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A CFD Analysis of Flow through a High-Pressure Natural Gas Pipeline with an Undeformed and Deformed Orifice Plate

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Abstract**—**This work aims to present a numerical analysis of the natural gas which flows through a high-pressure pipeline and an orifice plate, through the use of CFD methods. The paper contains CFD calculations for the flow of natural gas in a pipe with different geometry used for the orifice plates. One of them has a standard geometry and a shape without any deformation and the other is deformed by the action of the pressure differential. It shows the behavior of natural gas in a pipeline using the velocity profiles and pressure fields of the gas in both models with their differences. The entire research is based on the elimination of any inaccuracy which should appear in the flow of the natural gas measured in the high-pressure pipelines of the gas industry and which is currently not given in the relevant standard.

Keywords**—**Orifice plate, high-pressure pipeline, natural gas, CFD analysis.

I. Introduction

THE worldwide rise in the requirements for heat and energy have a huge influence on the decreasing amounts of mineral resources and a tendency to increase their prices. It is necessary to deal with them responsibly. One of these cases is using natural gas as an energy and heat source. Currently there are billions of normalized cubic meters of natural gas transferred and they are used each and every day all around the world. The most common flow measurement type, used in high-pressure pipelines, is measuring using the pressure differential, which mainly uses orifice plates inserted in the pipelines. This paper tries to focus on the behavior of the natural gas flowing through a high pressure pipeline with an installed orifice plate used as a flow meter. This type of measuring is still most common for flow measurements in the transit gas lines of Slovakia and other European countries.

The natural gas flowing through the transit gas lines consists of seven major gases like methane, ethane, propane, butane, pentane, nitrogen and carbon dioxide. The majority of the volumetric percentage is methane with 98.39% (Table I) [2], [3].

TABLE I
COMPOSITION OF THE NATURAL GAS IN THE VOLUMETRIC PERCENTAGE

gas	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	N_2	CO_2
[vol %]	98.39	0.44	0.16	0.07	0.03	0.84	0.07

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For this reason the paper will assume, that the natural gas used in the analysis will have physical and chemical properties like pure methane, due to their nearly identical chemical compositions. This paper shows the differences in pressure differentials, pressure fields and the velocity streams between an undeformed and deformed orifice plate. For these analyses 2 models were prepared. The undeformed model is not loaded with the action of any tensions. The geometry of the deformed model is affected by the action of the pressure differential, which causes a shift and deformation in the orifice plate. In these comparison analyses were a chosen pressure differential of 50 kPa and a plate 10 millimeters thick. The maximum shift caused by the deformation was 1.23 millimeters (Fig. 1) [1], [6], [7].

Fig. 1 Cross section of the undeformed and deformed model of an orifice plate (Δp=50 kPa, t=10mm)

II. Model Preparation

The model analysis is calculated using the ANSYS Workbench. Both models consist of three parts, two straight pipes and the orifice plate between them. In one model is an orifice plate modeled as an undeformed one and in the other is an orifice plate deformed by the action of the pressure differential. In the analysis only the inverted solid volume is used, which is the fluid flowing through the pipes and the orifice plate. In this case the natural gas is the fluid medium. The model is axisymmetric to reduce the number of cells and to simplify the calculation. Because of the axial symmetry the geometry consists of only one half of the section. The height of the pipe is 365 millimeters, the inlet length is 2,000 millimeters and the outlet length is 10,000 millimeters (Fig. 2). The thickness of the orifice plate is 10 millimeters.

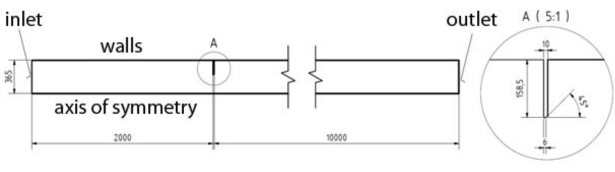

Fig. 2 Geometry of the model

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III. Mesh

The mesh of both models consists of 527,740 quadrilateral cells and it has 530,078 nodes. The surface of the model is split into the ten blocks [9]. Two blocks are for the orifice plate's part and four blocks are for each pipe (Fig. 3 (a)). This division is necessary to make the mesh thicker in the areas around the orifice plate (areas no.: 1, 2, 3, 4, 7, 8) and the pipe walls (areas no.: 4, 5, 8, 9). In areas 6 and 10 it is not as important to have so many cells and that is the reason why the mesh is thinner there [10]. The lower spacing near the walls and around the orifice plate is significant to obtain the behavior of the natural gas flow more realistically. In Fig. 3 (b) the mesh around the orifice plate is detailed.

