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Simulation-based determination of systematic errors of flow meters due to uncertain inflow conditions

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ABSTRACT

Computational fluid dynamics (CFD) provides well-established tools for the prediction of the velocity profiles in turbulent pipe flows. As far as industrial pipe and district heating systems are concerned, combinations of elbows are the most common pipe assemblies. Among the different pipe combinations, double elbows out-of-plane are of special interest, since they introduce strong disturbances into the flow profile and have a strong influence on many common types of flow meters. In front of a double elbow there is often another flow-disturbing installation. As a result the upstream conditions are unknown and an investigation of the resulting systematic bias on the measurement of the flow rate and the associated contribution to its measurement uncertainty is necessary. We demonstrate here that this can be achieved by a variation of the inlet profile in terms of swirls and asymmetry components. In particular, an ultrasonic and an electromagnetic flow meter are modeled in order to quantify the systematic errors stemming from uncertain inflow conditions. For this purpose, a generalized non-intrusive polynomial chaos method has been used in conjunction with a commercial CFD code. As the most influential parameters on the measured volume flow, the distance between the double elbow and the flow meter as well as the orientation of the flow meter are considered as random variables in the polynomial chaos approach. This approach allowed us to obtain accurate prediction of the systematic error for the ultrasonic and electromagnetic meter as functions of the distance to the double elbow. The resulting bias in the flow rate has been found to be in the range of 1.5–4.5% (0.1–0.5%) with a systematic uncertainty contribution of 2–2.4% (0.6–0.7%) for the ultrasonic (electromagnetic) flow meter if the distance to the double elbow is smaller than 40 pipe diameters. Moreover, it is demonstrated that placing the flow meters in a Venturi constriction leads to substantial decrease of the bias and the contribution to the measurement uncertainty stemming from the uncertain inflow condition.

1. Introduction

Elbow alignments are necessary in almost all pipe assemblies in industrial fields, especially district heating systems. They introduce disturbance to the flow profiles that require a straight pipe length of several diameters to be eliminated. Very often those parts are not sufficiently long to redevelop an ideal profile. Thus, flow rate measurements in ideal flow conditions are not available. It is well known that many flow meters react sensitively to disturbed flow profiles, as they are usually calibrated in ideal conditions at test rigs. To determine these errors an in situ calibration technique with Laser Doppler Velocimetry (LDV), was developed by Müller et al. [31]. The induced errors for large heat meters tested in district heating pipelines are typically higher than 3% and could reach more than 20%, see [14]. In cooperation with TU Berlin, PTB Berlin, ILA GmbH and Optolution Messtechnik GmbH the project "EnEff: Wärme: on-site calibration of flow meters in district heating" [11] was initiated. The idea is to develop a method which permits on-site calibration of installed flow meters in non-ideal installation conditions. A combination of LDV measurements and numerical simulations is desired to predict the flow rate even under problematic inflow conditions.

With a detailed description of the disturbed flow profiles, errors of flow meters can be predicted. Several research activities have taken place to measure flow profiles behind various disturbing pipe installations. Flow profiles following different standard flow disturbers have been studied with particle image velocimetry (PIV) by Eichler [8] and with LDV by Wendt et al. [42]. Yeh and Mattingly performed studies with LDV of the flow profiles downstream of single and double elbows as well as a generic header, tube bundles and t-junctions and showed the effect on the error shifts of turbine and orifice meters [27,28,50–52]. The

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generic header and the double elbows out-of-plane have been detected to produce the highest errors that only slowly subside after several tenths or even more than 100 diameters of straight pipe. Also Wendt et al. and Mickan et al. [30,43] determined error shifts behind single and double elbows out-of-plane for turbine gas meters. Ultrasonic flow meters have been studied experimentally in [5,22,39] and Electromagnetic flow meters in [4,15,19,35]. Depending on the disturbing geometry, the number and arrangement of the ultrasonic paths several percentages of error were determined. Modeled ultrasonic and electromagnetic flow meters were studied by Halttunen [10], where the LDV data of [22] after single and double elbows out-of-plane were used. The double elbows out-of-plane showed the highest errors up to almost 10% for the ultrasonic and about 2.5% for the electromagnetic flow meter.

Due to the cost involved in experimental measurements, they are typically carried out for a few special cases. Numerical simulations are an alternative tool to get an inside into the behavior of the three dimensional flow field. Consequently, ultrasonic flow meters can be modeled by computational fluid dynamics (CFD). For this purpose Eddy viscosity Reynolds-averaged Navier–Stokes (RANS) method are shown to be sufficient, see [17,18]. Tawackolian [39] found out that for ultrasonic meters with several wetted transducers in huge cavities scale resolving transient simulations are necessary.

