Приборостроение, метрология и информационно-измерительные приборы и системы

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NON-INTRUSIVE TEMPERATURE MEASUREMENT FOR LIQUID FLOW USING COMPENSATORS OF PIPELINES

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The article presents the results of a numerical study that aimed to accuracy improvement for non-intrusive measurements of the liquid flow temperatures in standard pipelines compensators. Non-intrusive measuring devices are one of the modern promising and profitable tools that stimulate the improvement of technologies and the involvement of world corporations in this sphere, while the growing intellectualization of measurements positively affects the safety and efficiency of the industry.

The numerical study result is consistent with the results of laboratory tests and shows the general regularity of flow velocity effect the error of non-intrusive temperature measurements. Shown that measurements after the upper or lower elbow of the compensator makes possible to reduce the measurement error in the Reynolds (Re) range of about 1000–7000, which is characteristic for the onset of turbulent flow of a liquid. Also shown that gravity negatively affects the accuracy of measurements, so preference should be given to horizontally located compensators.

Obtained that the flow in pipeline determines the largest temperature change in the wall region of the pipe for relatively high Re, and along the pipeline axis for small Reynolds numbers. In combination with the flow characteristics in the compensator, it changes temperature distribution and error, depending on the flow velocity in the pipeline. In particular, this effect determines error decreasing for temperature measurement in the compensators at low Re numbers.

The existing surface temperature sensors, with correction the surface temperature measurements to the flow temperature, require calibration to work on flows with Re numbers varying over a wide range, and binding these measurements to pipeline compensators can improve the quality of measurements due to smoothing and, fluctuation thermal and hydrodynamic influences.

Keywords: pressure, flow rate, temperature, non-intrusive measurement, accuracy, Reynolds number, pipeline compensator, flow modeling, temperature distribution.

Introduction

Non-intrusive measuring instruments are modern technical devices that allow to obtain information about the parameters of a measurement object without direct contact with it. At present, non-intrusive devices and measurement technologies have already taken a firm position among the measuring solutions that ensures the functioning of various industrial facilities with product lines equipped automatic process control system. The obvious advantages of using non-intrusive technologies are simplicity of installation and maintenance and as a result – low staff requirements, cost savings due to the absence of need to stop the technological processes for installation and maintenance, and, most importantly – increased reliability of pipelines with these measuring devices. Obviously, reliability increases due to the absence of tie-ins or additional flange connections, obstacles in the flow path that leads to a reduction in non-productive losses, reduces the methodical error of measurements. Constantly increasing requirements for reliability are also a reflection of modern trends in improving safety and reducing injuries.

However, there are some issues regarding accuracy, repeatability, response time, sensitivity, and other parameters of non-intrusive measurements. In addition, the limitations of the application and the peculiarities of use for all the variety of external and internal influencing factors remain uninvestigated.

1. Background of choosing the place of temperature measurement

This article is devoted to non-intrusive measurement of the temperature of the liquid medium in the pipelines. In the article [1], an experiment was performed on a flowstand with the cross section multizone temperature sensor in the form of a thin radial rod in a horizontal tube. The result of this experiment, shown in Fig. 1, shows that the temperature drop across the section of the pipe can reach one degree and depends on the flow velocity, while in the high-speed range (flow rate greater than 10 m^3/h) the value of the error stabilizes so further flow velocity changing does not affect unpredictable measurement error. Consequently, non-intrusive temperature measurement carries a significant error in the region of small values of Reynolds (Re) numbers (flow rate in the graph is less than 5 m^3/h), while the error value is not predictable.