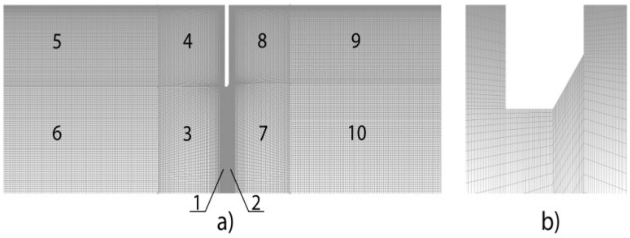

Fig. 3 (a) Mesh with the geometry splitting (b) The mesh detail around the orifice plate edge [7]

IV. Boundary Conditions and Model Solver

The behavior of the model was set for a high-pressure pipe with flowing methane as the fluid part. All boundary conditions are the same in both analyses. The value of the mass flow was 80 kg.s^{-1}. The boundary condition for the inlet was set to mass flow and for the outlet was set to the pressure outlet. All the boundary conditions for the inlet to the pipe are in Table II.

TABLE II
Boundary Conditions in the Inlet to the Pipe

Pressure	Temperature	Density	Mass flow rate
p [Pa]	T [K]	ρ [kg.m^{-3}]	m [kg.s^{-1}]
5.10^{6}	288.0	34.1	80.0

Because of the low Mach numbers the compressible fluid was changed into incompressible and the density-based model solver was changed into pressure-based. Due to the high Reynolds numbers and the necessity of the modeling flow near the wall a standard k-ε model was chosen [8].

V. Pressure Analysis

The measuring of the pressure differentials at the orifice plate is fundamental for the measurement of the mass flow rate. In Fig. 4 is the layout of the pressure fields in the section around the orifice plate for the models with an undeformed and deformed orifice plate.

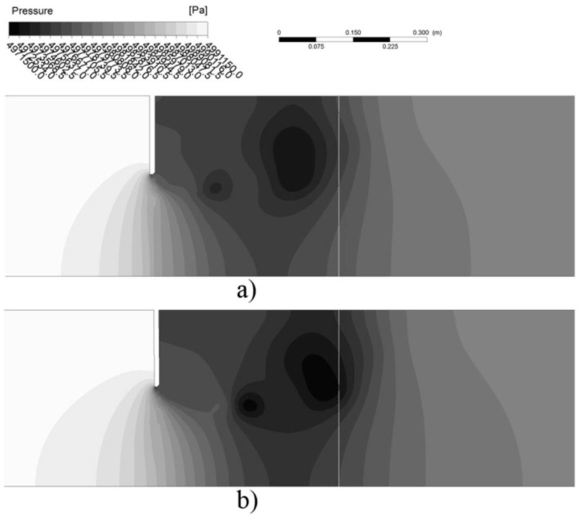

Fig. 4 Pressure fields in the section around the orifice plate [a) undeformed; b) deformed]

From Fig. 4 it is visible that the pressure fields behind the orifice plate are changed by the deformation of the plate. An area of pressure fields with lower pressures became larger, which caused the different pressures measured in the downstream. Finally it changed the pressure differential from which the volumetric flow is calculated. The place to measure pressures correctly in the system with the orifice plate is given in the standard ISO 5167-2:2003.

The standard ISO 5167-2:2003 mentions the rules of how to correctly measure the orifice plates. For orifice plates with D and D/2 tapings, the spacing l_1 of the upstream pressure taping is nominally equal to D. The spacing l_2 of the downstream pressure taping is nominally equal to 0.5D (Fig. 5), where D is diameter of the pipe connected to the orifice plate [4], [5].

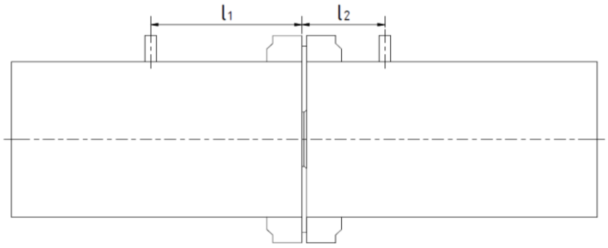

Fig. 5 Spacing of the pressure tapings for the orifice plates with D and D/2 tapings

To keep the measurement conditions valid pressures were measured by distances of 1.27 and 2.375 meters from the inlet. The dependence of the pressure on the distance measured near the wall is shown for both models below in Fig. 6.

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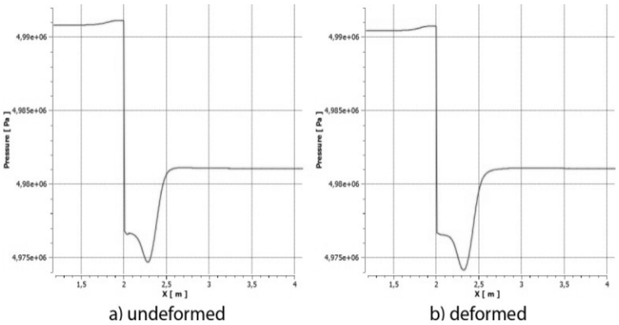

Fig. 6 Dependence of the pressure (measured near the wall) on the distance from the inlet to the pipe

The shape of the pressure dependence curve measured near the wall changed in the deformed model. The minimal pressure value, in the distance of 2.3 meters from the inlet to the pipe, dropped by 0.6 kPa, but more important was the value of the pressure in the downstream taping and it dropped by 2.0 kPa in the deformed model. This means that a small geometry deformation causes inaccuracies of the pressure values measured near the wall in the downstream tapings of the undeformed and deformed model of the orifice plate.

