

RESEARCH OF THE INFLUENCE OF DEFECTS IN THE HYDRAULIC PATH ON THE MEASUREMENT ACCURACY ELECTROMAGNETIC FLOWMETER

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Abstract

The paper considers issues related to identifying the causes of defects in the pipeline and presents the results of computer modeling. The simulation results are tested on a specially designed control and measuring path that fully reproduces possible defects.

Keywords: hydraulic system, control and measurement path, computer simulation, flowmeter, volumetric flow, stability of readings

1. INTRODUCTION

A number of technological processes in various industries are associated with the transportation of substances through pipelines. The main condition for effective management of technological processes is the availability of reliable information about the parameters of the measured substance, including mass and volume flow. Along with the measurement tasks, there are also questions of optimal process management, because the information obtained from flowmeters is used as input data for automatic control and process control systems.

At industrial enterprises of the Republic of Belarus, flowmeters of foreign production are mainly used to control technological processes. They are highly accurate and meet the ASME and DIN standards for their actual diameters of pass-through sections. Sections of pipeline systems at enterprises are mostly made according to standard linear dimensions in the GOST system. The actual linear dimensions in all these standards differ from the accepted nominal value. If this is not taken into account, it can lead to the creation of a step in the hydraulic path. Additional negative factors that affect the uniformity of the flow of the medium are also non-compliance with the alignment when installing measuring equipment, non-compliance with the length of straight sections, the presence of cranes, narrowing devices and bends. All these factors can have a significant impact on the flow uniformity, which, in turn, affects the reliability of flowmeter readings.

The purpose of this work is to conduct research on a specially manufactured control and measurement path with artificially reproduced defects for the DN50 pipeline when measuring liquid flow in the range from 0,09 to 30,0 m³/h.

Physical confirmation of the results obtained during simulation at the experimental facility will contribute to the development and improvement of methods for estimating flow values at production facilities to achieve better accuracy and increase confidence in the reliability and stability of flowmeter readings.

2. MATERIALS AND METHODS

The choice of flowmeters of an optimal design is important both for optimizing production and for ensuring the reliability of the results obtained when they work on different environments.

To solve such problems, flowmeter manufacturers make extensive use of field tests on flowmeter installations that operate on water or air, as well as numerical simulation of hydrodynamic processes using computational fluid dynamics software packages (CDF - computational fluid dynamics). Analysis of numerical and physical modeling of experiments on influence of straight section length on readings of flowmeters is presented in works [1-4].

In this study, verification of the results of numerical modeling was carried out by comparing the results of computer modeling with the results of physical experiments.

2.1. Experimental installation

For research, a design was developed and a hydraulic section [5] was manufactured - a control and measuring path, which will allow physically assessing the influence of pipeline geometry on the readings of flowmeters.

The general schematic hydraulic diagram of the flowmeter unit with the installed control and measuring path is shown in Figure 2.1.

