CHEMICAL ENGINEERING TRANSACTIONS

VOL. 39, 2014

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong

ISBN 978-88-95608-30-3; **ISSN** 2283-9216

DOI: 10.3303/CET1439228

Heat Generation Calculation On the Basis of Numerical Simulation Results of Supersonic Airflow in a Nozzle

Jacek Wernik, Krzysztof J. Wołosz*

Department of Process Equipment, Warsaw Univ. Tech. Plock Branch, 09-402 Plock, Jachowicza 2/4, Poland
krzysztof.wolosz@pw.plock.pl

This paper presents results of calculation carried out in order to obtain heat that can be potentially generated in pneumatic pulsator nozzle during the work cycle. Pneumatic pulsators widely applied in industry where loose materials are stored and/or transported. In silos, where loose materials are stored, the phenomena of bridging creation can be observed. The bridgings are structures specific for loose material. They develop while cohesion forces are larger than gravity. Annihilation of these structures is crucial for plant fluent workflow. Therefore, the equipment for bridging creation prevention and/or bridging annihilation is widely utilize in loose material silos.

The airflow is driven by pressure gradient towards the silo outlet. Inlet pressure is assumed to be time-dependent and in consequence other quantities are also time-dependent. Air is modelled as compressible, thermodynamically ideal gas with invariant gas constant.

The results of the simulation were the basis for calculation of heat generated during the airflow. Negative values of the heat indicates that the nozzle will be cooled during infinitely many work cycles. Nonetheless, the influence of the heat on the characteristics of the nozzle material remains unknown. Therefore, further work needs to be considered in order to investigate the nozzle stress durability. The values of the heat obtained in this study indicate that there is possibility of nozzle durability decrease.

1. Introduction

The paper presents results of calculation that has been conducted in order to obtain heat generated in pneumatic pulsator nozzle during the work cycle.

Pneumatic pulsators are widely applied in industry where loose materials are stored and/or transported. The pulsators are used to destruct bridgings or to prevent silo clogging. Bridgings are structures specific for loose material and are generated while cohesion forces are larger than gravity. Annihilation of these structures is crucial for plant fluent workflow. Therefore, the equipment for bridging creation prevention as well as for bridgings annihilation is widely applied in loose material silos. The pneumatic pulsators use compressed air to generate force that can act on the loose material bed in order to prevent cohesion forces increment. In practice, air acts on the loose material through pneumatic impact and moves it towards the silo outlet. Due to this impact, the pulsators are sometimes called air cannons. In some circumstances the pulsators can be equipped with augmented nozzles. The nozzles' tasks are to point the air stream (directonal nozzles) or to prevent the pulsator against the heat generated within the silo (heat-resistant nozzles). In most cases these tasks are performed simultaneously and one of those nozzles is the object being investigated and presented herein.

Motivation of investigation is a possibility of improvements in the nozzle design. The principle of pulsator operation is to produce unsteady airflow. During the flow, compressed air generates heat that can cause pulsator or nozzle failures. The aim of the study is to determine heat quantity that is generated during one work cycle of the pulsator.

R&D works have been undertaken on pneumatic pulsators since 2007 and the first results were reported in the following year (Wernik and Wolosz, 2008). The next step on CFD calculations and optimization of pneumatic pulsators was described by Urbaniec et al. (2009). Wider research of CFD and fluid-structure interaction on the subject of the pulsator the reader can find in the article by Wołosz and Wernik (2012).

Please cite this article as: Wernik J., Wołosz K.J., 2014, Heat generation calculation on the basis of numerical simulation results of supersonic airflow in a nozzle, Chemical Engineering Transactions, 39, 1363-1368 DOI:10.3303/CET1439228

The first attempt to make a research on pulsators' nozzles has been undertaken recently and the results of optimization of the nozzle has been reported by Wołosz and Wernik (2013). This paper presents analyses conducted subsequently during the development of a whole system for silo outlets clearance.