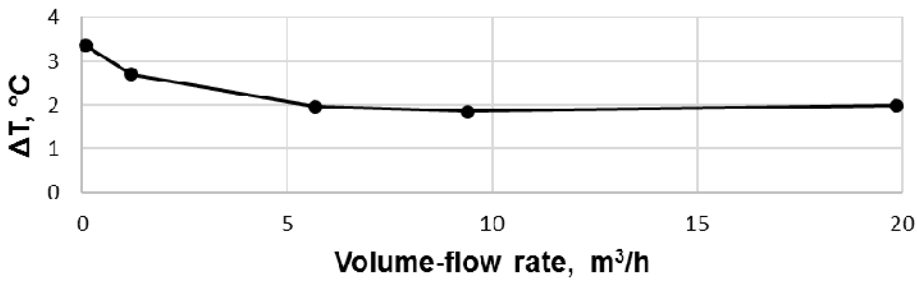


Fig. 1. Dependence for the temperature difference between the liquid on the surface and the axis of the pipeline (measurement error) and the volume flow

It is also obvious that for large Re numbers the flow in the tube is intensively mixed, that usually leads to the appearance of a uniform temperature field practically along the entire pipe cross section with some maximum gradients in a narrow vicinity of the pipe walls, where formed maximum measurement error. The thought of flow mixing is constantly present in the literature and, especially, in the literature on measuring the flow of multiphase flows [2], versus many devices with forced influence the flow [3]. There is design with natural influence the flow, for example, overcoming for relief of the terrain, features of laying the pipeline, etc. In particular, it is known that when a multiphase flow contains gas and liquids parts and move in a vertical direction, the structure of the flow has an annular or, on the contrary, axial concentration of the gas, while in the center of the tube the gas content can be greater than that near the wall [4–8]. We do not know how such a flow structure can affect the quality of non-intrusive measurements, but in any case, restructuring the flow structure in a small enough area naturally leads to mixing, which is especially pronounced at the turning points of the pipe.

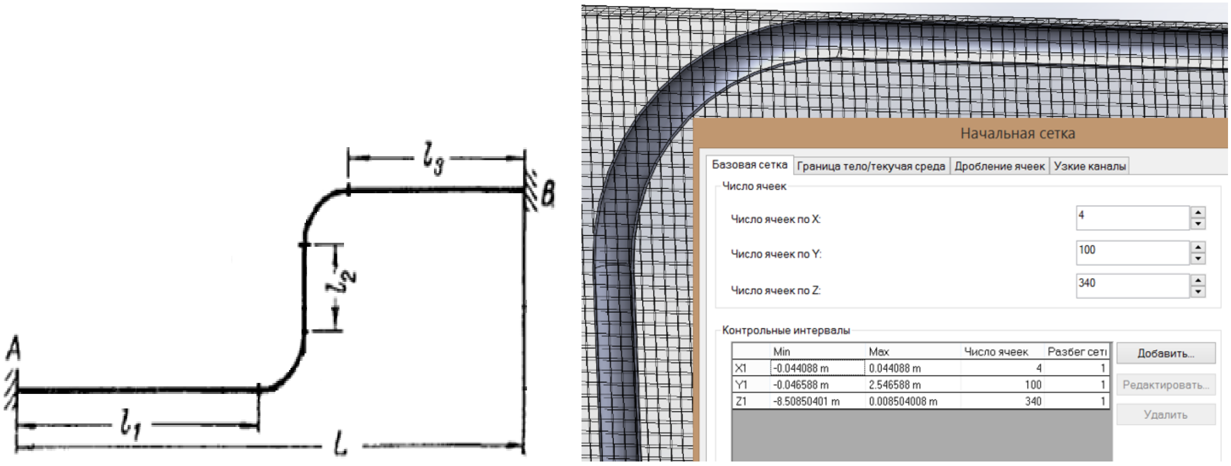
Standard pipe laying always accompanied by the installation of compensators of various configurations to meet the requirements for rigidity to thermal elongations, strength [9], etc. We will study the effect of the geometric parameters of compensators the accuracy of non-intrusive measurements to determine the potential of using compensators as measuring places.

2. Compensators: features of application, settings and initial data for modeling

According to GOST R 55989–2014, the compensator is a section of pipe with a special design to perceive the temperature deformations of the pipeline due to its flexibility. High static loads, pressure drops, hydraulic shocks, etc. cause deformation of pipeline materials, therefore, when planning the pipeline, it is necessary to take into account overloads and to perform a design with the self-compensation ability. Compensators are used in the oil and gas industry, energy, housing and communal services and many other areas of the economy and there are various types and designs: open, bellows, stuffing boxes and others [10].