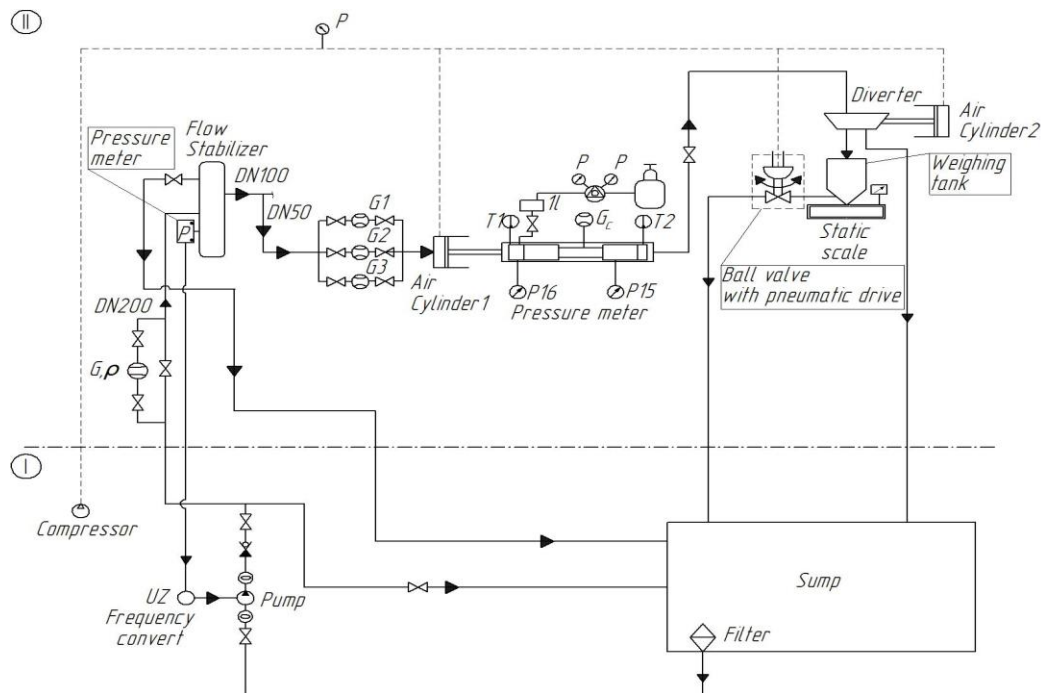
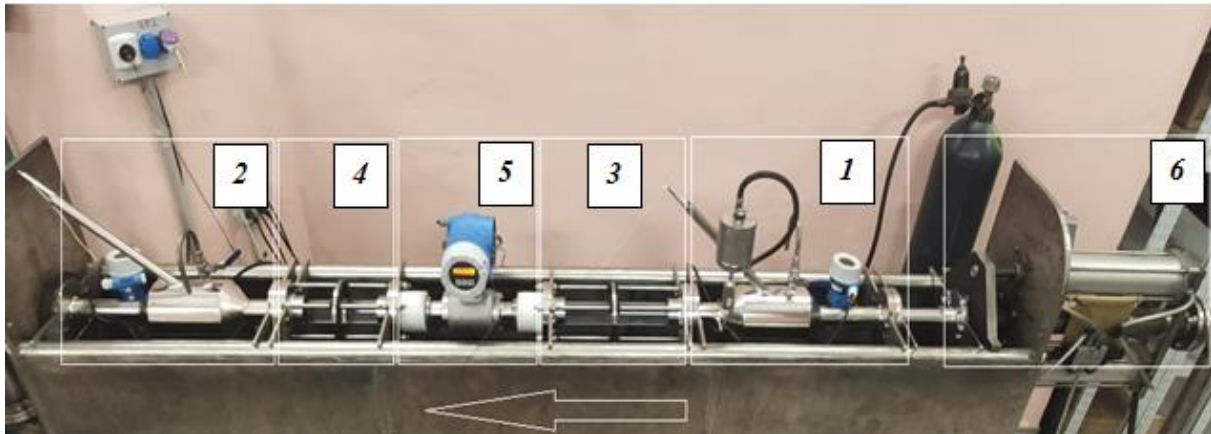


Figure 2.1. Schematic hydraulic diagram of a flowmeter research installation

The control and measuring path with artificially reproduced defects is mounted on a special desktop Figure 2.2 and consists of the following main elements: an input spacer with a dye supply system for flow visualization, an input straight section made of transparent material, a block with a control flowmeter, an output straight section made of transparent material, an output spacer. All elements and blocks are centered by special adjustment brackets when installed on the desktop. After centring, the entire assembly is clamped by the force of the pneumatic cylinder, ensuring complete tightness of the system.

Input spacer (1) is designed to accommodate the dye supply system and sensors for monitoring the temperature of the medium (water) and pressure in the pipeline in front of the rectilinear inlet section. The non-standard form of the input spacer is due to the technical and metrological requirements for the installation of instrumentation.

The input straight section (3) is a collapsible structure consisting of a tube of transparent material – quartz glass (for visual control of the flow structure), two flanges, studs and fasteners. It is intended to create a stable flow profile at the inlet in front of the flowmeter by observing the length of the straight section according to [6].



1 - input spacer; 2 - output spacer; 3 - input straight section; 4 – output straight section; 5 - block with a control flowmeter; 6 - block of pneumatic cylinders.

The arrow indicates the direction of flow.

Figure 2.2. Control and measuring path with artificially reproduced defects. General form

Block with a control flowmeter (5) intended for measuring of descriptions of the hydraulic system and control of changes of value of expense. A block with a control flowmeter is installed between the input (3) and output (4) straight sections.

For modeling defects during research, specially designed adapters or washers are used, which are installed immediately before and after the control flowmeter.

The output straight section (4) is intended to create a stable flow profile at the outlet after the control flowmeter and visual control of the flow structure. The straight output section is a collapsible design similar to the construction of the input straight section (3). The length of the output straight section, in accordance with the requirements of the operational documentation for the control flowmeter, must be at least $5 \times DN$ [6].

