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Study of Heat Transfer in Fins of Pneumatic Pulsator Using Thermal Imaging

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Compressed air shockwave is applied in pneumatic pulsator. Numerical methods and engineering expertise were used in the design of pneumatic pulsator so far. Accuracy and reliability are vitally important in Research and Development of process equipment. Therefore, we used thermography in the further studies. Heat, which is discharged to the environment, is produced due to friction in the channels of pneumatic pulsator during airflow. The external surfaces of channel are finned to increase the heat transfer from the pneumatic pulsator. The article presents results and analysis of an experimental investigation on determining the thermal performance of a heat transfer in fins using thermal imaging camera. Temperature distribution of the finned surface of the channel was measured using a single heat source with varied heat flux inputs. The results confirm the rational design of the body in terms of thermal conditions. The obtained temperature distribution using thermal imaging agrees approximately with the values obtained during numerical simulations (method of Computational Fluid Dynamics). This confirmed correctness of measurements. The use of a thermal imaging camera is a valuable technological addition during the tests.

1. Introduction

When designing industrial apparatus, it is crucial to create reasonable construction of the device. Nowadays, there are many advanced techniques of computer support for engineering works. It enables the engineers to shorten the time during designing stage. However, a significant factor is the verification of the project through industrial tests conducted on the device prototype or through lab tests. Only such reliable tests let the engineers get an answer for the question whether designed construction is reasonable and its parameters obtain intended values. Pioneering studies on the pneumatic pulsator were described by Urbaniec et al. (2009). Then, a developed construction of pneumatic pulsator was a subject of numerical simulation conducted with advanced software. First obtained results concerning the heat transfer through the head fin of the pulsator were presented by Wernik and Wolosz (2014). Conducted simulations had a primary character and the verification of the studies was carried out in actual conditions with a pyrometer. In the course of further works, other studies are being conducted. To perform numerical simulations, COMSOL Multiphysics software is used. There is also a test stand which uses a touch-free diagnostic method based on thermal imaging. Using a modern thermal camera is a fast and easy method to test the conditions of heat transfer through the body of the device. Currently, it is the most popular method of imaging and registering the distribution of temperature in devices and technical objects. It is possible to use the thermal camera as a tool for quantitative (e.g. determination of the heat transfer coefficient) and qualitative (e.g. identification of technological defects of a cast) effectiveness of transferring heat. Obtained results enable verification and validation of developed numerical models of finned head of pneumatic pulsator. Appropriate design of finned head, which causes an increase in heat transfer surface, enables an effective heat transfer to the environment.
In order to validate numerical model of heat conduction in pneumatic pulsator, investigations of the temperature distribution were carried out using FLIR SC7600 thermovision camera. The obtained thermograms were found to be in satisfactory agreement with the temperature distribution determined by numerical simulations.

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2. Idea of pneumatic pulsator

During storage of loose and crumbled materials, there are various adverse phenomena. Materials become aggregated or form various shapes such as bridges and vaults. This results in problems during clearing the silos' outlets. Methods which prevent from this and general designing recommendation for silos construction are presented in (Wolosz and Wernik, 2012). Among technically available means used to store loose materials, one of the most effective devices is the pneumatic pulsator. It may be treated as a pneumatic system to remove blockages for flowing materials and material bridges in silos and in vessels of loose and granular materials. In recent years, the range of using such devices was expanded by an operation of removing sticking material and growths emerging during heat treatment of materials in metallurgy, cement and limestone industry as well as in incinerations. Such devices are powered with compressed air or neutral gas from general networks of compressed air or gases.
The functioning of the pneumatic pulsator consists in triggering abrupt flows of compressed air during abrupt opening of outlets from the vessels with compressed air (in the industry, it is common to see the vessels with a capacity to 400 $dm^{3,}$ depending on the designation). Full content of compressed air is released from the vessel in an abrupt way flowing through the pipe of a big diameter. Nozzles are also used. Matters concerning the air flow through the nozzle are described in (Xuewen and Wen, 2015). Abrupt expansion of released compressed air causes an effect of pneumatic hit.
Rules of functioning of pneumatic pulsator are presented in Figure 1.

