XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

DEVELOPMENT OF PHOTONIC VORTEX FLOW METER FOR FLOW RATE MEASUREMENTS AT HIGH TEMPERATURES AND PRESSURES

Henrik Krisch[1], *Ali Gedikli*[2], *Ernst von Lavante*[3] *and Pouya Mirzaei*[1,3]

[1] KROHNE Messtechnik GmbH, Dept. Development Sensors, Duisburg, Germany, h.krisch@krohne.com
[2] KROHNE Innovation GmbH, Dept. Development Sensors, Duisburg, Germany, a.gedikli@krohne.com
[3] Faculty of Engineering Sciences, University of Duisburg-Essen, Duisburg, Germany, ernst3.vonlavante@uni-due.de

Abstract–The present publication describes a new design of a flow meter for metering fluids using fiber sensing methods. Mach-Zehnder interferometer was implemented for the detection of the vortices. The signal generation is based on the frequency detection of a vibrating diaphragm placed in a specially optimized measuring chamber. The stress of the vibrating diaphragm is sensed using a Mach-Zehnder (MZ) fiber interferometer, with fiber arms fixed to the diaphragm. This solution allows measuring flow rates of liquids, gases and vapors with temperatures up to +700°C and pressures up to 300 bar. Excellent linearity was achieved by numerical flow simulations of the entire meter. The pressure chamber was optimized to minimize the amount of air trapped in it.

Keywords: flow measurement, fibre optic sensors, fiber interferometer, pressure and stress sensors, vibrations, membrane, diaphragm, vortex flowmeter.

1. INTRODUCTION

In principle, the vortex-shedding flow meters use the separation frequency of vortices behind a bluff body to measure the mean flow velocity of a fluid flow. Downstream of the bluff body, von Karman vortex street develops; its width D and distance T between the vortices depend on this frequency, and therefore on the bluff body's shape. Preferably, the vortex-shedding frequency should depend linearly on the mean flow velocity for a wide Reynolds number range. The dependency of the vortex frequency f, the mean flow (bulk) velocity um and the width of the bluff body D is expressed by the dimensionless Strouhal number Sr, $Sr = (D\times f)/um$, or the dimensional K-factor, $K=f/Q$, with Q being the volumetric flow.

The corresponding flow fields have been studied by, among others, Reik et al. [1] using experimental approach, Younis and Przulji [2] by computing the corresponding turbulent flow field and von Lavante et al. [3] applying a combination of numerical simulations and global experiments for validation. The signal detection and processing have been discussed by, among many contributions, Igarshi [4], Takamoto et al. [5] and Venugopal et al. [6]. A detailed study of the flow field in small size commercial vortex-shedding flow meters with inflow and outflow conditioned by a Venturi nozzle and a diffusor has been published by von Lavante et al. in [7]. More recently, Miau et al. [8] and Yang et al. [9] studied the effect of upstream disturbances on the accuracy of various VFMs, and Gedikli [10] who extended the investigations to include different installations of bluff bodies for several bluff body shapes.

In the classical design of the KROHNE vortex flow meter (Optiswirl 4700), as seen in Figure 1 [12], a paddle is used as a sensor, containing piezoelectric elements. When flow passes about the bluff body a von Karman vortex street develops and the paddle surface underlies a periodic pressure change. The piezoelectric elements transform the mechanical movement of the paddle in electrical signal which can be evaluated in a signal processing unit. Such a sensor construction is restricted to medium temperatures under 240° C due to the utilization of the piezo-electric elements. In order to achieve an accurate measurement at temperatures as high as 700° C, a new concept of the detection of the vortex shedding frequencies in the vortex flow meter has been developed. Here, instead of using a paddle which is positioned behind the bluff body, the periodic change of pressure is detected by introducing two circular holes that are positioned in the side wall at an appropriate location close to the bluff body and serving as a conduit transmitting pressure variations to a pressure chamber. The periodically changing pressure acts on the diaphragm in this chamber, deflecting them. The movement of the membrane, being in order of magnitude of nm, is finally detected by an optical system. Here, the stretching of an optical fiber is translated via Mach-Zender configuration into opto-electrical signal in a processing unit placed far away from the high temperature parts of the meter. The entire setup can be seen in Fig. 1.

The new system worked very well when liquids were metered. However, in the case of liquids being the metered fluid, in some cases an increase of nonlinearity of the signal frequency was noticed. Subsequent experimental investigations revealed that the increased nonlinearity was caused by the pressure chamber not completely filled with the metered liquid, displaying large air bubbles. Several attempts to improve the filling of the chamber by changing its shape were met with only partial success. It was, therefore, decided to carry out a numerical simulation of the process of the pressure chamber being filled by liquid. In parallel effort, the corresponding modifications of the chamber shape were studied experimentally.