Output spacer (2) is designed to install sensors to control the temperature of the measuring medium (water) and pressure in the pipeline at the outlet after the control flowmeter.

The fixing of all the components of the control and measuring path in the line on the working table is carried out by clamping all the elements to each other by the force created by the block of pneumatic cylinders (6) of the standard flowmeter installation system.

2.2. Computer modeling

The calculation of fluid flow parameters inside the control and measurement sections was performed using the Flow Simulation module – a computational tool for modeling flow processes (CFD-analysis), fully integrated into the SolidWorks software package [7-8].

Flow Simulation models the motion of a flow based on a solution of the Navier-Stokes equation, which is an interpretation of the laws of conservation of mass, momentum and energy for a fluid flow. The equations are supplemented by fluid state equations defining the nature of the fluid, and by empirical dependencies of fluid density, viscosity and thermal conductivity on temperature. Inelastic non-Newtonian fluids are considered by introducing a dependency of their dynamic viscosity on flow shear rate and temperature, and compressible liquids are considered by introducing a dependency of their density on pressure. A particular problem is finally specified by the definition of its geometry, boundary and initial conditions.

Most of the fluid flows encountered in engineering practice are turbulente to predict turbulent flows, the Favre-averaged Navier-Stokes equations are used, where time-averaged effects of the flow turbulence on the flow parameters are considered, whereas the other, i.e. large-scale, time-dependent

phenomena are taken into account directly. Through this procedure, extra terms known as the Reynolds stresses appear in the equations for which additional information must be provided. To close this system of equations, Flow Simulation employs transport equations for the turbulent kinetic energy and its dissipation rate, the so-called k-model.

The conservation laws for mass, angular momentum and energy in the Cartesian coordinate system rotating with angular velocity Ω about an axis passing through the coordinate system's origin can be written in the conservation form as the following system of equations (2.1 – 2.4):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0, \quad (2.1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i u_j) + \frac{\partial p}{\partial x_i} = \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{ij}^R) + \tau_i, \quad i = 1, 2, 3 \quad (2.2)$$

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}(u_j(\tau_{ij} + \tau_{ij}^R) + q_i) + \frac{\partial p}{\partial t} + \tau_{ij} \frac{\partial u_i}{\partial x_j} + \rho \varepsilon + S_i u_i + Q_H, \quad (2.3)$$

$$H = h + \frac{u^2}{2} + \frac{5}{3}k - \sum_m h_m^0 y_m, \quad (2.4)$$

Equations (2.1 - 2.4) are written in dimensionless units using generally accepted notation ρ is the fluid density, t - time, u is the fluid velocity, S_i is a mass-distributed external (for example, to take into account gravity in the calculation $S_{i,grav} = -\rho g_i$, where g_i is gravitational acceleration component along the i-th coordinate direction), H is the enthalpy, h is the thermal enthalpy, Q_H is a heat source or sink per unit volume, τ_{ij} is the viscous shear stress tensor, q_i is the diffusive heat flux, k is kinetic energy of turbulence, h_m^0 is an individual thermal enthalpy of the m-th mixture component, y_m is a concentration of the m-th mixture component.

The subscripts are used to denote summation over the three coordinate directions.

For Newtonian fluids the viscous shear stress tensor is defined by equation (2.5):

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \quad (2.5)$$

Following Boussinesq assumption, the Reynolds-stress tensor has the following form - equation (2.6):

$$\tau_{ij}^R = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) - \frac{2}{3} \rho k \delta_{ij}. \quad (2.6)$$

where δ_{ij} is the Kroncker delta function (it is equal to unity when $i = j$, and zero otherwise), μ is the dynamic viscosity coefficient, μ_t is the turbulent eddy viscosity coefficient and k is the turbulent kinetic energy. Note that μ_t and k are zero for laminar flows [7-8].

A laminar/turbulent boundary layer model is used to describe flows in near-wall regions. The model is based on the so-called Modified Wall Functions approach. This model is employed to characterize laminar and turbulent flows near the walls, and to describe transitions from laminar to turbulent flow and vice versa. The modified wall function uses a Van Driest's profile instead of a logarithmic profile. If the size of the mesh cell near the wall is more than the boundary layer thickness the integral boundary layer technology is used. The model provides accurate velocity and temperature boundary conditions for the above mentioned conservation equations. During the calculations, three variants of geometric models for the DN50 tract were considered [7, 9].

