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Experimental and numerical study of a choke valve in a turbulent flow ☆

M. Huovinen [a,*], J. Kolehmainen [b,**], P. Koponen [a], T. Nissilä [a], P. Saarenrinne [b]

[a] VTT Technical Research Centre of Finland Ltd, Centre for Metrology MIKES, Tehdaskatu 15, Puristamo 9P19, 87100 Kajaani, Finland
[b] Tampere University of Technology, Korkeakoulunkatu 6, 33720 Tampere, Finland

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ABSTRACT

This study investigates a flow past a choke valve by experimental and numerical means. The flow profile after a choke valve with high Reynolds number of approximately 1,000,000 was measured using a LDV and computed using RANS simulations. Two turbulence models were used for the simulation, namely k–ε and k–ω turbulence models. It was found out that the k–ω model produces more similar results to LDV measurements than the k–ε model. This study also reports citable flow profiles past a choke valve computed by both turbulence models.

Furthermore, the accuracy of the LDV based volume flow measurements was also discussed. The volume flow estimates were compared with simulation results, and with flow meter results. Results showed that LDV can be used for volume flow estimation even in unsymmetrical situations, such as after the choke valve, with error ranging from 0.3% to 2.6%.

1. Introduction

Butterfly type choke valves are used extensively in industry to adjust volume flow from a pump. The ability of choke valves to limit the flow through it is based on creating an additional pressure loss over the valve that in turn decreases the flow velocity and flow rate.

This pressure loss in itself is dependent on the flow characteristics, and causes disturbances in the piping system after the valve. If choke valve is used in a flow meter calibration system, the calibration point should be chosen adequately far away from the choke valve to avoid unintended disturbances that might affect the flow meter under calibration.

Currently, there is a little prior research done in the literature about the butterfly choke valve disturbances regardless of their wide range of applications. For instance, in the article [1] the downstream disturbance effects on the flow through a poppet valve were discussed.

The hydrodynamic torque characteristics and cavitation of butterfly type valves have been relatively widely studied with respect to turbulent disturbances. In the article [2] the hydrodynamic force caused by the bypassing flow on a butterfly valve was measured by an electric motor. However, the article did not connect the torque with underlying flow structures.

The earliest studies related to butterfly valves were on the cavitation phenomena. Cavitation phenomena in a butterfly valve have been studied in articles [3,4]. Since both studies were conducted prior to invention of LDV or high speed camera technology, they were solely based on pressure sensors and analytical reasoning, and did not present information on the velocity profile or turbulence associated with the flow past the butterfly valve.

The pressure field across the valve plate was also studied in a compressible flow in the article [5]. The study conducted series of experiments on small model butterfly valves to find stagnation properties and pressure on the butterfly valve.

The earlier simulations related to butterfly valves were done using Euler equations for compressible flow. An example of such study is given in [6]. The study computed three-dimensional flow field on the surface of the butterfly valve, but did not discuss the flow profile across the whole valve.

Two dimensional incompressible flow past a butterfly valve was simulated in the article [7]. The study solved the time averaged velocity profile after the valve, but did not discuss the three-dimensional structure of the flow. A later study [8] used Fluent software to compute three dimensional incompressible flow past the butterfly valve with low Reynolds number (the bulk Reynolds

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* Principal Corresponding author.
** Corresponding author.
E-mail addresses: mika.huovinen@vtt.fi (M. Huovinen), kolehma8@gmail.com (J. Kolehmainen), petri.koponen@vtt.fi (P. Koponen), timo.nissila@vtt.fi (T. Nissilä), pentti.saarenrinne@tut.fi (P. Saarenrinne).

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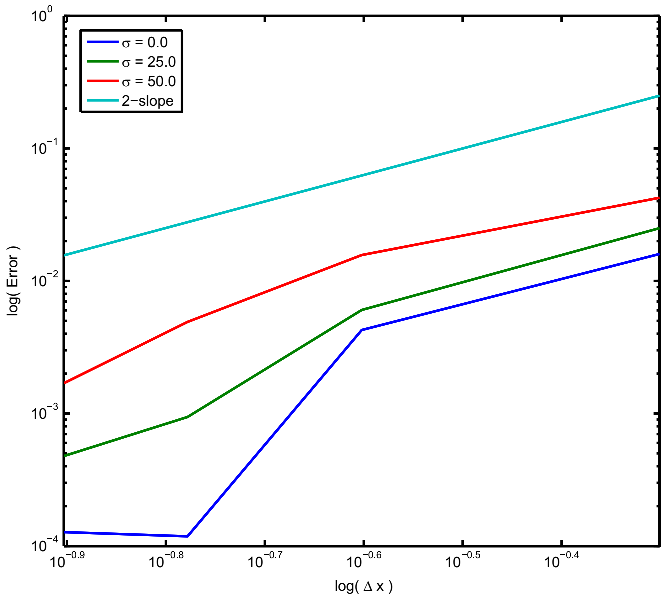

Fig. 1. Figure showing log–log plot of error with respect to different measurement point densities. The 2-slope corresponding $O(\Delta x^2)$ is also shown for reference.