Fig.1 Current Krohne vortex flow meters.

2. CONCEPT OF VORTEX FLOW METER

In the photonic detection of the vortex shedding frequencies a diaphragm is often used as a transducer to measure dynamic pressure differences acting on its surface. The pressure waves are conducted to its surface via properly designed conduits leading from an optimized location in the measuring section, [13]. The resulting strain and elongation induced by the deflection of the diaphragm can be detected by a variety of strain gauge sensors. The use of silica optic fiber based interferometric sensor permits operation at high temperatures, offers high sensitivity, and wide dynamic range [14]. A vibrating circular flat diaphragm or membrane is described by a well-known partial differential equation and can be solved numerically by means of finite element methods.

Applying interferometric principles, the fibre elongation is converted into a phase modulation of a carrier wave transmitted through the optical fibre [15]. The modulation frequency is connected to the vortex frequency and therewith to the volume flow through the pipe.

Fig.3 displays a cross section of sandwich-type photonic vortex flow meter DN25, consisting of a bluff body inside a measuring section, a pressure chamber placed on the top of the bluff body and a diaphragm located vertically in the middle of the pressure chamber.

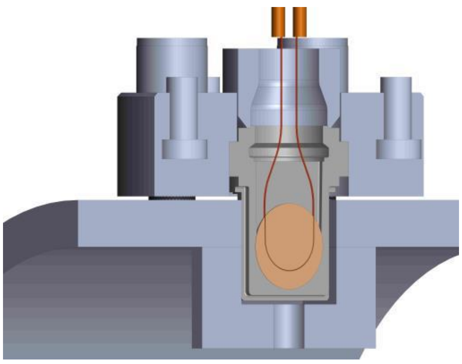

Fig. 2. View of the membrane and fiber optic location

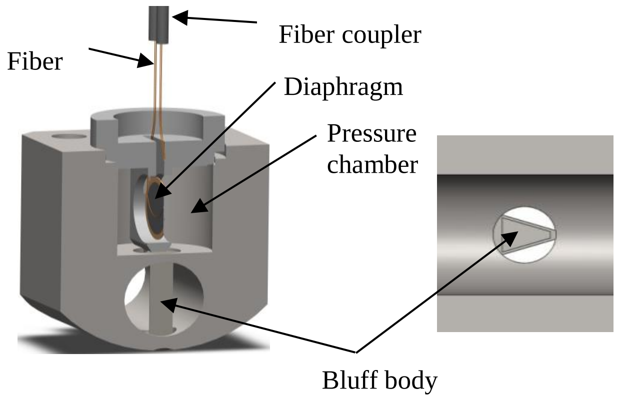

Fig.3 Cross section of the photonic vortex flow meter

The typical magnitude of the diaphragm deformations is in the range of few nm. The required properties at this extremely small deformation included dynamic pressure measurements from 60Pa up to 100kPa, range of pressure frequencies from 1Hz up to 5kHz, high operating temperatures (up to +700 °C) and high pressures up 300 bar, with harsh environment conditions (e.g.: measuring flow of aggressive mediums). These represent extremely challenging conditions dictating a novel solution, leading to the proposed photonic sensing system.

3. EXPERIMENTAL INVESTIGATION

The previous investigations of the present authors carried out to possibly minimize the effects of air bubbles in the pressure chamber led to an optimized shape of the chamber as well as its location. This led to a further improvement of the linearity of the k-factor.

The new shape has been investigated experimentally, proving the optimization approach. The results showed that the mean value of the k-factor, for all Reynolds numbers over 20000 were in the case of one phase calibration (only water) always less than the values with two phases (with existence of air bubbles).

The deviation of these values has been calculated as below:

$$\text{Two phases: } \mathrm{k-factor}_{mean} = 84057$$
$$\text{One phase: } \mathrm{k-factor}_{mean} = 82573$$

$$\text{Deviation of } \mathrm{k-factor}_{mean}: \frac{84057-82573}{82573} \times 100 = 1.79\%$$

In the experimental approach, a modified photonic sensor vortex-shedding flow meter manufactured at Krohne Messtechnik GmbH was subjected to investigation in its modified testing facility. The fluid being metered was water at pressures up to 3bar; the measuring section of the meter was DN25. In all cases, the piping could be considered hydraulically smooth. Each configuration was studied at bulk velocities of approximately 1.0, 3.0 and 5.0 m/s. The corresponding Reynolds numbers Re_D were between 15000 and 75000. The facility was using signals from the reference meter (MID).