A supersonic flow with shock-waves can be considered analytically only for rather simple cases. Transient characteristic of airflow makes analyses in real operating conditions very difficult. Ideal gas flows and its reflection from simple shapes are considered in Ben-Dor (2007) where numerical values are compared to experimental data. Good practice in investigation of shock-waves can be observed in Honma et al. (2003) work where the CFD results are well validated with experiments during flow from open duct end.

2. Numerical model

Numerical model of airflow calculation is based on the nozzle geometry. Structural mesh against the nozzle visualization is presented in Figure 1 below.

The airflow is driven towards the outlet by pressure gradient. Inlet pressure is assumed to be time-dependent, hence other quantities are also time-dependent. Outlet pressure is calculated according to wave-transmissive boundary condition as described in Section 2.2. Flow is assumed to be symmetrical and transient. Air is modelled as compressible, thermodynamically ideal gas with invariant gas constant.

Due to short time of phenomena one nozzle work cycle is assumed to be adiabatic. This assumption does not exclude situation when the generated heat will be transferred onto the walls during infinitely many work cycles.

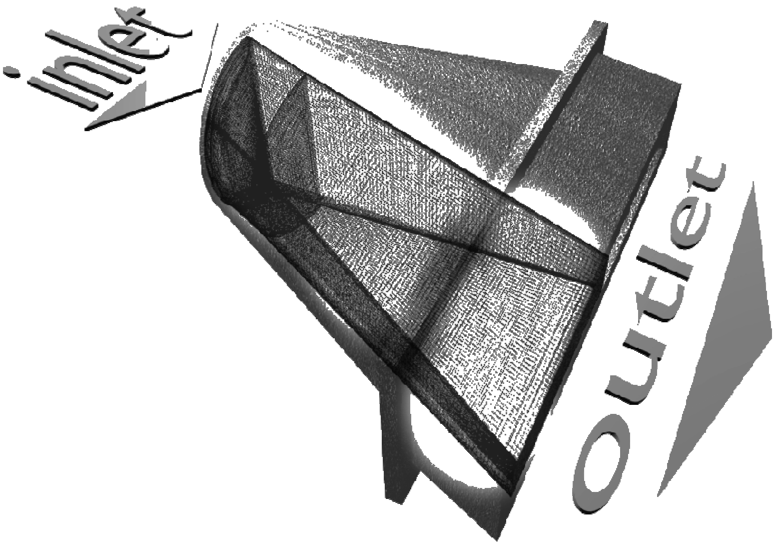

Figure 1: Numerical mesh model with nozzle visualization

2.1 Governing equations

Airflow in the nozzle is governed by the conservation laws: of mass, of momentum, and of energy. As far as it was possible the numerical model was chosen to be precise representation of actual conditions (OpenFOAM, 2013). Equations of the laws mentioned above are presented below respectively:

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

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

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

where ρ denotes density, t – time and $\mathbf{u}$ – fluid velocity vector, λ is thermal conductivity, e – internal gas energy, and C_v denotes specific heat at constant volume. Eqs(1) - (3) need to be complemented with the following ones of gas constant, internal energy, and Fourier's law:

$$R = C_p - C_v = \frac{p}{\rho T} = 287 \quad \mathrm{J \cdot kg^{-1} \cdot K^{-1}} \tag{4}$$

$$e = C_v T \tag{5}$$

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

where $\mathbf{q}$ denotes heat flux density, and T - temperature.

2.2 Boundary conditions

Numerical modelling is not only equation but first of all boundary and initial conditions. As the flow is driven by pressure gradient, Dirichlet type condition is applied for pressure and temperature on inlet while velocity is calculated with respect to Neumann type condition $\partial\mathbf{u}/\partial\mathbf{n} = 0$. More advanced calculation is carried out on the outlet. There is wave-transmissive boundary condition applied which is Robin type, in general, and is reported by Gustafson and Abe (1998). This condition calculates source terms on the outlet with assumption of far field being at some distance from the outlet:

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

where ϕ is source term, $\mathbf{n}$ – normal vector to outlet, and K is related to assumed distance from the far field $K = \mathbf{u}/l_\infty$. The wave-transmissive boundary condition can be regarded as a simplification of the flow area in zones where detailed results are not the aim of simulation. Furthermore, this condition transfers outlet results onto the nozzle environment.