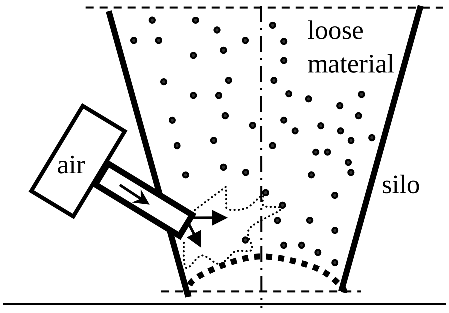

Figure 1: The principle of operation of pneumatic pulsator

2.1 Specific features of construction

Pneumatic pulsator consists of two components: pressure vessel in which compressed air is stored and a head through which compressed air is flowing. Construction of the vessel is simple. It is built in a horizontal type, consists of two boiler ends and a drum. In consideration of polish law provisions, it is subjected to the technical supervisory and it has to fulfill following condition:

$$V \cdot P > 50\ bar \cdot dm^3 \qquad (1)$$

where:
V – capacity of vessel, dm^3,
P – hypertension - a pressure limit values specified by the manufacturer or set pressure of the safety valve, bar.

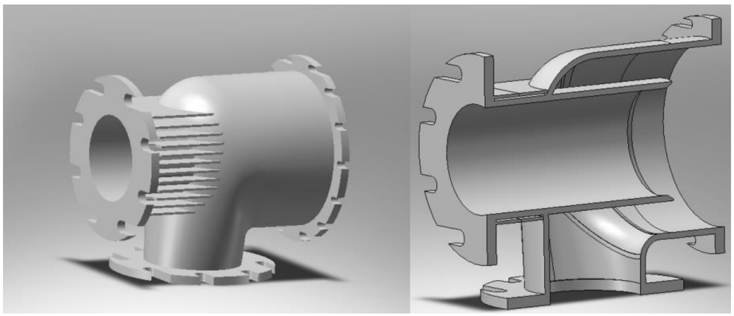

Figure 2: General view and cross-section of the head of the pulsator (own elaboration)

It is good to conduct strength calculations of the vessel with specialist software. Calculations a pressure vessel of the pneumatic pulsator was conducted with Visual Vessel Design. Construction of the head of the pneumatic pulsator is more complicated. Its general look and cross-section is presented in Figure 2. Elements, which are irrelevant for testing the heat phenomena in the ducts (e.g. piston), were omitted. It was assumed that the subject of the test in area of heat transfer in pneumatic pulsator is ducts of changeable diameter and changeable direction of airflow. In spite of well described phenomena in area of heat transfer and momentum, there are no wider studies on construction of pneumatic pulsators.

2.2 Momentum and heat transfer

Current and general knowledge of the theory of momentum and heat transfer during airflow through the duct has been described in the literature on nozzles and shock waves. Dispersal of a shock wave and determination of Mach numbers are not a problem in analytic descriptions of simple cases of flow. When considering the tests of two and three-dimensional flows, in which reflection of the wave occurs, this is a phenomenon which is not fully understood.

The subject of the theory of heat transfer in the flow is one-dimensional flows of compressible liquids, located in time, which are being transformed. Usually, it is an adiabatic process. Therefore, basic equation consisting of mathematical description of flow was completed with an equation of liquid transformation. Conservation of momentum equation, which is considered in fluid mechanics, has not been taken into account since distribution of velocity on the duct's section is not needed (average velocity is enough). Kinetic energy in two different sections is known only approximately, what is commonly accepted in practical topics. In order to determine this energy precisely, one should integrate kinetic energies of particular streams moving with local velocity.

As a result of compression, kinetic energy of the stream transforms into internal liquid energy which appears in the increase of temperature and pressure of this liquid. In high temperatures, the ingredients of the air are dissociated and, in even higher temperatures, they are ionized, so that the results obtained in assumption of ideal gas do not reflect the reality.

In ducts of the pulsator, heat is generated as a result of friction of flowing air and walls. This is why it is important to transfer the heat from the surface of the head of pneumatic pulsator to the environment. Intensification of heat may be obtained by using the fins on the surface of it. Owing to this, it is possible to multiply the stream transferring the heat which emerged in the pulsator's duct. Matters concerning the extension of the area of heat transfer have been presented in the literature by Kraus et al. (2000).

Studies on geometry of head fins of pneumatic pulsator were conducted with use of numerical simulations. In order to verify their correctness, necessary measurements on the lab stand with thermal camera were conducted.

3. Numerical determination of temperature distribution

Use of numerical methods, and in particular finite element method (FEM) is widely described in the literature. Examples of its use can be read in (Baskharone, 2014). In general, use of FEM in order to solve particular scientific or engineering task consists of two separate processes:

- Development of calculation model,
- Solution of particular task with developed model.