In Fig. 4, the K-factor of a VFM with the pressure chamber completely filled with water is presented. Clearly, for the Reynolds numbers significant for the meters operating in the required range the linearity is very good, with the typical increase of the K-factor at low velocities.

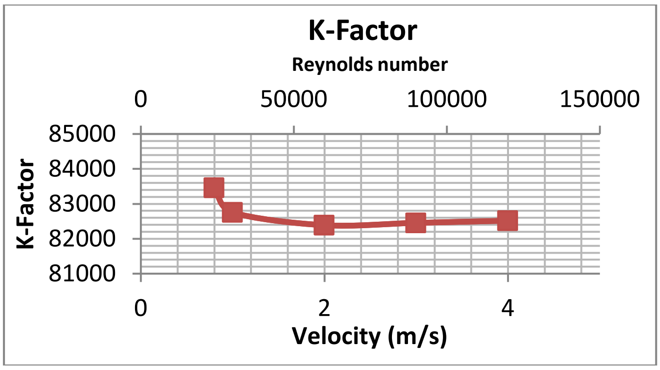

Fig. 4 K-factor for VFM DN25 with two phases; water and air

When the cavity inside the pressure chamber was at least partially filled with air that could not be bled, however, the linearity deteriorated significantly, and the K-factor displayed a variation shown in Fig. 5.

The flat design tended to contain a much smaller amount of air than the cavity design, but still there was at times no complete removal of air when the chamber was oriented upright in vertical direction. When the chamber was oriented horizontally or pointed downward, the chamber was completely filled with water.

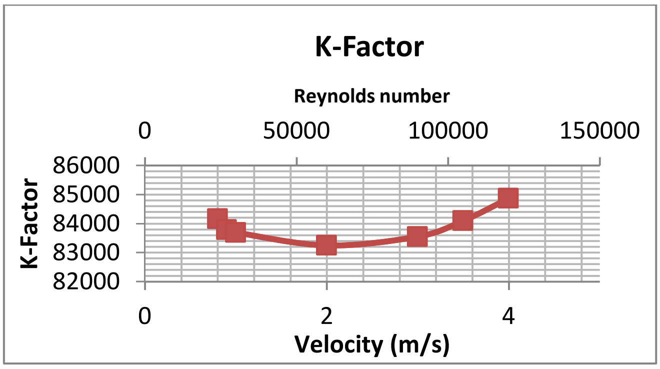

Fig. 5 K-factor for VFM DN25 filled with one phases; water

4. NUMERICAL INVESTIGATION

Following our experimental investigations, it was decided to carry out further numerical simulations to answer some of the questions raised by the experiments.

The numerical work was carried out for the same geometric configuration for two different physical conditions: one which consisted of water and one with two phases, with water and air inside of the chamber at the starting point of the simulation. The simulations were repeated for two flow velocities of 3 m/s and 5 m/s. For both velocities, some air in the pressure chamber.

The results indicated that the frequencies in the case with air bubbles were higher than without, being in agreement with the experiment.

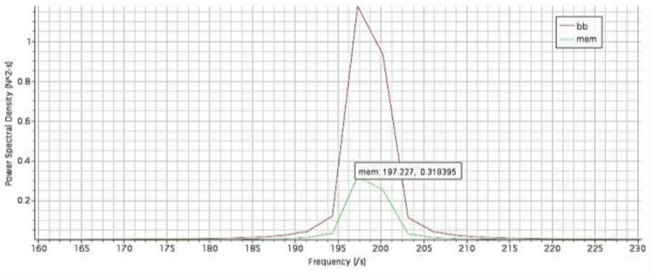

Fig.6 FFT curve for vortex frequency on diaphragm and bluff body at flow velocity 5 m/s – two flow phases

Frequency detected on the membrane with two phase fluid was predicted as f = 198.758 Hz, as compared with the case with just one phase (water), which was f = 197.227 Hz.

