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Experimental investigation of the influence of an orifice plate on the pressure pulsation amplitude in the pulsating flow in a straight pipe

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A B S T R A C T

This paper presents the results of experimental study on the influence of an orifice plate on the levels of pressure pulsation downstream, in the conditions of pulsating flow in the object of research (a straight pipe). The impact of an orifice plate on the pressure pulsation levels was quantified. A decrease in the pressure pulsation level with a decrease in the cross-sectional area of an orifice plate (therefore, a decrease of its aperture ratio - β coefficient) was observed, indicating the usability of this element of piping systems to attenuate pressure pulsations. Experimental data were analysed using a dynamic model of the pipe in software developed in the MATLAB programming environment. The experimental results also indicated the values of the resonant frequencies of the pipe. These were subject to cross-check against a theoretical one-dimensional acoustic model, which may be used to define the natural frequencies of such pipes. According to this model disturbances in working fluid travel at the speed of sound. Compliance of the results of the experiment with the model authenticated the outcomes of the experiment. Moreover, it confirmed that the application of a one-dimensional acoustic model to estimate the resonant frequencies of a straight pipe is a reasonable approach.

1. Introduction

Piping systems for fluid transportation are components of industrial process plants in power, chemical, petrochemical, as well as in oil & gas extraction, processing and other industries [1].

One of the phenomena, which may be particularly troublesome for maintenance of such systems, is excessive pressure pulsation present in an oscillatory flow regime characterised by oscillations (pulsations) of fluid parameters about a mean value. Such a regime may be referred to as pulsating flow. It may be present due to oscillations caused by the fluid machinery and/or the geometry of a piping system [2–6]. In specific conditions, it may result in an acoustic resonance (described in Section 6.2), manifested by the formation of standing acoustic waves [7,9]. It results in higher pressure pulsations, which

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may endanger the integrity of piping systems, cause their energy inefficiency or their harmfulness to the environment (more details in Section 2).

Orifice plates are elements of a piping system, which are mounted locally to reduce the effective flow cross-sectional area of a pipe. They are usually applied to measure the rate of the flow or to restrict the flow.

Extensive research on their parameters, such as resistance coefficient K, flow coefficient Cv and discharge coefficient Cd, in steady-state conditions, has been conducted up to date. Results may be found in, for example, Crane Technical Paper [8].

Pulsating flows can also cause significant mechanical vibrations and, in the case of orifice plates, flow measurements errors [9]. Therefore, characteristics of orifice plates in this flow regime were also investigated.

Some notable studies (only certain examples are enumerated in this paper) concentrated on the accuracy of flow measurements with orifice plates in pulsating flows. These are described, for example, in the works by Gajan et al. [10], Mottram [11–13], Mohammad and Mottram [14], Reis and Hanriot [15], Stannikov and Fedorov [16], Jungowski and Weiss [17], McKee [18]. There are also ISO international standards discussing the errors in measurements of fluid flow (due to the presence of pressure pulsation) by pressure differential devices [19,20]. Therefore, these aspects have been covered in detail.

Other studies, for example by Addison et al. [21], investigated pulsed vortex flow in conduits with orifice plates. Moreover, extensive research on pressure wave transmission through various pipeline elements, including orifice plates, was also conducted and described in details by Jungowski and Botros in 1970s and 1980s, for example in [9,22,23]. Finally, in some recent studies, Cyklis and Mlynarczyk discussed the usefulness of nozzles as pressure pulsation damping devices [24–26].

In case of excessive pressure pulsation, efforts should always be undertaken to eliminate them at the source of the problem, for example in the cylinder of a reciprocating compressor or its proximity. If this approach fails, other ways could be applied – for example, changing the acoustic characteristic of a piping system. However, it may not always be possible. Furthermore, there may be emergency situations, when the parameters of the flow are suddenly distorted by external phenomena or are changed by the operator of the system.

Consequently, introducing additional pressure pulsation damping devices, for example orifice plates, may provide a quick solution to the problem. However, they should be applied as a last resort, as their application usually results in increasing the cost of construction and maintenance (even though it could be perceived as the fastest and easiest way). In this case process equipment characterised by a higher power is required, to cover the additional static pressure losses [8,27,28] in the piping installation.

Consequently, it was considered purposeful by the authors to try to quantify the effects of orifice plates on pressure pulsation drop in pulsating flow regimes. The aim was to define a single relationship between the aperture ratio (β coefficient, definition in Section 3 - both notions are used interchangeably in the paper) of the orifice plates and pressure pulsation drop, focusing on a practical engineering perspective (motivation provided, in more details, in Section 2).

Therefore, the first aim of the study was to investigate the influence of an orifice plate installed at the inlet of a straight pipe on the level of pressure pulsation in the downstream pipe, under the conditions of pulsating flow in this pipe (flow induced by a Pulsation Generator, PG).

The second aim was to assess the correctness of the usage of the one-dimensional acoustic model of pulsating flow in the estimation of the acoustic resonance frequencies in a piping system [4,29,30].

The structure of the paper is as follows. Section 2 offers more information on the harmful effects of pressure pulsation of the piping systems. Section 3 describes the object of research (a straight pipe) and the fluid (compressed air) transportation system. Section 4 presents the measurements' methodology and the test rig used in the experiment. Section 5 covers the conditions and plan of the measurements, which consisted of five series in the range of induction frequencies from 20 Hz to 180 Hz. Section 6 offers background information regarding the one-dimensional acoustic model, resonance phenomenon and calculation of natural frequencies of a straight pipe. Moreover, this section introduces the concept of the dynamic model of a straight pipe with a closed end boundary condition [4]. Implementation of this model enabled the quantification of the influence of orifice plates on the pressure pulsation levels. Section 7 provides a brief description of the data analysis methods implemented. A script and GUI software in the MATLAB programming environment were developed to post-process the measurements' data. They are described in detail in [31] and [32]. The workflow in the software involved data quality check and its sorting, which were followed by FFT and harmonic analysis. In Section 8 experimental results are presented in the form of amplitude-frequency and phase-frequency characteristics of the investigated pipe (in which frequency of the source of pulsation/I harmonic of the response of the system is the independent variable). Finally, the conclusions from the research are outlined in Section 9.

2. Detrimental effects of pulsating flow

Pressure pulsations in pulsating flow may endanger the integrity of a piping installation by exceeding the design pressure of such a system, causing leakage from the flanged joints of the pipes, resulting in subsequent depressurisation [2,31,32].

Moreover, excessive pressure pulsation may be a source of dynamic forces, which result from an unbalanced pressure layout (more information in Section 6.2). These dynamics forces may induce dangerous mechanical vibrations of the pipes, as well as vibrations of its primary and secondary supports. It happens when the eigenvalues and eigenmodes of a mechanical structure are the same or close to the frequency of the dynamic forces arising from pressure pulsations. In these circumstances, forced mechanical resonance of the construction is likely to occur [2,6,32–36].