The magnitude of longitudinal movements from internal pressure and temperature should be calculated, for example, for junctions between trunk pipelines and the binding pipelines, in places of overcoming through water channels, etc. To reduce the longitudinal movements of the pipeline, uses U-shaped, Z-shaped or other shape compensators. It strongly recommended for pipes with flow temperature above 50 °C.

The most typical open compensator is considered, the diagram is shown in Fig. 2a, with minimum permissible geometric parameters, obtained on the base calculation procedure [11].



a) b)

Fig. 2. Z-shaped pipe (compensator): a) compensator diagram; b) grid – initial decomposition

The data in Table 1 correspond to the standard pipeline diameters (the minimum allowable bend radius of the pipeline must be at least five of its diameters [10]) and used in the finite element modeling in the FlowSimulation SW computing environment (Fig. 2b).

Table 1

The minimum length of the compensating elbow of the Z-shaped compensator with the flexibility of pipe bends

Nominal diameter (DN), mm	The minimum length of the compensating elbow for flow temperatures l_2, m		
	t = 150 °C	t = 250 °C	t = 300 °C
80	1,5	2,1	3,5
150	2,5	3,5	5,5
300	5	7	11

3. Simulation modeling. Distribution of temperatures in the cross section of pipe compensator

Calculations performed in the FlowSimulation module with initial settings that consider gravity and roughness of the inner walls [12]. Water selected as a fluid flow with a temperature of 80 °C.

Here, two problems are solved together: the problem of hydrodynamics for an incompressible fluid (Euler's equations) and the thermal problem (heat balance equations) [13]. As the boundary conditions in the problem of hydrodynamics, the set flow rate at the inlet to the compensator and the preset pressure at its output are used. In the thermal problem, it is necessary to determine the influence of flow hydrodynamics the temperature distribution, so the influence of external conditions outside of pipe wall is eliminated and the boundary condition on the inner side of wall is assumed to be adiabatic (zero heat flux). For the thermal state of the input stream to absorb the kinetics of the liquid and the temperature, thereby, being redistributed in accordance with the velocity distribution, a sufficiently long rectilinear pipeline section is required before the first elbow of compensator. The temperature of the liquid at the inlet to the compensator is 80 °C and uniformly distributed over the cross section of the tube. Note that the standards recommend perform flow measurement at the pipe with length of the rectilinear section of the pipe at least 10 diameters [14].

At this stage, the correct choice of flow rate values has a great importance, since it is necessary to simulate various flow regimes. Let us preliminarily select the Reynolds numbers characterized the different flow regimes in the pipelines and determine the corresponding velocities of the fluid flows. These numbers are: 1300 – exclusively laminar flow regime, 2200 – transitional regime, characterized by the appearance of “disturbances” of the flow, 4500 – the beginning of the turbulent flow regime, 22000 –

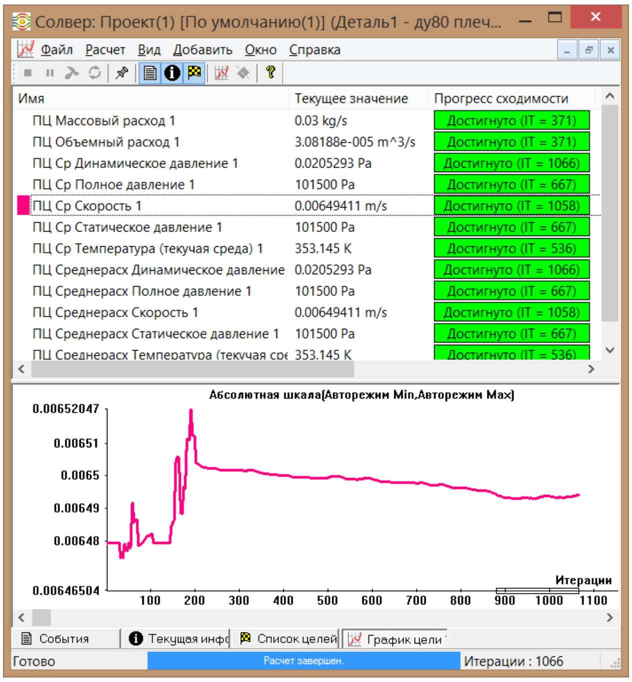


Fig. 3. The result of the calculation – The graph of iterative convergence by the flow rate for one of the calculated cases with the initial grid settings

the deeply turbulent flow regime [15]. These numbers approximately correspond to mass flow rates of 0.03; 0.05; 0.1 and 0.5 kg/s, which are then converted into the flow velocity necessary for the numerical solution of the hydrodynamic problem for DN, 80, 150 and 300 mm pipes.