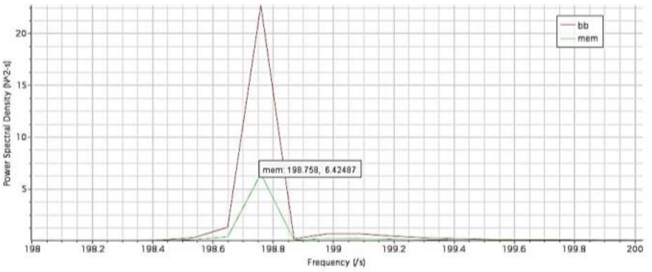

Fig.2 FFT curve for vortex frequency on diaphragm and bluff body at flow velocity 5 m/s – one flow phase

The deviations of those values are calculated as below:

$$D = \frac{(198.75-197.22)}{198.75} \times 100 = 0.77\%$$

Although the experimental results indicated the correct tendencies for the design of the chamber, they neither revealed the details of the process of air escaping the chamber nor answered the question why some designs of the chamber were better than others. Therefore, it was decided to carry out numerical simulation of the dynamics of the air escaping the chamber. It was hoped that a thorough analysis of the corresponding flow fields would provide an answer to this question. The present numerical simulations employed the commercial CFD program adapco Star CCM+.

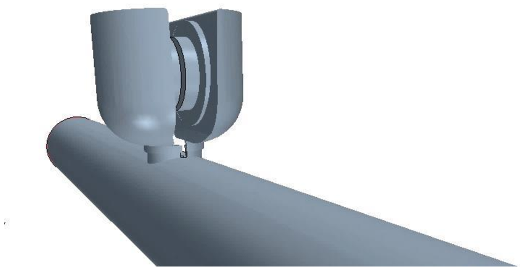

Fig.3 Geometry of prototype of vortex meter DN25

The numerical treatment of the two-phase flow was accomplished via the so called Volume-of-Fluid-method (VOF) method. This model was well suited for the simulation of the flow of several immiscible fluids, as is the case for the present investigation. The downside of the VOF-method is the need for a relatively fine grid, resulting in a significant increase of the numerical effort. Very fine grid is particularly required in the region of the phase boundaries, as the model assumes that all phases share the same velocity, pressure and temperature fields [11].

With this in mind, the grid was created using the Star CCM+ grid generator including the following models: surface remesher, trimmed mesher and prism layer mesher. The surface remesher was optimizing the surface of the geometry for the volume meshing, thus increasing the grid quality. The trimmed mesher produced predominantly hexahedral volume cells, providing a very good cell skewness, or else polyhedral cells where otherwise not possible. The boundary layer was resolved using the prism layer mesher, which generates orthogonal prismatic cells next to the walls. Furthermore, a local grid refinement at the bluff body, as well as inside the cavity, has been carried out. The investigated meshes consisted of approximately one million cells.

The simulations were done for two basic configurations, the original chamber with oval cross section and cavity designated A, and the modified chamber with smaller oval cross section and flat diaphragm holder referred to as B. Both were run for three bulk velocities, 1 m/s, 3m/s and 5 m/s. t the inflow, the turbulent intensity was assumed to be 1%, consisting of pure water (no air). The configuration B, having an reduced volume chamber and modified flat shape was by far superior, eliminating most of the air trapped in the chamber. A typical result of the simulation can be viewed in Figure 8.

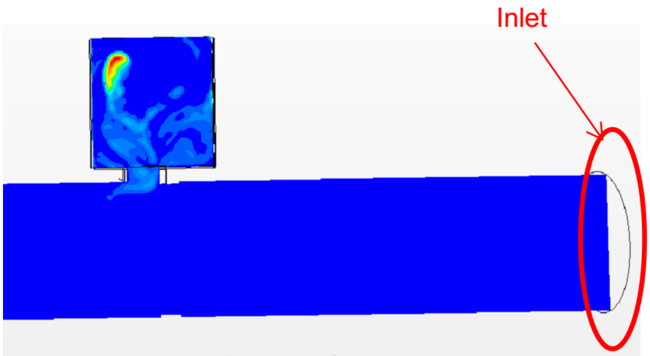

Fig.4 View of pressure chamber along the meter axis for shape B, showing minimal amount of air. Flow velocity u = 3 m/s

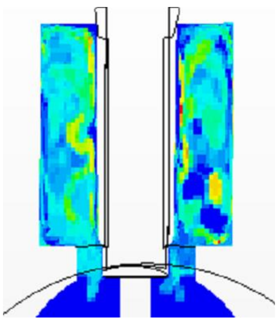

Fig .5. Cross sectional view of configuration in Fig. 8. Blue = water; red = air

5. CONCLUSIONS

The interferometric method of detection utilizing elongation of a optical fiber was generally more sensitive than comparable methods. The paticular photonic components were designed and realized for high temperature and high pressure use. This was accomplished by high temperature coupler, special guids suitable for high pressure, optimized positioning of the optical fiber on the diaphragm and flat round diaphram for the best sensivity of diaphram deflection.

