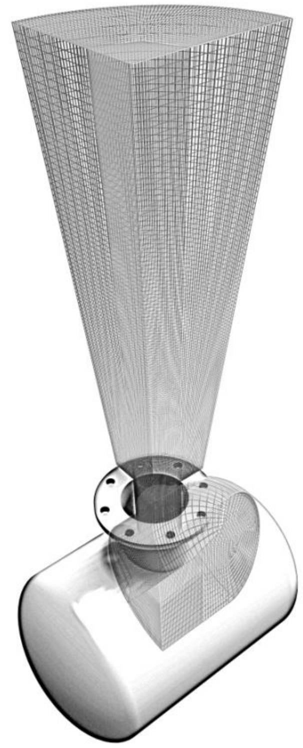

Figure 2: Numerical mesh visualisation on the background of the pressure accumulator

Present article can be regarded as analysis of fast vessel evacuation though an opening. The pressure accumulator is a vessel installed in a pneumatic pulsator unit and the evacuation proceeds though a flange. The flange joins the accumulator with the head of the pulsator which controls airflow. However, to determine how much energy is accumulated in the pressure accumulator the absence of the head is assumed. Hence, there is no device to produce energy loss and maximal value of energy could be determined with total energy flux as well.
Air parameters during thermodynamic process obey the ideal gas law:

$$p = \rho R T \quad ; \quad R = 287 \frac{\mathrm{J}}{\mathrm{kg \cdot K}} \tag{1}$$

where p is pressure, ρ – density, R–specific gas constant for air, and T is temperature.
Information on progress during vessel evacuation can be obtained by utilising the ideal gas law Eq(1) with continuity equation. There are some simplifications applied in analytical description, namely isothermal or adiabatic model application. Study reported by Dutton and Coverdill (1997) compares gas parameters obtained analytically and experimentally. There was presented a high-grade consistency of both analytical models and how the model application depends on the vessel size. There was case investigated recently by Péneau et al. (2009) which considers sudden hydrogen vessel evacuation. Similar study reported by Han et al. (2013) presents range of the gas flow. However, all investigated cases can be compared to the analytical results by reason of assumption that gas pressure near the vessel opening is equal to pressure inside the vessel and it has stagnation value. This kind of assumption cannot be applied in the present study. Models reported in bibliography consider cases where gas parameters in the vessel are aside from the environment. Present study investigates case where diameter of the flange is comparatively large to the vessel dimensions. Therefore, there is possibility of vena-contracta and pressure fluctuation which are

caused by inertia of air. Furthermore, reflections of shock waves can make reversal airflow. That type of vessel evacuation has not been investigated so far.

2. Methods

2.1 Numerical model

Due to the scope of investigation, only a part of surrounding was taken into account. Numerical model cover a quarter of gas volume in the vessel and surrounding in vicinity of the vessel opening. Visualisation of mesh on the background of the vessel is shown in Figure 2. The size of numerical model is sufficient for prediction of the amount of energy which is transported with air.
The pressure accumulator has volume of 115 L, the opening is the flange of nominal diameter of 150 mm, and internal diameter of the accumulator is 450 mm.
The study uses Finite Volume Method for discretisation of fluid dynamics equations. There are equations used for compressible transient flow along with ideal gas law according to Eq(1). Basic equations of governing laws are as follows:

- mass conservation equation (continuity):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{2}$$

where t is time, and $\mathbf{u}$ is velocity vector,

- momentum conservation equation:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) - \nabla \cdot \mu \nabla \mathbf{u} = -\nabla p \tag{3}$$

where μ denotes dynamic viscosity of air, and p is pressure,

- energy conservation equation:

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho \mathbf{u} e) - \nabla \cdot \left(\frac{k}{C_v}\right) \nabla e = p \nabla \cdot \mathbf{u} \tag{4}$$