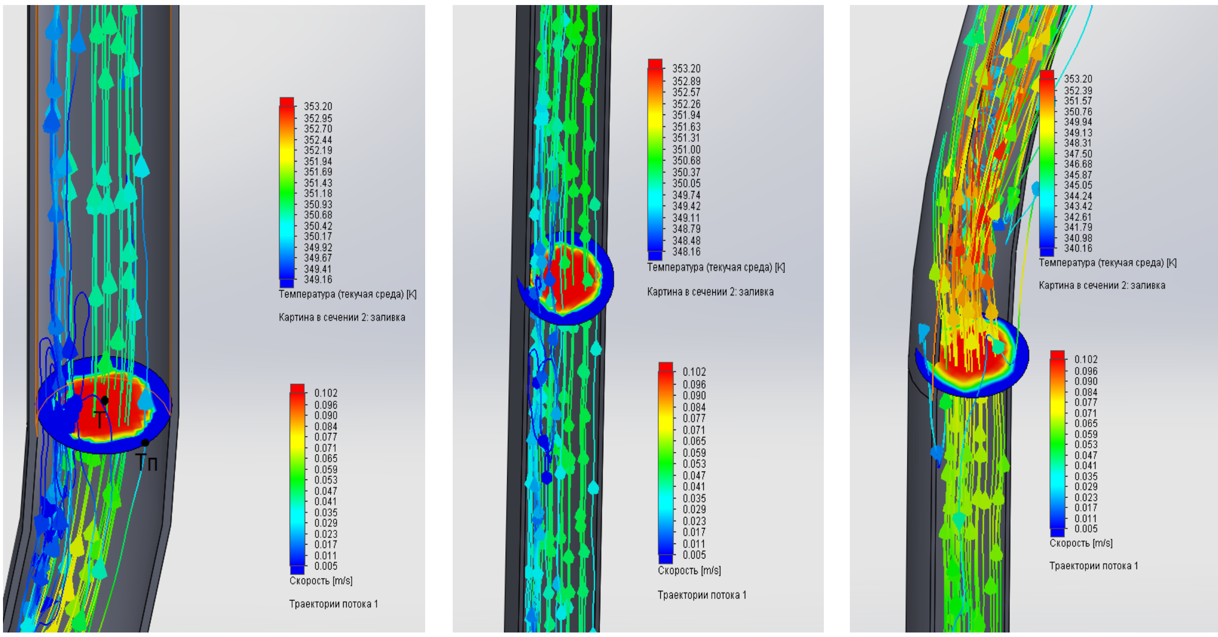
In Fig. 3 shown graph for a flow of 0.03 kg/s in a DN 80 pipe that demonstrate the iterative convergence of the problem with a standard relative error of 0.001. If we decrease in the basic size of the grid, there is no changes in the achieved values of the flow velocity, which determines the approximate convergence of the problem with the above error of iterative convergence. If we increase flow velocity with pronounced turbulent flow, the structure of the flow can be very complicated, that requires to check the approximation convergence each time.

As the main result of the simulation, the relative error in measuring the flow temperature at the pipeline surface in the vertical elbow of the compensator is considered:

$$\delta = \frac{T_s - T}{T} \cdot 100\ \%, \quad (1)$$

where T_s – pipe surface temperature, T – center line flow temperature.

Fig. 4 shows examples of the obtained temperature distributions with flow lines for a flow rate of 0.1 kg/s in the DN 80 pipe.



a) b) c)

Fig. 4. Temperature distributions in the pipe cross section at the beginning (a), middle (b), end (c) of the vertical elbow of compensator

4. Simulation results

Verification of gravity influence to simulation results is shown in Fig. 5. We see that gravitation has a significant influence on the accuracy, especially in the middle range of Reynolds numbers with introducing some "orderliness" into the flow in the form of its annular or other axisymmetric shape, that contributes to its structuring with a less level of turbulence. It increases the temperature measurement error (1) in the cross section of the pipeline. Concluded that the gravity calculation option must be included in subsequent calculations.