2.3 Heat generated

During the flow thought the nozzle the air is compressed and decompressed which generates temperature increases and drops according to Eq(4). One cycle of work lasts for such a small period of time that the gas process is assumed to be isentropic. Nonetheless, infinitely many consecutive work cycles will generate the heat which can be transferred onto the wall of the nozzle. According to Szumowski et al. (1988) the heat of airflow is calculated from energy balance and the heat increment of a system is a result of delivered heat and external work:

$$\frac{dE}{dt} = H + L \tag{8}$$

where H is heat exchanged with environment and heat of physicochemical reactions in time unit, L - work exchanged with environment in time unit.
Material derivative of energy is:

$$\frac{dE}{dt} = \frac{\partial}{\partial t}\int_V \rho\left(e + \frac{1}{2}\mathbf{u}\cdot\mathbf{u}\right)dV + \oint_S \rho\left(e + \frac{1}{2}\mathbf{u}\cdot\mathbf{u}\right)\mathbf{u}\cdot\mathbf{n}dS \tag{9}$$

where e is internal gas energy, and S – is boundary surface of the system. In supersonic airflow through the nozzle the isentropic gas process is assumed and there are no internal heat sources (no chemical reactions). Therefore:

$$\frac{dE}{dt} = \oint_S \rho\left(e + \frac{1}{2}\mathbf{u}\cdot\mathbf{u}\right)\mathbf{u}\cdot\mathbf{n}dS \tag{10}$$

The model of heat determining is based on average values of source terms on inlet and outlet. For volume fields of scalars and vectors the average values are calculated as follows:

$$\overline{\phi_S} = \frac{1}{S}\int_S \phi \, dS \tag{11}$$

Mass flow of gas is surface scalar field and is calculated for each cell. To obtain the value of mass flow through inlet or outlet the cell flows need to be summed for entire boundary. There is also a need of flows to make double because of symmetry boundary condition utilization :

$$\Phi = 2\int_S \rho \mathbf{u} \cdot \mathbf{n} dS \tag{12}$$

Values for scalar and vector fields are not influenced by symmetry boundary conditions.
While the wall of the nozzle is assumed to be impermeable and by using Eq(10) and (12) the heat can be stated as follows:

$$\dot{Q} = \frac{dE}{dt} = \dot{Q}_{\mathrm{in}} - \dot{Q}_{\mathrm{out}} = \Phi_{\mathrm{in}} \left(e + \frac{1}{2} \mathbf{u} \cdot \mathbf{u} \right)_{\mathrm{in}} - \Phi_{\mathrm{out}} \left(e + \frac{1}{2} \mathbf{u} \cdot \mathbf{u} \right)_{\mathrm{out}} \tag{13}$$

Indexes in and out indicates inlet and outlet boundary respectively.
The numerical simulation was carried out by using *sonicFoam* application which is part of *OpenFOAM* toolbox released by The OpenFOAM® Foundation (2013).

3. Results and discussion

The obtained results are the consequences of changes of driving force in time. These changes can be observe in the form of time distribution of pressure and velocity magnitude. It is shown in Figure 2. Values of heat at inlet and outlet change in similar way vs. time. Larger differences can be seen at the end of work cycle. The result is caused by high decompression of air at outlet.
The pressure time function has been imposed at inlet. As it can be noticed in Figure 2a) the maximal value of outlet pressure is more than twice as the inlet maximal pressure. That indicates that the nozzle does not produce pressure loss and therefore it can be successfully applied in pneumatic pulsator.
Figure 3 presents values of heat delivered and heat discharged from the nozzle with air versus time. There are also presented values of heat increment obtained according to Eq(13).
Overall energy that can act on the nozzle walls can be calculated from the definition of power with discrete data characteristics taken into account.

$$Q = \int_{t_0}^{t_1} \dot{Q} dt = \sum \dot{Q} \cdot \Delta t \tag{14}$$

For constant time step $\Delta t = 10^{-5}$ s the overall energy Q = -3,704.2 J. Such value indicates that the heat-resistant nozzle fulfills its function.