Above-mentioned Eqs(2)-(4) need to be fulfilled with heat conduction equation (Fourier's law):

$$\mathbf{q} = -\lambda \nabla T \tag{5}$$

where $\mathbf{q}$ denotes heat flux density, λ – thermal conductivity, and T is temperature.
Internal gas energy e occurred in Eq(4) is calculated as follows:

$$e = C_v T \tag{6}$$

where C_v jest specific heat at constant volume.
Phenomenon of vessel evacuation is assumed to be turbulent, therefore, there has to be a turbulence model applied in order to obtain reliable results. In the case of lack of the turbulence model, there must be Direct Numerical Simulation (DNS) applied which requires very dense mesh and high calculation costs (Moin and Mahesh, 1998). The standard k-ε model was used in this study and equations of this model are described by Menter (1994).

2.2 Boundary and initial conditions

The vessel is filled with dry air compressed up to 6 bars at the beginning. Air is also present in the surrounding of the vessel at the initial pressure of 1 bar. Initial temperature is set to 300 K in all considered zone.
The flange is located perpendicular to lengthwise axis of the vessel; hence, the airflow in the vessel is not axisymmetric. Therefore, axisymmetric model could not be used in investigation. However, the flow is symmetrical crosswise and lengthwise so symmetry plane boundary condition was applied twice. The amount of cells decreases four times because of utilisation symmetry of flow.
Robin type boundary condition was applied on the boundaries which numerically model the surrounding of the vessel. Crucial feature of the boundary condition is that it does not cause shock waves to be reflected from the boundary. It happens when Neumann or Dirichlet type boundary conditions are used. This boundary condition "transmits" shock waves to the zone which is not considered, therefore, it is named wave transmissive boundary condition. The wave transmissive boundary condition has parameters, such as far field pressure or far field temperature, equivalent to surrounding ones.

3. Gaseous energy

Energy which is transferred in time unit with gas released from vessel is a flux of integral enthalpy (general energy) of gas. It can be stated, with averaged values taken into account, as follows:

$$\dot{E} = \int_S i_e \left(\rho \mathbf{u} \cdot \mathbf{n}\right) \mathrm{d}S \tag{7}$$

where i_e denotes specific enthalpy, $\mathbf{n}$ is vector normal to cross-section of vessel opening, and S – area of cross-section.
Eq(7) can be simplified by using relation of mass flux (with symmetry of numerical model taken into account) which is as follows:

$$\dot{m} = \int_S \rho \mathbf{u} \cdot \mathbf{n} \mathrm{d}S \tag{8}$$

Averaged value of specific enthalpy is a sum of internal energy, pressure energy, kinetic, and potential one. Hence:

$$i_e = e + \frac{p}{\rho} + \frac{1}{2}\left(\mathbf{u} \cdot \mathbf{u}\right) + zg \tag{9}$$

Potential energy zg can be neglected because of its almost infinitesimal influence on the total value of energy flux. Moreover, this type of energy is important when two places of energy system are balanced and they are significantly far one from another along gravity vector direction.
Energy flux transported with evacuating gas is:

$$\dot{E} = \dot{m}\, i_e = \dot{m}\left(e + \frac{p}{\rho} + \frac{1}{2}\left(\mathbf{u} \cdot \mathbf{u}\right)\right) \tag{10}$$

Energy flux shown by Eq(10) is the amount of energy transported in time and it is power in physical meaning. The energy flux is calculated for the purpose of obtaining energy which can be regarded as maximal possible work done by air. Energy is time derivative according to definition of power. In order to obtain the amount of energy which is transported with gas, we have to integrate the function of energy flux, shown by Eq(10), from the beginning until a moment t in time. The definite integral can be replaced by sum, for discrete values, as follows:

$$E = \int_0^t \dot{E} \mathrm{d}t = \sum_{i=0}^{t} \dot{E}_i \Delta t_i \tag{11}$$

4. Results

Results presented in this chapter are obtained and/or determined from the averaged values of flow parameters. These values were area-weighted averaged in the cross-section of the flange as near as possible to surrounding. There are averaged values of absolute pressure and temperature of air shown in Figure 3. All plots show axes of abscissae in logarithmic scale because the most dynamic period of phenomena takes place at the beginning of the process. As it can be seen, the pressure reaches value almost equal to the value of surrounding within the period of about 0.03 s which is about 7.5 % of time of all time being considered, i.e. 0.392 s. The largest temperature drop is about 120 K within very short period of time.
Figure 4 shows values of averaged velocity and Mach number in the opening cross-section. Values of velocity are values of velocity vector normal to the flange cross-section. It can be noticed that after the period of large drop the velocity starts oscillating around value of 0. Negative value of velocity means that there is a recessive flow from surrounding to the vessel.