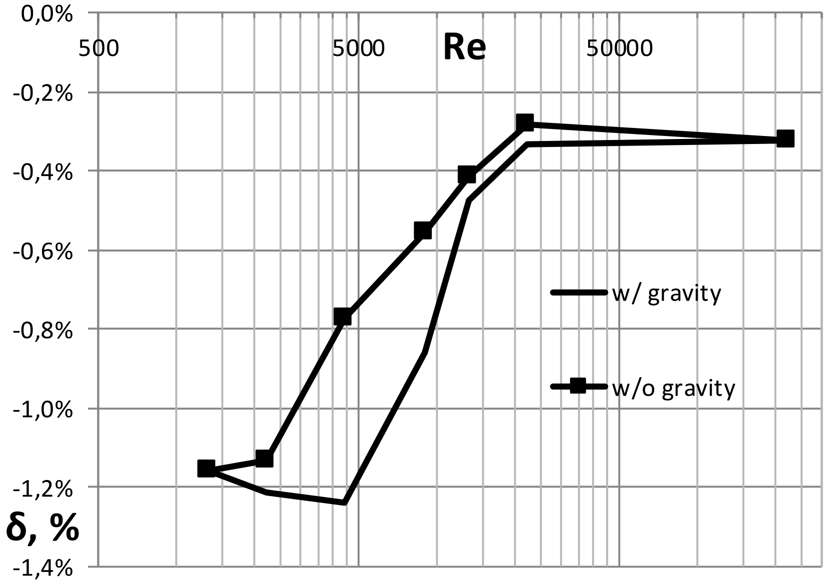


Fig. 5. The gravity influence on the measurement error in the middle of the vertical elbow of the compensator (DN = 80 mm, elbow l_2 = 1.5 m)

Graphs on the Fig. 6, 7 are illustrate the relative errors of non-intrusive flow temperature measurement in relation to the flow regime (Reynolds number value) for DN 80 pipeline for three measurement sites: at the beginning, middle and end of the vertical elbow of the compensator.

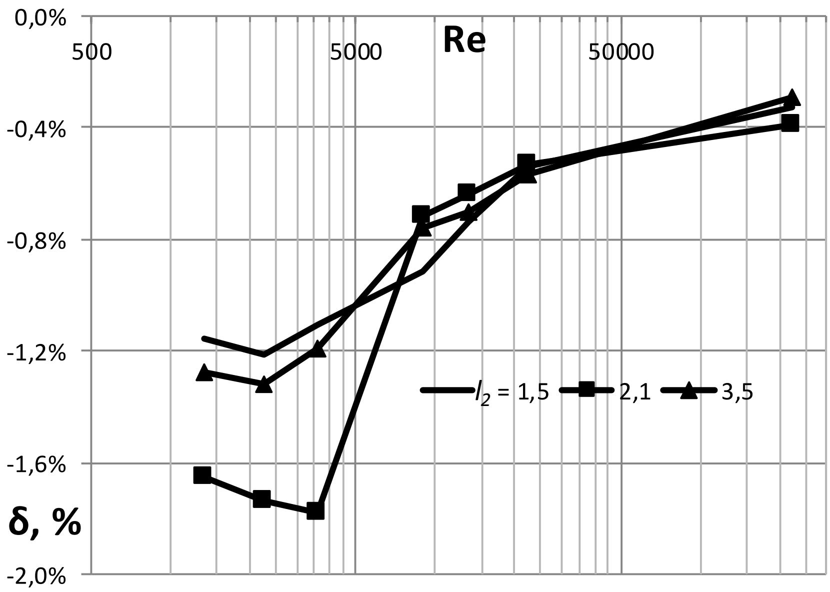


Fig. 6. The errors in the non-intrusive temperature measurement for DN 80 pipeline at the beginning of vertical section of the compensator with the length of the elbow l_2 = 1.5; 2.1; 3.5 m