The calculations considered three options of geometric models for the path DN50:

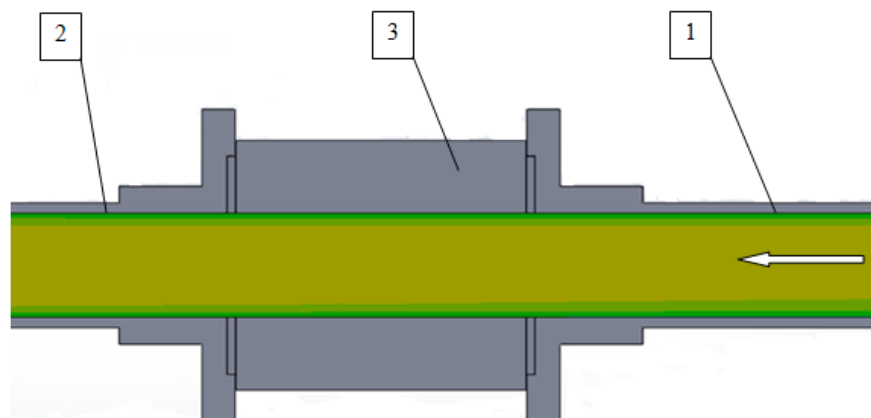
Option 1: model of the path DN50 without artificially reproduced defects (to assess the presence and influence of structural obstacles to flow in the spacer): pockets for the temperature sensor and the dye feed tube are shown in figure 3.1);

Option 2: model of the path DN50 with artificially reproduced defects in the form of a pair of adapters (from DN50→DN40 to DN50→DN60, transition step $h=2$ mm);

Option 3: model of the path DN50 with artificially reproduced defects in the form of a pair of washers with an internal diameter of the washer from DN40 to DN60 with a transition step of 2 mm.

Numerical simulation of the fluid flow in the control and measuring path was performed for the medium-water; static pressure at the outlet of the control and measuring path - 101325 Pa (atmospheric); medium temperature + 20 °C; kinematic viscosity of the medium at 20 °C - $1,006 \cdot 10^{-6}$ m²/s.

Since the input spacer (position 1, figure 2.2) of the control and measurement path has a complex geometry due to the placement of control devices (pressure and temperature sensors, dye supply devices) on it. First of all, it was necessary to check how the presence of these technical devices will affect the formation of the flow structure at the entrance to the flowmeter.



1 - Straight input section; 2 - Straight output section; 3 - Block with a control flowmeter

Figure 2.3. Distribution of flow rate in a block with a control flowmeter mounted without defects

Figure 2.3 shows that the flow is stable. The results of calculations showed that for any given flow rate value, the flow after the input spacer is stabilized at the length of the straight section corresponding to no more than $7 \times DN$, so to reduce the computer processing time, the influence of the geometry of the input spacer from the geometric model of the control and measurement path was excluded.

2.3 Processing of experimental research results

The physical implementation of this computer model was carried out on an exemplary flow measurement unit by static weighing in accordance with [3]. The principle of the flow measurement method by static weighing is that the initial mass of the tank is initially determined, then the flow is directed to the receiving tank by means of a deflecting device that starts a timer to measure the filling time (until a sufficient amount of liquid is collected in it to obtain the desired accuracy), and after stopping the flow, the final mass of the tank with the liquid contained in it is determined. Then, based on the information obtained about the collected mass of the liquid, the collection time, and other data for each experimental point, the following were determined:

- volume flow rate of the reference unit, m^3/s :

$$Q_{ij} = \frac{M_{ij}}{t_{ij} \cdot \rho_{ij}}, \quad (2.7)$$

where M_{ij} is the value of the accumulated mass, kg; t_{ij} is the filling time of measuring tank, s;

ρ_{ij} is the fluid density, kg/m^3 ; i, j is an indices of the measurement and the point of consumption.