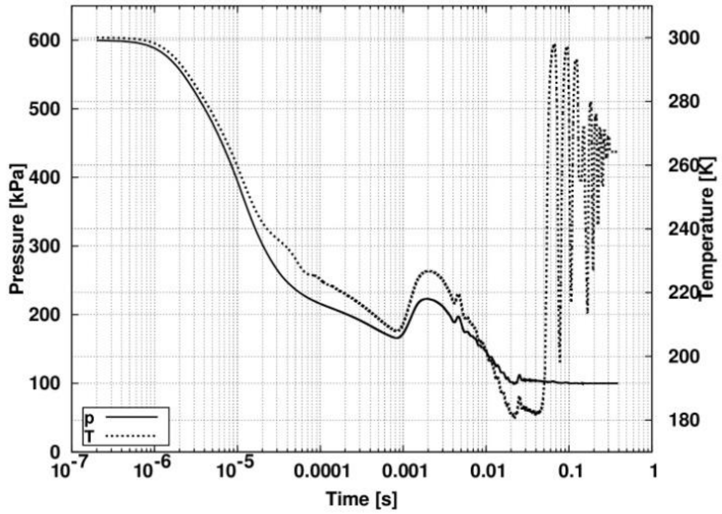

Figure 3: Pressure and temperature plot at the opening of the vessel

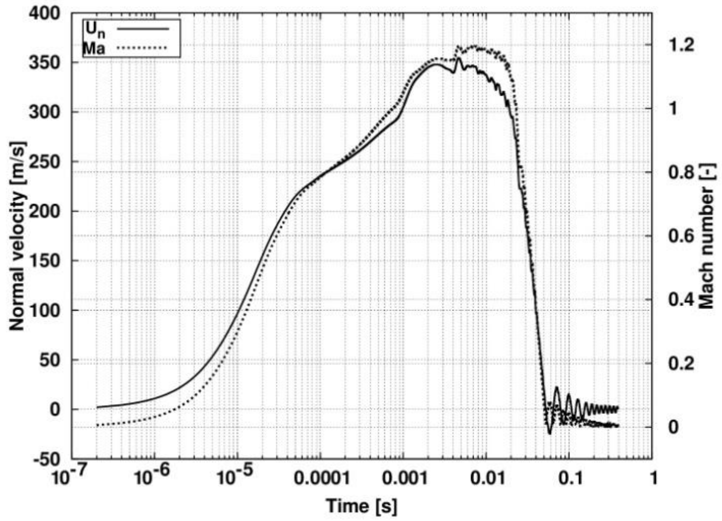

Figure 4: Normal velocity and Mach number plots at the opening of the vessel

There is energy flux and energy increment shown in Figure 5. The largest value of energy flux is $\dot{E}$ = 24.3 MW. The amount of energy transported with gas from the beginning till the end of the time of study is E $\approx$ 683 kJ.

5. Concluding remarks

The article reports the study of sudden evacuation of the vessel which is filled with air compressed to 6 bar as a starting point. There are values of energy flux and general energy transferred with gas also determined during the process of vessel evacuation. The results of numerical simulation do not meet analytical results accurately. Very steep pressure graph and velocity fluctuation points show that there is divergence between obtained results and analytical ones. Analytical models are based on assumption in which interaction between gas in the vessel and surrounding is not taken into account. The graph of normal velocity shows that there is a reverse flow occurrence which is “not allowed” in analytical models. The pressure accumulator has the opening diameter of about 1/3 of the diameter of the vessel. Therefore, shock waves reflections and reverse flow is predicted as shown in the graph of velocity in Figure 4. Authors find it useful to employ Robin-type boundary conditions during simulation in which environment influence need to be taken into account.