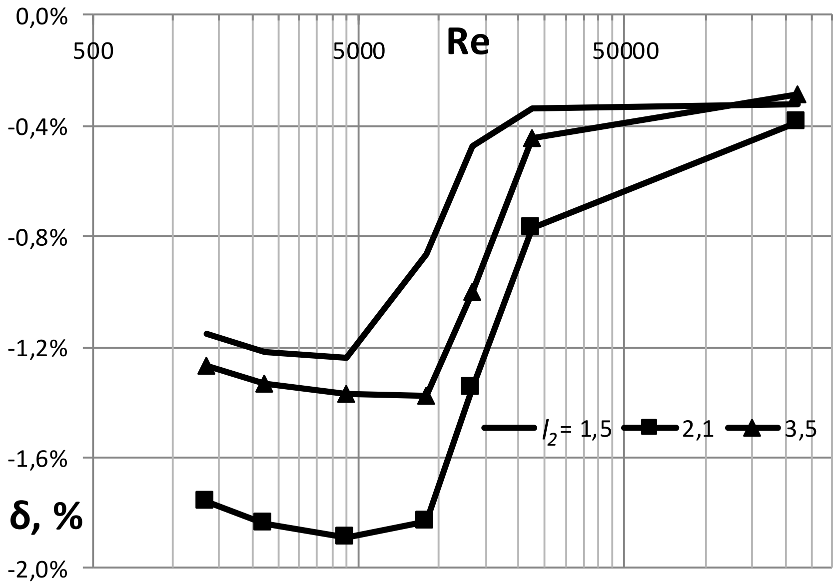


Fig. 7. The errors in the non-intrusive temperature measurement for DN 80 pipeline at the middle of vertical section of the compensator with the length of the elbow l_2 = 1.5; 2.1; 3.5 m

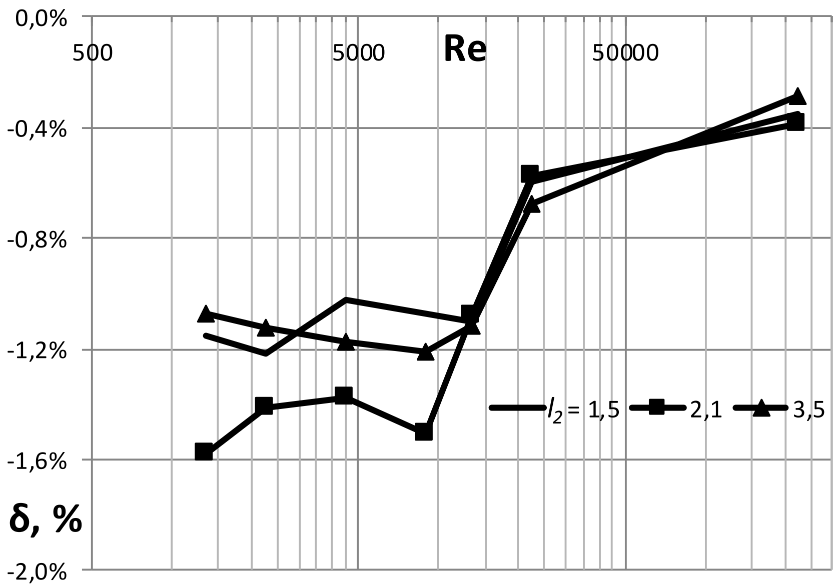


Fig. 8. The errors in the non-intrusive temperature measurement for DN 80 pipeline at the end of vertical section of the compensator with the length of the elbow l_2 = 1.5; 2.1; 3.5 m

Seen that the errors obtained for the start and end of compensator elbow smaller (Fig. 8) than for the middle of elbow (Fig. 6–8). It points an additional turbulence of the flow by each elbow. It is also shown by temperature distributions for this pipe diameter: for example, the range of temperature distributions (measurement error) in the cross section of the pipe (Fig. 4a) after the lower bend is significantly less (349.15–353.2 K) than before (Fig. 4b) with the upper bend (340.16–353.2 K), with the changing at the lower side of the range. It follows that the measurements should be carried out at the end of the vertical section of the pipe behind the upper bend.