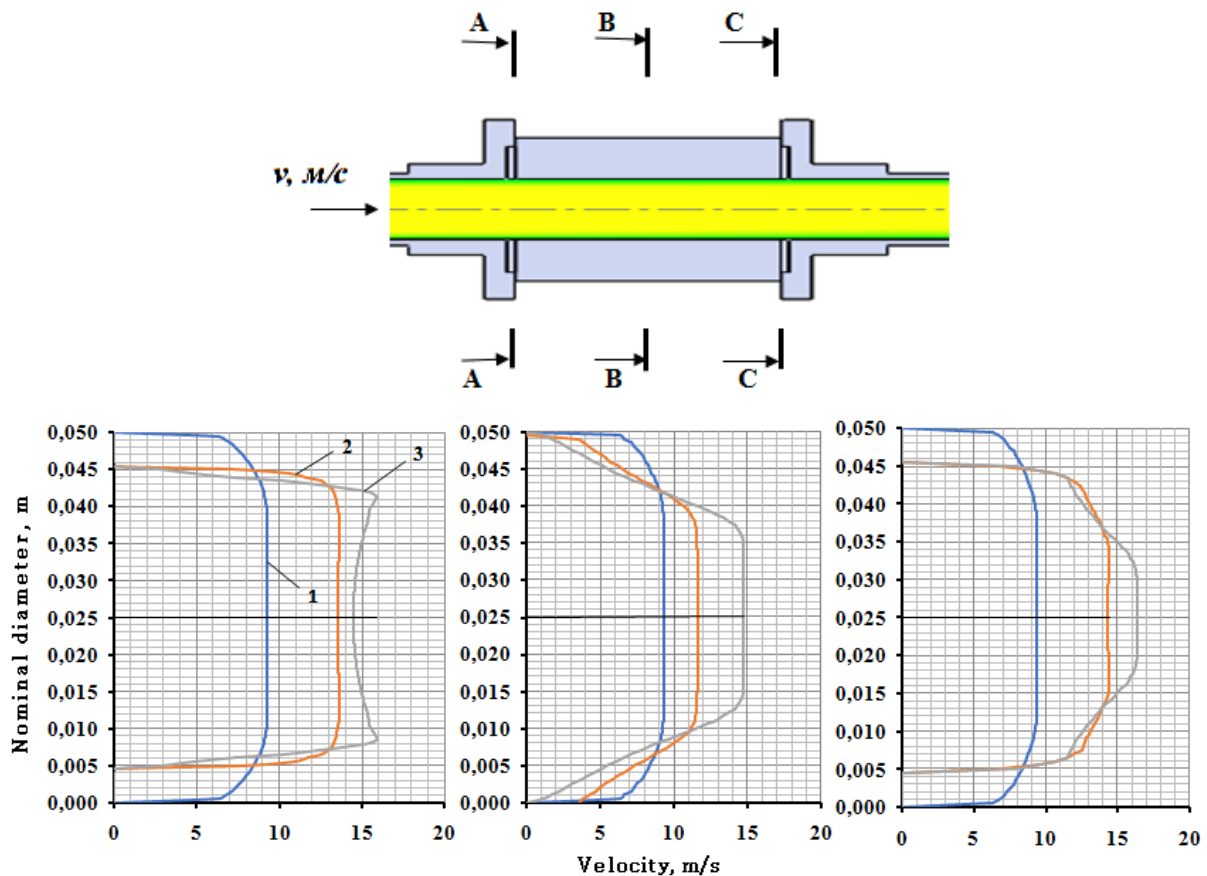
- the error in measuring the volume flow, %, was determined by comparing the flow values measured by the control flowmeter and the flowmeter installation according to the formula 2.8:

$$\delta_{Qi} = \frac{Q_i - Q_{ij}}{Q_{ij}} \cdot 100\% \quad (2.8)$$

The error in the flow measurements was determined at three points $0,05 \cdot Q_{max}$, $0,2 \cdot Q_{max}$ and $0,5 \cdot Q_{max}$ [5].

3. RESEARCH RESULTS

Figure 3.1 shows the calculated graphs of the distribution of the flow velocity profile in three sections during the passage of model defects of various types for the medium - water.



1 - a path without established defects; 2 - a path with artificially reproduced defects of the type «pair of conical adapters DN50→DN40»; 3 - path with artificially reproduced defects of the type «pair of washers DN40»

Figure 3.1. Distribution of velocity field during laminar motion in three cross sections of electromagnetic flowmeter DN50

Figure 3.1 shows that the distribution of the flow rate (1) on all selected cross sections of the flowmeter DN 50 without artificially established defects remains constant.

When passing sections with a reproduced defect of the type – «pair of conical adapters» (2), imitation of diameter mismatch – «step» (the ratio between the pipeline diameter and the flowmeter diameter corresponds to 0,8). Flow at the inlet to the flowmeter (section A-A) narrows by approximately 8 mm in diameter. The flow velocity along the axis increases with respect to the flow velocity in the absence of defects by 32%. In this case, in a wide section, a jet is formed, separated from the rest of the medium, by the interface and collapsed into vortices (as shown in Figure 3.2). In the middle section of the flowmeter (B-B), the flow velocity along the axis reaches its maximum value, and at the outlet from the flowmeter to the section (C-C), a narrowing phenomenon occurs mainly similar to that which occurs in the case of sudden expansion when impact losses occur. Only in this case, these losses are manifested by the expansion of the jet compressed after entering from a wide part of the system to a narrower one.