When one obtains the solution with particular package to the numerical simulation, it should not be the end of solving the problem. Obtained result is usually vitiated by an error. There are many possible sources of the solution error. These are the most important ones:

- Model development error (applied mathematical model does not reflect the reality), validation parameters error (adapted values of parameters of partial differential equations and boundary conditions i.e. material data, data on interaction between the object and the environment, are an error),
- Numerical error (discretisation error),
- Rounding errors (in respect of using a limited accuracy of numbers representation in the computer, the solution obtained with software does not relate to the approximate solution which would be obtained if the numbers representation was more accurate).

After obtaining the solution, the results should be verified. One should check how accurate used mathematical model reflects the reality. In case of pneumatic pulsator, mathematical model is relatively simple and numerical simulations do not pose any problems. For this purpose, advanced computer package COMSOL Multiphysics was used.

Some assumptions in numerical model were as follows:

- heat conductivity of aluminium alloy 240 W/(m K),
- ambient temperature 18 °C,

- average heat flux at the internal surface of the channel 60 W/m^2.

The thermal interaction between pneumatic pulsator and the environment can be reflected by a boundary condition expressing heat convection from the surface of the pneumatic pulsator to the ambient air:

$$-(\mathrm{k}\,\frac{\partial \mathrm{T}}{\partial \mathrm{n}}) = \mathrm{h}(\mathrm{T_{inf}} - \mathrm{T_{amb}}) \tag{2}$$

where:

h - convective heat transfer coefficient, W/m^2 K,
T_{inf} - surface temperature, K,
T_{amb} - ambient temperature, K,
$\frac{\partial T}{\partial n}$ - temperature derivative along the direction normal to isothermal surface.

Using the obtained result and inserting air viscosity and thermal conductivity at 18 °C into the above equation, the approximate value of the heat transfer coefficient at the outer surface of the pneumatic pulsator was calculated as 40 W/(m^2 K).

Temperature distribution determined with this software was presented in Figure 3. Verification of the results was carried out on the lab stand with a thermal camera.

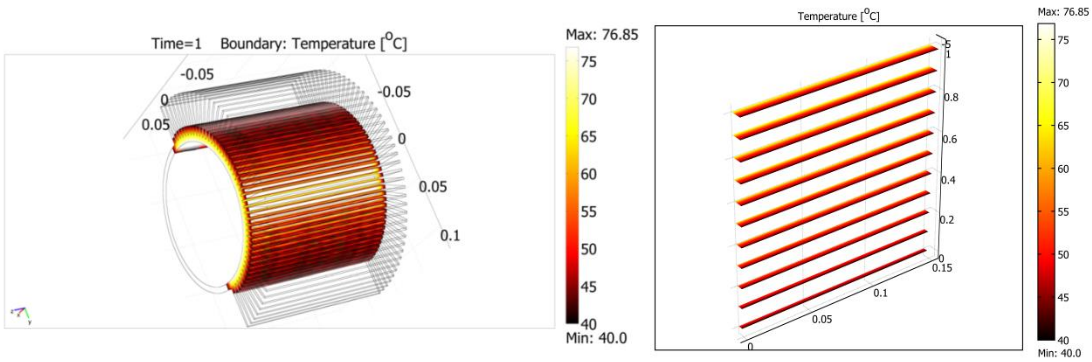

Figure 3: The temperature distribution of the fins determined with the use of COMSOL Multiphysics

4. Thermal test of heat transfer

Thermal imaging is a touch-free diagnostic method based on the observations of infrared radiation emitted by every body of the temperature higher than absolute zero and on the transfer of this radiation into image, visible light. In other words, this testing method consists in visualization, registration and interpretation of temperature distribution on the surface of tested objects. Thermal tests are possible to be used in places, where the temperature of the surface can be measured. However, interpretation of thermograms is a difficult and complex task. It is not only recognition of the objects but also concluding about current heat phenomena and features related to them. The temperature in particular point of object's surface may be a result of many different factors which have to be understood and considered during the interpretation (Abdulshahed et al., 2015). When conducting thermal tests, one should take into consideration the fact that infrared radiation occurs in particular environment and in order to carry out a precise measurement of temperature distribution, it is necessary to compensate the influence of various disturbing external factors for appropriate parameters:

- Humidity,
- Virtual temperature,
- Distance between the object and the camera,
- Environment temperature,
- Emission coefficient.