The pressure value in the downstream taping remained unchanged in the area near the wall, but fluctuated in the rest of the field. In Fig. 7 is the dependence of the pressure measured in the distances of both pressure tapings. It is visible that the curve, which shows the pressure field of the downstream, changed its shape. Deformation caused a radius with a minimum pressure value to drop from 0.25to 0.2 meters. The minimal pressure value dropped by 3.5 kPa from the value 4.976 MPa to 4.9725 MPa.

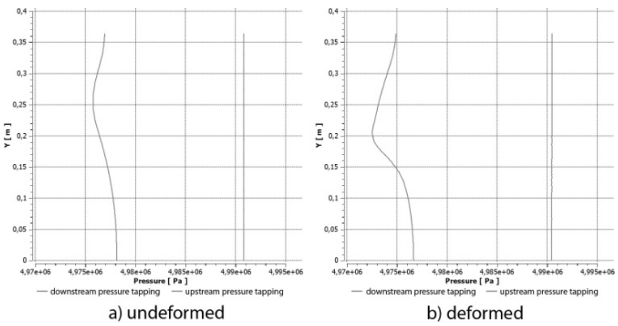

Fig. 7 Dependence of the pressure measured in the distances of the pressure tapings

VI. Velocity Analysis

The shape deformation has an impact on the velocity and it changes the velocity fields mainly behind the orifice plate (Fig. 8). The deformation changed the flowing angles of the orifice plate and the natural gas stream behaved differently compared to the undeformed model. The velocity field with a value near zero was increased right behind the edge of the plate. On the other hand, the velocities of the natural gas behind the orifice plate's hole increased and the area of their velocity fields became greater.

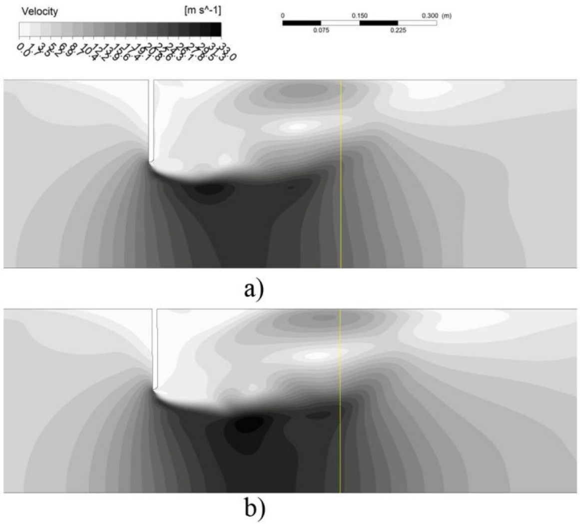

Fig. 8 Velocity fields in the section around the orifice plate.

The shape of velocity profile behind the orifice plate is not identical with the shape in front of it. The common turbulent profile is interrupted by the orifice plate and the shape of the velocity profile is replaced by a new one. The visible velocity profiles in the section of 0.5D behind the orifice plate (downstream taping) are shown below (Fig. 9).

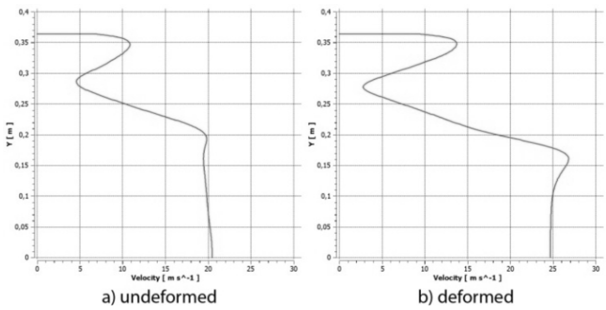

Fig. 9 Velocity profiles in the section of 0.5D behind the orifice plate

The maximum velocity (measured in the downstream taping) in the undeformed model was reached in the axis of symmetry and its value was 20.4 $m.s^{-1}$ (Fig. 8). In the deformed model velocity reached its maximum in the radius of 170 millimeters and the value was 27 $m.s^{-1}$.

VII. Conclusion

Deformation has a great impact on the stream field in a high-pressure pipeline. The shape deformation causes different behavior in the natural gas stream. The velocity fields and velocity vectors changed, which impacted on the pressure fields. Both maximum and minimum pressure and velocity values appear in different areas. Finally it causes varying pressure differentials even though the boundary conditions of both models are identical. The final accuracy of the measurement could be affected if the deformation was not included in the calculation of the final volumetric flow. Our research will show the behavior of natural gas in a 3-dimensional space. Both results will be compared, if the dimensional difference has a huge impact on the flow of natural gas.

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