It is also obvious that the influence of the compensator the measurement error is manifested at the beginning and middle of the Re number range under consideration. For large Re numbers the flow is naturally turbulized, that minimizing the measurement error, and no additional measures are required.

Fig. 9 and 10 show graphs for the relative errors of non-intrusive flow temperature measurement, depending on the flow regime (Reynolds number) for DN 150 and 300 pipelines when temperature measuring the in the middle of the vertical elbow.

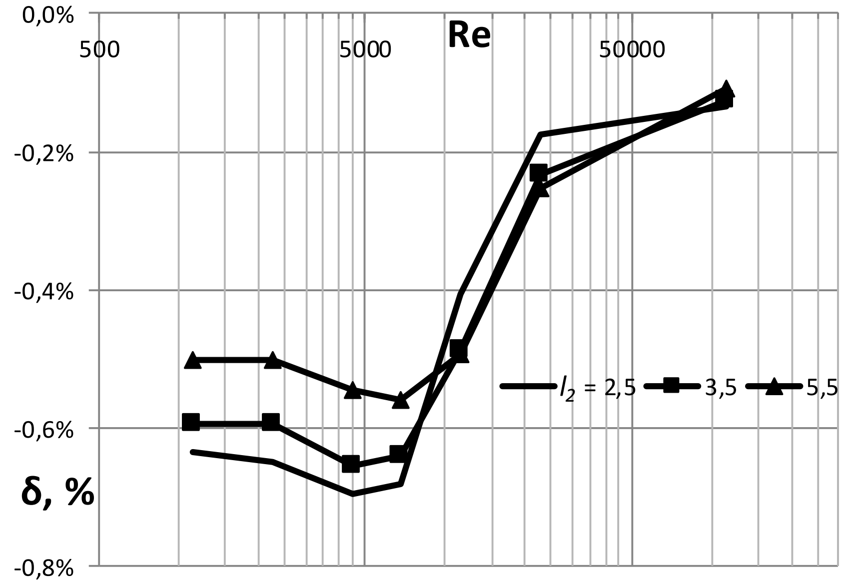


Fig. 9. The errors in the non-intrusive temperature measurement for DN 150 pipe compensator with the length of the elbow l_2 = 2.5; 3.5; 5.5 m

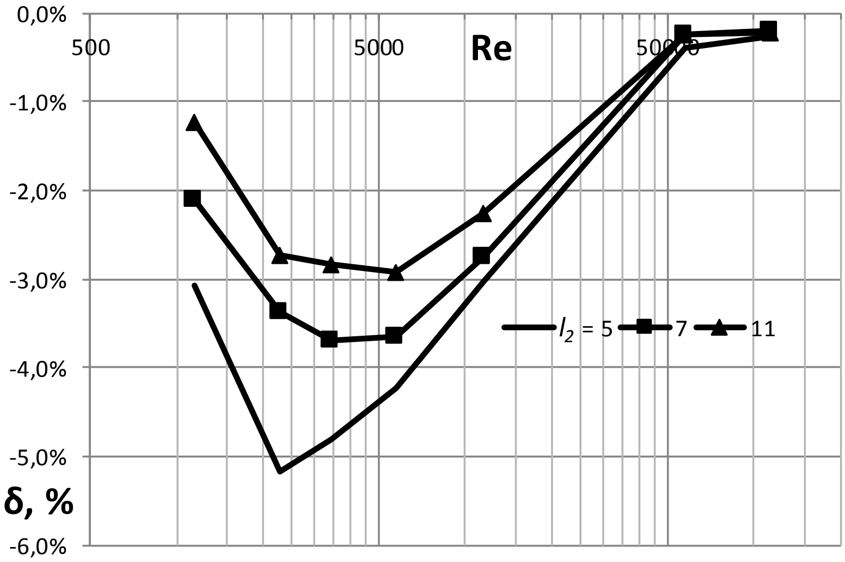


Fig. 10. The errors in the non-intrusive temperature measurement for DN 300 pipe compensator with the length of the elbow l_2 = 5, 7, 11 m

Obtained dependencies show that there is a repetition of the error-correction trends, but for the DN 150 pipeline, the errors at the beginning and the middle of the Re number range are less than those obtained for the pipeline with the DN 300. It is not possible to explain the physics of such a large error changing at this stage of study, since a more costly approach is required, based on systematic study (variation) of the pipeline parameters. In this work a different technique was used – studying the effect on the error of existing types of compensators by enumeration of their standard sizes.