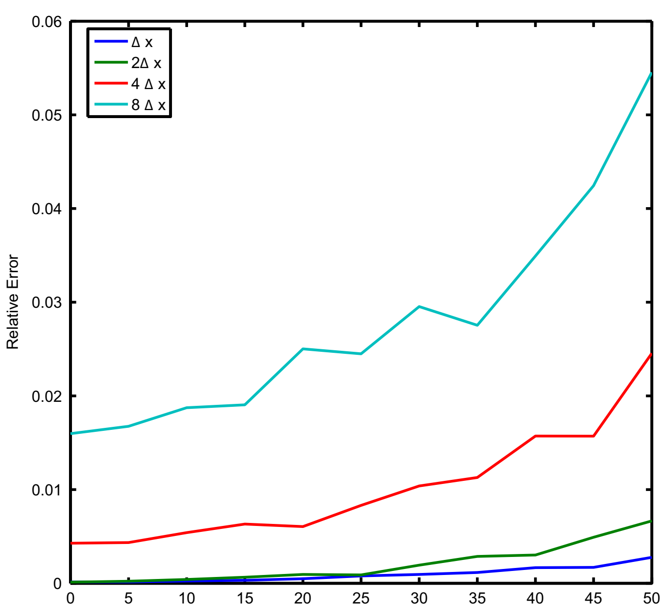

Fig. 2. Figure showing relative error with different values of σ. The larger the σ value, the less smooth and symmetrical the velocity profile becomes.

number was around 25,000) using the k–ε turbulence model.

A typical problem associated to LDV measurements in calibration use is the determination of the mean volume flow rate. If the flow field is symmetric, then the problem becomes relatively simple, and one LDV measurement line along the radius is sufficient to determine the mean volume flow rate.

In the asymmetric case the problem becomes slightly more complex. Methods known in the literature can be roughly categorized as velocity-area methods and multi-point methods [9]. Velocity area methods are based on dividing the pipe cross section into distinct annulus. Measured velocity values are weighted at each annulus and the weighted velocity is multiplied by the annulus area to obtain volume flow rate. The uncertainty of velocity-area methods increases with increasing flow asymmetry [9], and hence is best suited to nearly symmetric flows.

Multi-point methods are based on the known velocity profile. Their advantage is that if the velocity profile is satisfied they only need a few measurement points to obtain an accurate flow rate estimate [9]. However, these methods make strong assumptions on the flow profile and are not generally applicable.

More general methods use direct integration by polynomial splines or other functions to obtain the volume flow rate [10]. These methods may be based on radial integration, in which case they are only applicable to symmetric flows, or across the pipe cross section.

2. Volume flow estimation

2.1. Estimation methods

Mean volume flow over a pipe cross section can be estimated from pointwise LDV measurements when the relative positions of the measurement points are known. The approach presented next is intended for sparse nonuniform velocity measurements.

Let x_i, y_i, v_i denote relative coordinates and mean velocity obtained at the i:th measurement point. The mean volume flow can be obtained from a flux integral

$$\dot{V} = \int_A v \cdot \mathrm{d}A, \tag{1}$$

where A denotes the cross sectional surface, v denotes velocity, and $\cdot$ denotes inner product.

If in Eq. (1) the velocity and surface are orthogonal the inner product simplifies to a simple product. In case of LDV, this is satisfied if the intersection plane of the double beam LDV is parallel to pipe cross section.

Since most pipes are round, further discussion will be presented in polar coordinates. Integrating Eq. (1) in polar coordinates with radial spacing Δr and angular spacing $\Delta\theta$, the integral

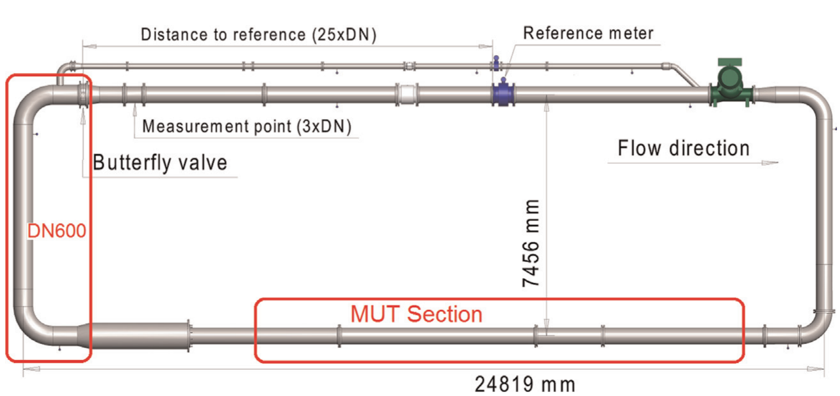

Fig. 3. Figure showing D500 calibration rig.