The most important parameter is an emission coefficient. For the surface of pneumatic pulsator's head covered with paint, it was assumed that its value amounts to 0.95. An aluminium head of pneumatic pulsator was subjected to the heat stream flowing from the duct axis which caused the temperature of 65 °C on internal walls of the duct. Thermogram of finned head obtained with use of the camera FLIR SC7000 was presented in Figure 4.

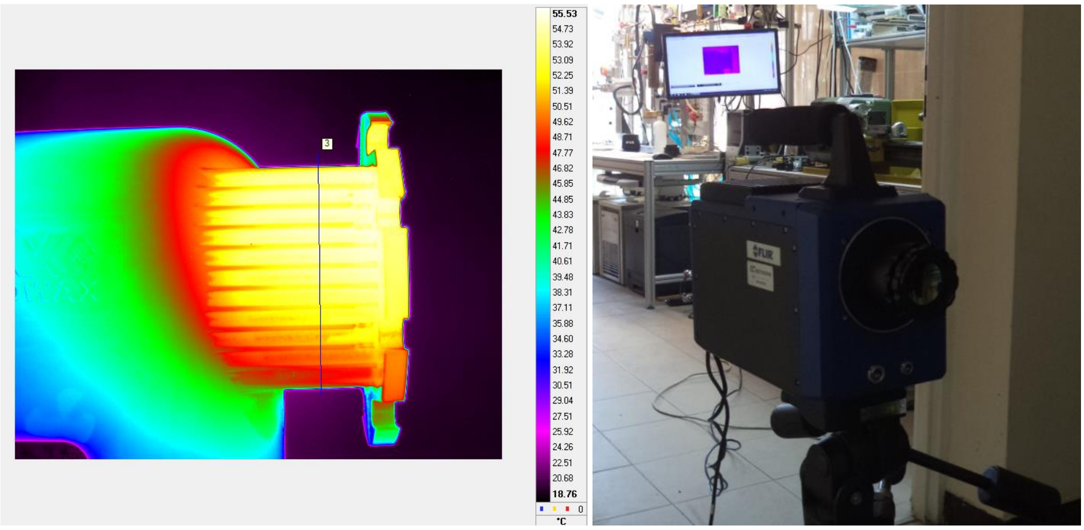

Figure 4: Thermogram of the finned head of the pneumatic pulsator

Temperature values obtained in particular points may be easily imported to present them in the arrangement: width in pixel - temperature. Temperature distribution on the surface of finned head of pneumatic pulsator was presented in Figure 5.

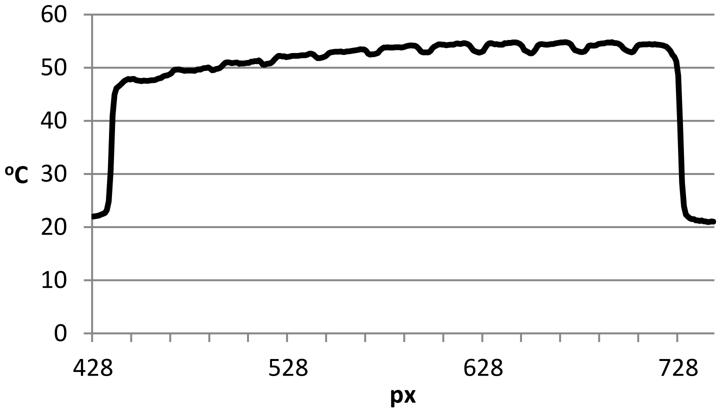

Figure 5: The temperature distribution along the surface of the head

5. Conclusions

The analysis concerned the temperature distribution on external surface of the head of pneumatic pulsator. The tests were conducted in ambient temperature of 20 °C and temperature of internal walls of the duct of 65 °C. The tests were carried out in two stages. Firstly, 3D model of finned head of pneumatic pulsator was developed which was the basis for numerical simulations conducted with use of software package - COMSOL Multiphysics. Then the temperature distribution was determined. Owing to the fact that numerical methods give approximate results, it was necessary to verify them. In order to do this, heat measurements were performed on real head in the lab stand. Generated thermograms confirmed the temperature values which were similar to those obtained from numerical simulations. It may be assumed that numerical models were developed correctly. With use of thermal camera, it is easy to verify the numerical models for testing heat transfer of the head of pneumatic pulsator with straight fins. Thus, the use of thermography significantly improves the design process. Further tests are related to different types of fins' construction i.e. trapezoidal and round fins.

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