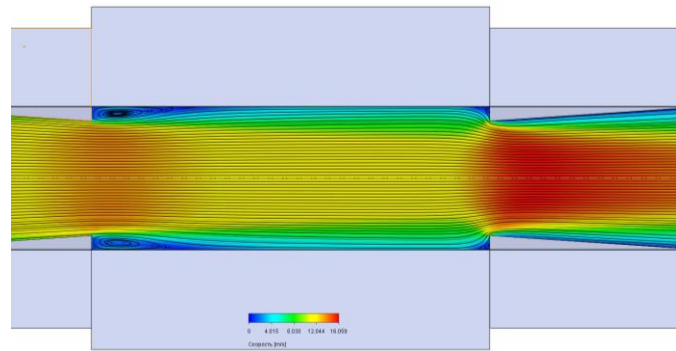


Figure 3.2. Flow rate in the path DN50 with artificially reproduced defects of the type «pair of conical adapters DN50 → DN40»

When passing sections with a reproduced defect of the type – «pair of washers» (3) before the obstacle, there is a sharp narrowing of the flow, and at the inlet to the flowmeter its sudden expansion (Figure 3.3). The flow velocity along the axis increases with respect to the flow velocity without artificial defects by 36%, but the maximum speed value of 16 m/s is achieved at a point spaced from the edge of the obstacle by 8 mm, respectively, a change in the flow profile occurs. In the middle section, the flow profile begins to stretch, approaching the parabolic law in shape. The axial flow velocity reaches its maximum value in section (B-B), and at the outlet of the flowmeter into section (C-C), when narrowing, a phenomenon similar to that observed at the inlet is repeated. The flow velocity along the axis at the outlet of the flowmeter corresponds to the flow velocity at the inlet, however, the shape of the flow profile distribution is different, as shown in Figure 3.1.

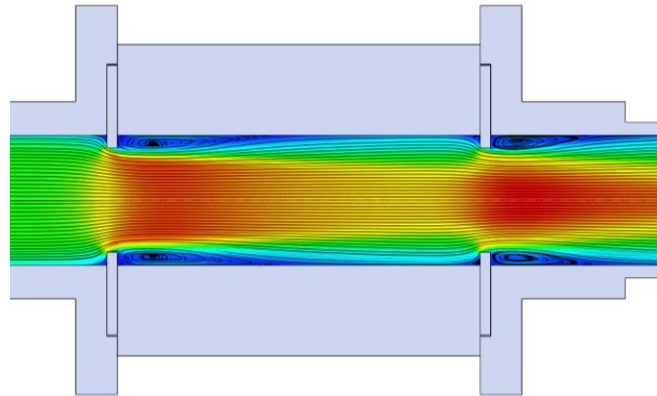
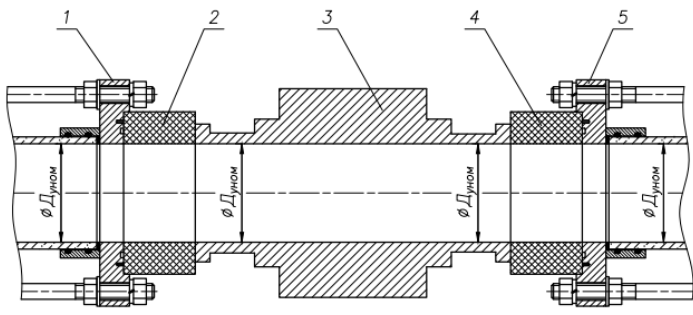


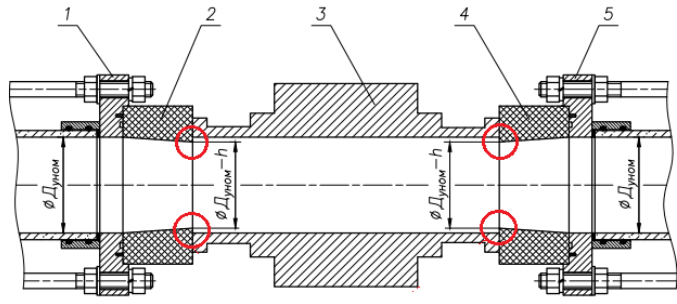
Figure 3.3. Fluid flow rate in the path DN50 with artificially reproduced defects of the type «pair of washers DN40»