Maximal value of flux of energy which is transported with gas meets the highest values of outflow velocity. It can be concluded that the most significant share in general energy is kinetic energy what meets Eq(10). Large temperature fluctuation, as shown in Figure 3, has much less impact and is similar to the impact of pressure/density ratio. The value of energy which is accumulated in pressure accumulator cannot be calculated without momentum change taken into account. The main objectives of this work were results of energy flux and total quantity of energy which can be released from the pressure accumulator with environment influence and momentum changes taken into account. The further work will lead to exergy analysis of the pneumatic pulsator unit.

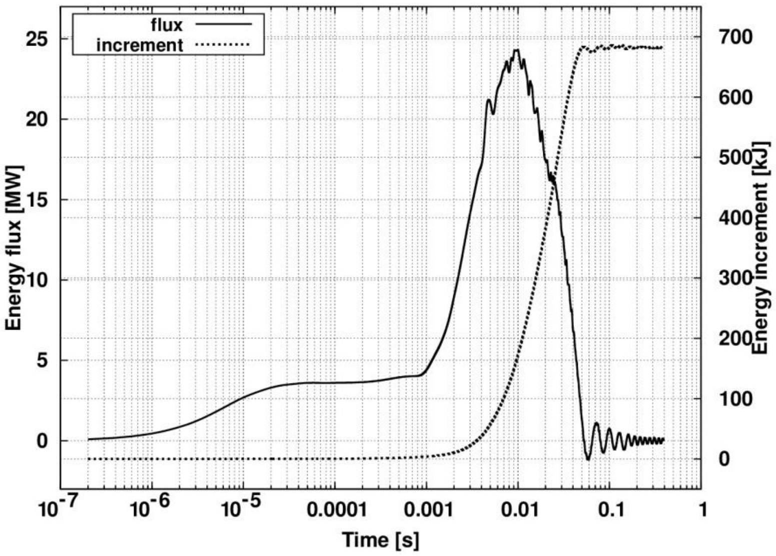

Figure 5: Energy flux and increment of energy according to Eqs(10-11)

References

Dutton J.C., Coverdill R.E., 1997, Experiments to Study the Gaseous Discharge and Filling of Vessels, Int. J. Eng. Educ., 13, 123–134.

Han S.H., Chang D., Kim J.S., 2013, Release characteristics of highly pressurized hydrogen through a small hole, Int. J. Hydrog. Energy, 38, 3503–3512.

Menter F.R., 1994, Two-equation eddy-viscosity turbulence models for engineering applications, AIAA J. 32, 1598-1605.

Moin P., Mahesh K., 1998, Direct Numerical Simulation: A Tool in Turbulence Research, Annu. Rev. Fluid Mech, 30, 539–578.

Péneau F., Pedro G., Oshkai P., Bénard P., Djilali N., 2009, Transient supersonic release of hydrogen from a high pressure vessel: A computational analysis, Int. J. Hydrog. Energy, 34, 5817–5827.

Urbaniec K., Wernik J., Wołosz K.J., 2009, Optimal design of the head of a pneumatic pulsator, Chemical Engineering Transactions, 18, 237–242.

Wernik J., Wołosz K.J., 2012, Pneumatic pulsator design as an example of numerical simulations in engineering applications, Cent. Eur. J. Eng., 2, 76–82.

Wołosz K.J., Wernik J., 2014a, ICEEM07: Three-Dimensional Flow Optimization of a Pneumatic Pulsator Nozzle with a Continuous Adjoint, Int. J. Nonlinear Sci. Numer. Simul., 16, 3-9.

Wołosz K., Wernik J., 2014b, Heat generation calculation on the basis of numerical simulation results of supersonic airflow in a nozzle, Chemical Engineering Transactions, 39, 1363-1368.