4. Concluding remarks

Numerical simulation of supersonic compressible flow has been carried out and presented in this paper. Airflow model is considered as an ideal gas flow. Due to the fact that the outlet mean temperature of air is relatively low and does not exceed 420 K the ideal gas assumption can be stated. The values of temperature do not produce an error with ideal gas assumption as can be read in Lunev (2009).
The results of the simulation were the basis for calculation o heat generated during the airflow. Negative values of the heat indicates that the nozzle will be cooled during infinitely many work cycles. Nonetheless, the influence of the heat on the characteristics of the nozzle material remains unknown. Therefore, further work needs to be considered in order to investigate the nozzle stress durability. The values of the heat obtained in this study indicates that there is possibility of nozzle durability decrease.

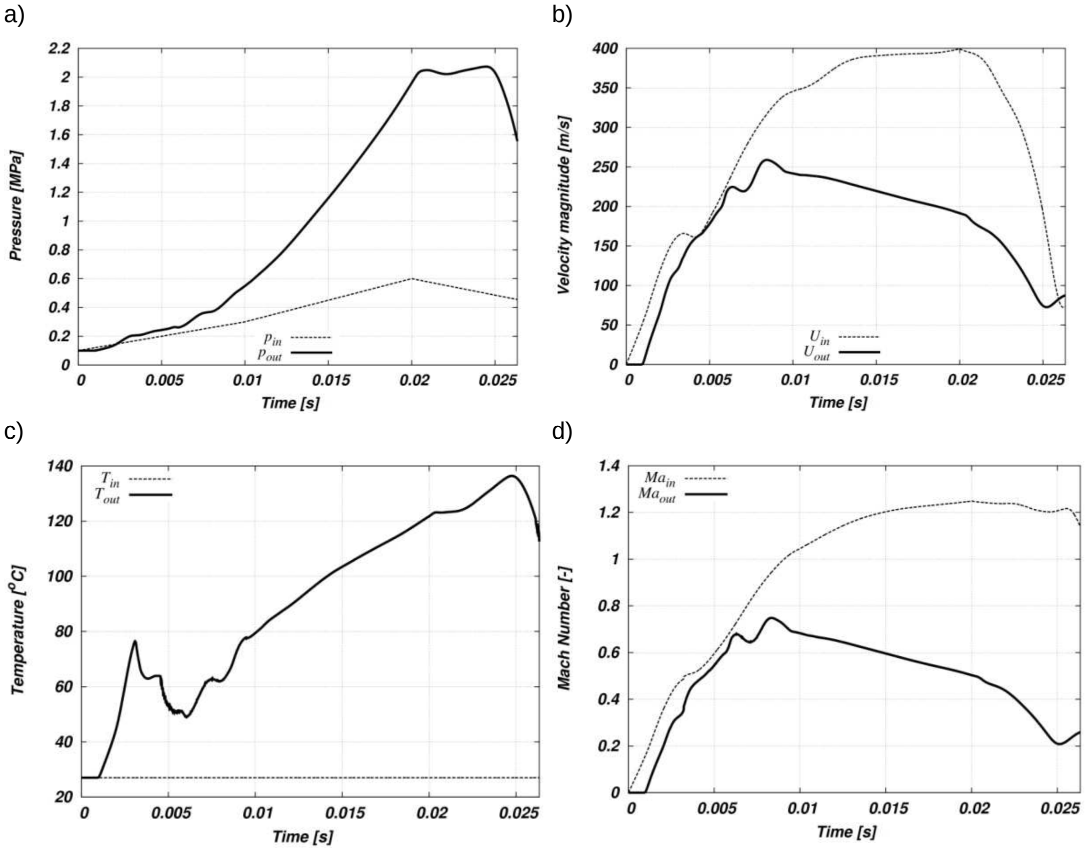

Figure 2: Inlet and outlet variations in time of: a) pressure, b) velocity magnitude, c) temperature, d) Mach number