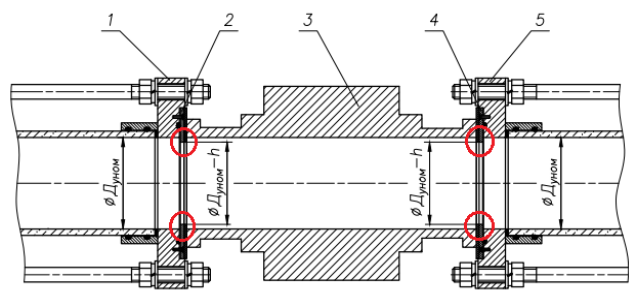
After passing through a defect, such as a constriction device («pair of washers DN40» or «pair of adapters DN50→DN40»), the flow again expands to a full section and is made stable, while the average flow rate decreases.

Table 3.1 shows some models of reproducible defects and values obtained experimentally at the input and output of the test duct at constant engine speed $N=2400\text{rpm}$.

Table 3.1.

			
1– input straight section, 2, 4 – adapters, 3 – control flowmeter, 5 – output straight section			
$Q, m^3/s$	0,00092	0,00373	0,00876
p^*, Pa	337000	319900	207700
p_{16}, Pa	18800	34600	105200
p_{15}, Pa	18700	33400	98800

			
1– input straight section, 2, 4 – adapters, 3 – control flowmeter, 5 – output straight section			
$Q, m^3/s$	0,00092	0,00372	0,00862
p^*, Pa	337200	319400	209000
p_{16}, Pa	19000	36000	110100
p_{15}, Pa	18800	33500	96800

			
1– input straight section, 2, 4 – adapters, 3 – control flowmeter, 5 – output straight section			
$Q, m^3/s$	0,00092	0,00358	0,00833
p^*, Pa	337100	306800	219500
p_{16}, Pa	19100	36900	122400
p_{15}, Pa	18900	34100	96400

Notes:

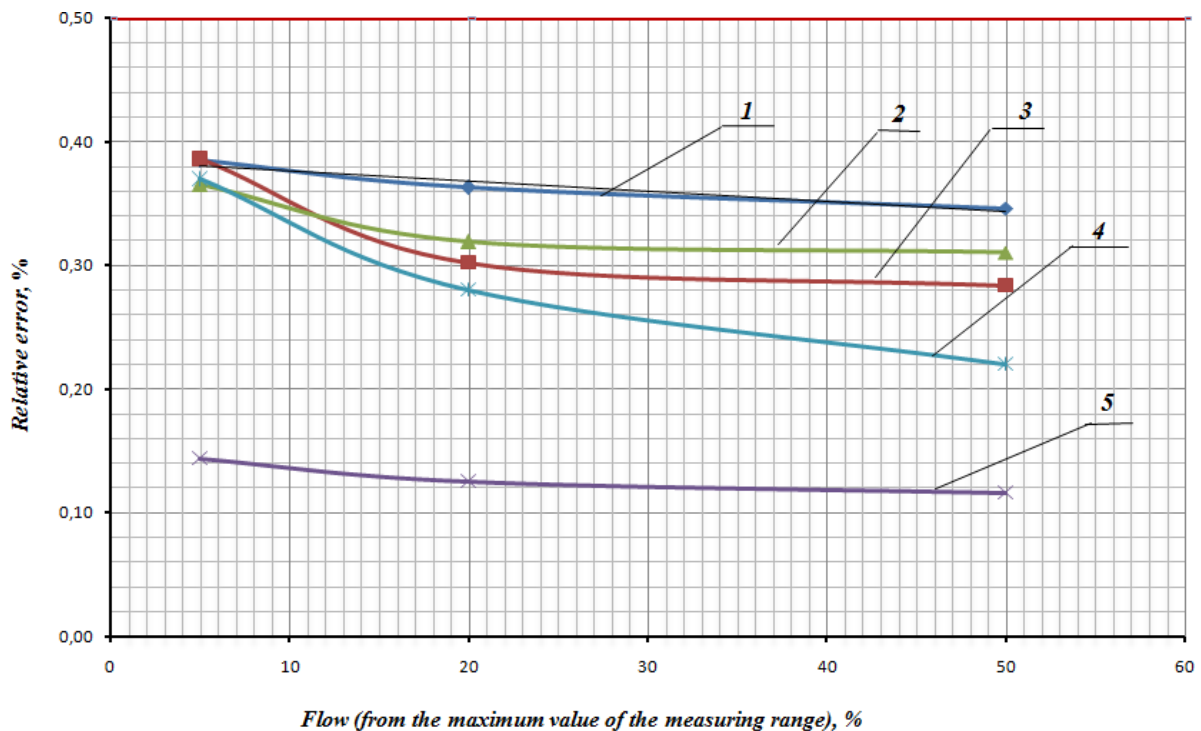
p^* - pressure in the stabilization tank to ensure constant flow, Pa;