As the aim of error studies is mostly to correct the flow meter reading, there have been several investigations to improve the measurement values especially for ultrasonic flow meters (USFM). Ruppel [32] developed an error correction procedure based on pressure probes in the flange of the meter to measure the wall shear stress; Yeh et al. [50] proposed a procedure with several ultrasonic paths and flow pattern recognition. Carlander [6] drew a conclusion about self-diagnostics due to the turbulence of the measurement value. There are also two patents [2,10] which claim to have a correction procedure for USFM depending on the distance of the last upstream disturbing installation.

However, all these studies assumed an ideal flow profile before the disturbing geometry. Industrial applications are characterized by high Reynolds numbers. The distance between elbows is typically not sufficiently long to redevelop such an ideal profile. Even if this were so, the flow meter could be installed in front of the elbow. Thus a realistic uncertainty study for flow meter correction must include several elbow combinations. For example, Knˇourek [23] simulated several t-junctions and elbows connected behind each other. Usually not every possible elbow configuration can be considered.

To approach the problem in a more general way, in this paper a double elbow out-of-plane is studied with uncertain inflow conditions with CFD, at a Reynolds number of $3\cdot10^5$. An uncertainty quantification is carried out by combining two double elbows at random distance and orientation to each other. The statistical quantities for the velocity profiles were calculated by employing the method of polynomial chaos, see Section 2. With this approach, the sensitivity of flow measurements behind a double elbow to uncertain inflow conditions can be quantified and a more general study of flow meters will be presented. Ultrasonic and electromagnetic flow meters are chosen as examples, as they are widely used and their measurement principles are non-intrusive. Moreover, it is shown that a constriction right before the flow meter is to straighten the velocity profile and improves the meter performance considerably. Different shapes of such converging nozzles could be designed to optimize flow conditioning or minimize pressure loss. In this work, two representative designs are studied and proposed: a Venturi nozzle and a rectangular constriction.

The paper is organized as follows: Section 2 briefly describes the concept of uncertainty quantification with polynomial chaos. This approach is applied to a double elbow out-of-plane to study its sensitivity to uncertain inflow conditions. Expected profiles with standard deviations were calculated and compared with measurement results in Section 3. In Sections 4 and 5, these profiles were used to study the error for ultrasonic and electromagnetic flow meters, respectively uncertainties for random angular and axial alignment were calculated. The results were also compared to measurements. Furthermore, expected errors and standard deviations for disturbed inflow profiles to a Venturi nozzle and a rectangular constriction are presented in Section 6. Section 7 provides a summary of the main results and conclusions.

2. Concept of uncertainty quantification

A common approach in uncertainty quantification is to use a Monte-Carlo type method. Uses of Monte Carlo methods require large amounts of solutions of the deterministic problem. This becomes an issue when the system is nonlinear and the solution is computationally expensive to obtain such as for problems arising in CFD.

Here, an alternative approach is shortly introduced which is referred to as “polynomial chaos” or sometimes also as “Wiener” or “Wiener–Hermite chaos” in the literature [44]. The idea of the method is to expand random variables with finite second moment in a series of orthogonal polynomials. The method is applicable to a wide range of problems, where the influence of uncertainties within process conditions or variations of material parameters needs to be quantified. In general, the polynomial chaos methods are classified into two approaches: the so-called intrusive methods as well as the non-intrusive ones, see, e.g., [48]. Especially the non-intrusive, sampling based version of polynomial chaos plays an important role when dealing with uncertainties in the context of nonlinear and computationally expensive systems, see [20,25,26,49]. The advantage of the non-intrusive approach is that an existing solver for the underlying deterministic problem can be used as a “black box” without modification. For a more elaborated introduction we refer to [24].

For the introduction of this concept of uncertainty quantification, a physical system

$$\mathcal{L}(x, \xi, g(x, \xi)) = 0,$$

like the incompressible Navier–Stokes equations (4), is considered. Here g denotes some quantity of interest, for example, the velocity field u in Section 3.2 or the volume flow rate in Section 4. Due to uncertain initial or boundary conditions, material parameters, etc., some randomness is introduced in the system. This is modeled by a vector of random parameters $\xi = (\xi_i)_{i=1}^{m}$ with joined probability density function $p = \prod_{i=1}^{m} p_i$. The idea of the gPC method is to expand random variables with a finite second moment in a series of orthogonal polynomials, i.e.,

$$g(\xi) = \sum_{i=0}^{\infty} \hat{g}_i \Psi_i(\xi), \tag{1}$$

where $(\Psi_i)_{i=0}^{\infty}$ is a family of orthonormal polynomials with respect to the weighted inner product

$$\left\langle \Psi_i, \Psi_j \right\rangle_w := \int_{\mathbb{R}^m} \Psi_i(s)\Psi_j(s)w(s)ds,$$

with weight function w. The family of the orthogonal polynomials and the probability density function of ξ_i, $i = 1, \ldots, m$, is connected by the Askey scheme, see [8] and Table 1. In this paper, we only deal with uniformly distributed random variables and therefore