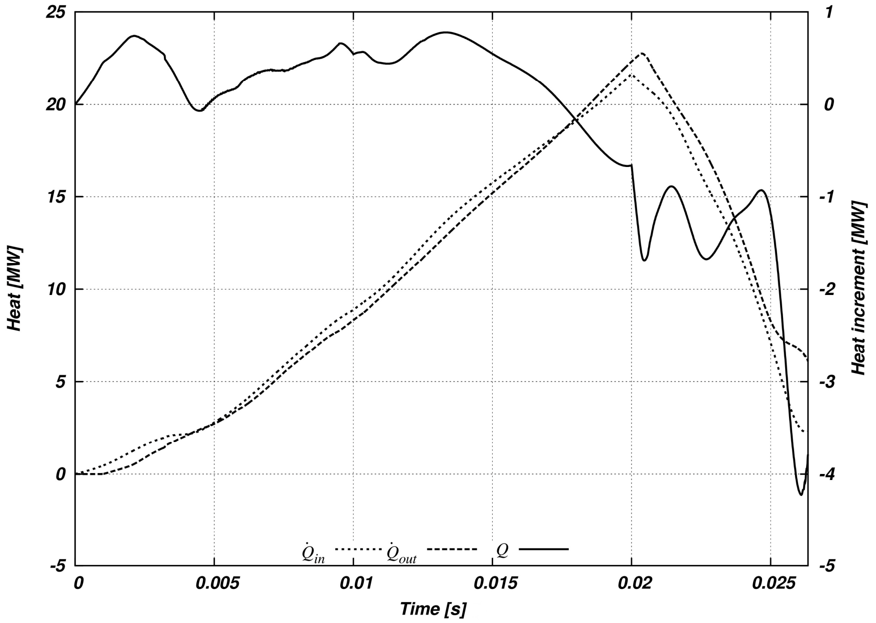

Figure 3: Time dependency of heat delivered and discharged from the nozzle and difference between them

References

Ben-Dor G., 2007. Shock Wave Reflection Phenomena. Springer, Berlin Heidelberg, Germany.

Gustafson K., Abe T., 1998, (Victor) Gustave Robin: 1855–1897, Math. Intell., 20, 47–53.

Honma H., Ishihara M., Yoshimura T., Maeno K., Morioka T., 2003. Interferometric CT measurement of three-dimensional flow phenomena on shock waves and vortices, Shock Waves, 13, 179–190.

Lunev, V., 2009. Real Gas Flows with High Velocities. CRC Press, Boca Raton, USA.

OpenFOAM, 2013, Programmer's Guide, OpenFOAM Foundation, Bracknell, UK.

Szumowski A., Selerowicz W., Piechna J., 1988, Gas dynamics (in Polish), WUT Publishing, Warsaw, Poland.

The OpenFOAM® Foundation, 2013, <www.openfoam.org> accessed on 3.4.13.

Urbaniec K., Wernik J., Wolosz K.J., 2009, Optimal design of the head of a pneumatic pulsator, Chem. Eng. Trans., 18, 237–242.

Wernik, J., Wolosz, K., 2008. Numerical Simulations of Air Flow in a Pneumatic Pulsator, in: 3rd International Conference "From Scientific Computing to Computational Engineering", 9-12 July 2008, Athens, Greece, 9–12.

Wołosz K.J., Wernik 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., 2013. Three-dimensional flow optimization of a nozzle with a continuous adjoint, Proceedings of the 7th International Conference Environmental Engineering and Management: Integration Challenges for Sustainability Conference, 18-21 September 2013, Vienna, Austria, 209–210.