p_{16} - pressure at the inlet to the control and measuring path, Pa;

p_{15} - pressure at the outlet of the control and measuring path, Pa.

As can be seen from table 3.1, the pressure in the models of the control and measuring path is less than the pressure, depending on the set flow rate. This pressure loss is due to defects of the type constricting device. The lower the value, the less excess will be observed within the control and measuring path. When modeling a defect of type «pair of conical adapters DN50 → DN40», a flow drop of 2,5% occurs, and when installing a defect of type «pair of washers DN40», was a flow drop of 5,0% is recorded in relation to the specified flow value for the path model without defects.

Figure 3.2 shows the distribution graphs of the main relative error of measurements from the specified value of flow rate without defects in the path and during installation of defects of the type: «pair of washers DN40», «pair of washers DN60», «pair of conical adapters DN50 → DN40», «pair of conical adapters DN50 → DN60».



1 - hydraulic path without defects; 2 - hydraulic path with a defect of the type «pair of washers DN60»; 3 - hydraulic path with a defect of the type «pair of washers DN40»; 4 - hydraulic path with a defect of the type «pair of conical adapters DN50 → DN60»; 5 - a hydraulic path with a defect of the type «pair of conical adapters DN50 → DN40»

Figure 3.2. Graph of the magnitude of the additional measurement error at a given flow point when reproducing defects with a ratio of the inner diameter of the pipeline to the diameter of the flow part 0,8; 1 and 1,2

Figure 3.2 shows that defects such as the mismatch of the internal diameter of the pipeline section and the internal diameter of the flowmeter during installation do not lead to changes in the linearity of the

metrological characteristics and repeatability of the flowmeter readings. The degree of shift varies depending on the type of installed defect and the ratio of the internal diameter of the pipeline to the diameter of the flow part in the extreme experimental values of 0,8; 1 and 1,2.

Based on the results obtained, we can conclude that it is possible to correct the accuracy of electromagnetic flowmeters, even if the minimum requirements for the length of the straight section (5xDN) are met and there is a defect the type «pair of conical adapters DN50 → DN40», in which the maximum offset of the error value is shown. In most cases, the value of the additional measurement error does not exceed 0,50%, so even when solving technological accounting problems, correction may not be necessary.

4. CONCLUSIONS

1. Theoretical studies of the influence of defects in the hydraulic tract on the distribution of the velocity field in the hydraulic tract are carried out. The results of computer simulations in the Flow Simulation package are consistent with theoretical ideas about the behavior of a fluid when it moves in confined spaces, as well as the devices narrowing and expanding the flow, in particular, described in [1-4]. Consequently, the Flow Simulation package can be used to solve internal hydrodynamic problems in industrial enterprises at the stages of studying, designing, introducing new and intensifying existing processes.
2. To stabilize the flow in front of the flowmeter, it is recommended that a straight section of length from 5 to 15 nominal diameters be observed. The length of the straight section for each type of flowmeter is set by the manufacturer and is indicated in the Operation Manual.
3. A series of physical experiments was carried out to identify the degree of influence of hydraulic path defects on the accuracy of the stability of measurements of electromagnetic flowmeters. As a result of experiments, it was found that:
 - a. the readings of electromagnetic flowmeters substantially depend on the symmetry of the velocity field of the measured flow;
 - b. when modeling a defect of the type «pair of conical adapters DN50 → DN40», a flow drop of 2,5% occurs, and when installing a defect of the type «pair of washers DN40», was a flow drop of 5,0% is recorded in relation to the specified flow value for the model path without defects, such a flow drop is accompanied by an increase in pressure, when overcoming the flow resistance of existing obstacles in the system;
 - c. if the internal diameter of the pipeline and the internal diameter of the flowmeter of the flowmeter do not match (to ratios of diameters from 0,8 to 1,2), then value of the additional measurement error in most cases does not exceed 0,50%, which allows correction of the flowmeter settings using the correction factor if necessary.

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