In the present numerical and experimental study, the reduction of volumetric air fraction in a pressure chamber of a photonic sensor vortex shedding flow meter has been achieved. It was found that a significant air fraction in the chamber lead to a deterioration of the signal linearity. Subsequent experiments revealed that certain design features, such as total volume and the presence of a cavity caused the air to be trapped in the chamber without removal in observable time period. A new design of the chamber with reduced volume at without the cavity was proposed that enabled the air to escape in most cases.

The optimized shape of the pressure chamber lead to much better linearity of the k-factor.

REFERENCES

[1] M. Reik, R. Höcker, C. Bruzzese, M. Hollmach, O. Koudal, T. Schenkel, and H. Oertel, "Flow Rate Measurement in a Pipe Flow by Vortex Shedding", Forsch. Ingenieurwes. 74 (2010), pp. 77-86.

[2] B. A. Younis and V. P. Przulji, "Computation of Turbulent Vortex Shedding", Comput. Mech. 37 (2006), pp. 408-425.

[3] E. von Lavante, J. Yao, and S. Perpeet, „Effects of Disturbed Inflow on Vortex-Shedding from a Bluff Body“, AIAA paper 2000-2220 (2000).

[4] T. Igarshi, "Flow Resistance and Strouhal number of a Vortex Shedder in a Circular Pipe", JSME 42 (1999), pp. 586-595.

[5] M. Takamoto, H. Utsumi, N. Watanabe, Y. Terao, "Installation Effects on Vortex Shedding Flow Meters", Flow Meas. Instrum. 4 (4), (1993), pp. 277-285.

[6] A. Venugopal, A. Agrawal and S.V. Prabhu, "Influence of Blockage and Shape of a Bluff Body on the Performance of Vortex Flow Meter with Wall Pressure Measurement", Measurement 44 (2011), pp. 954-964.

[7] E. von Lavante, U. Banaszak, T. Jubin, S. Tournillon and H. Krisch, "Numerical and Eperimental Investigation of Small Size Vortex Shedding Flow Meter", proccedings of the 7th Int. Symposium Metrologia, Havana, Cuba (2008).

[8] J. J. Miau, C.W. Wu, C. C. Hu and J. H. Chou, "A Study of Signal Quality of Vortex Flow Meter Downstream of Two Elbows out of Plane", Flow Meas. Instrum. 13 (2002), pp. 75-85.

[9] C. T. Yang, J. H. Shaw and M. C. Wu, "Verification of a PZT Vortex Sensor in Disturbed Pipe Flows", proccedings of 2nd Int. Symposium on Instrumentation Science and Technology, Jinan, China, (2002).

[10] Gedikli, A.-O., ‘’Numerische und experimentelle Untersuchung der instationären Strömungsfelder von Wirbelzählerkonfigurationen’’, Ph.D.- Thesis, University of Duisburg-Essen, Germany, 2012.

[11] A: C.W. Hirt and B.D. Nichols: Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries. Journal of Computational Physics 39, 201-225 (1981).

[12] Handbook Optiswirl 4070 VortexFlowmeter, KROHNE 02/2013 - 4000150606 MA OPTISWIRL4070C R07 en

[13] Krisch, H., Fernandes, N., Gossner, K., Lau, M., and Tournillon, S., “High-Temperature Fiber-Optic Sensor for Low-Power Measurement of Wide Dynamic Strain Using

Interferometric Techniques and Analog/DSP Methods,"IEEE Sensors Journal 12(1), 33–38 (2012).

[14] Krisch H., Nasilowski T., Fernandes N., Lau M, Lutkowski P., Skupski M., Gossner K., Tournillon S., Plaga R., Jaroszewicz L., Wolinski T. "Analysis of optical fiber interferometer sensor bonded to flat diaphragm for dynamic stress measurement at high temperature", Proc. of SPIE Vol. 7753 77531O-1, 21st International Conference on Optical Fiber Sensors, (May 17, 2011)

[15] Henrik Krisch; Markus Lau; Sylvain Tournillon "Optical fibre sensor for measurement of the large range of strain and frequency vibrations of flat diaphragm" Proc. SPIE 7653, Fourth European Workshop on Optical Fibre Sensors, 765316 (September 08, 2010); doi:10.1117/12.866620; Fourth European Workshop on Optical Fibre Sensors; Porto, Portugal | September 08, 2010