Analysis of the graphs allows us to conclude that temperature drop decreasing with velocity increasing agrees with the experimental study presented at the beginning of this paper. Seen that the shape of the obtained curves are similar, but as the diameter of the pipe increases, the error decreases with even greater Re numbers, and the transition process from the laminar to the turbulent regime occurs more smoothly.

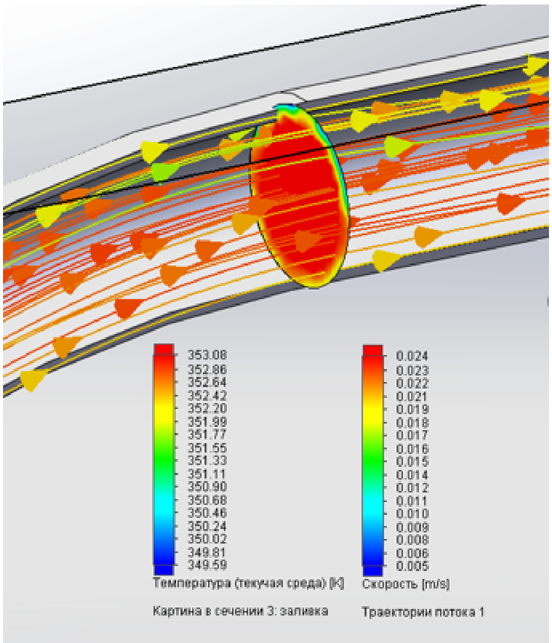


Fig. 11. Temperature distributions in the pipe cross section after vertical elbow of compensator for low speed flows

The error decreasing for small Re numbers, seen in Fig. 5–10 in the left part of the graphs is most likely associated with the redistribution of velocities in the flow: the velocity diagram in the laminar flow assumes an increasingly parabolic form with decreasing velocity (and not uniform as in the turbulent flow). It leads to increasing of kinetic energy and, because of the conservation laws, a decreasing of flow thermal energy.

It should be noted that the temperature distribution in Fig. 11 at a flow velocity of 0.024 m/s (it is about 5 times lower than the speed in Fig. 4) in the range of 349.59–353.08 K. It is obvious that the maximum value of the temperature range located on the pipe axis has already started to decrease, that was not at the high flow velocities shown in Fig. 4. In some degree it balances the temperature field and thereby reduces the measurement error.

Conclusion

Conducted numerical study is consistent with the results of laboratory tests and allows us to answer the question of whether compensators can be used as a place for non-intrusive measurements of flow temperature in pipelines. Indeed, it is possible, but after the upper or lower elbow of the compensator and these measurements can improve the accuracy in the range of Reynolds numbers about 1000–7000, that characted for the onset of turbulent fluid flow. Gravitation adversely affects the accuracy of measurements, so preference should be given to horizontally located compensators.

The existing surface temperature sensors, with correction the surface temperature measurements to the flow temperature, require calibration to work on flows with Re numbers varying over a wide range.

It should be emphasized that non-intrusive measuring devices are one of the modern promising and profitable tools that stimulate the improvement of technologies and the involvement of world corporations in this sphere, while the growing intellectualization of measurements positively affects the safety and efficiency of the industry.

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НЕИНТРУЗИВНОЕ ИЗМЕРЕНИЕ ТЕМПЕРАТУРЫ ПОТОКОВ ЖИДКОСТИ С ИСПОЛЬЗОВАНИЕМ ТРУБОПРОВОДНЫХ КОМПЕНСАТОРОВ

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Приводятся результаты численного исследования, которое направлено на повышение точности неинтрузивных измерений температуры жидкой среды в трубопроводах на основе использования типовых компенсаторов. Неинтрузивные средства измерений являются одними из современных перспективных и выгодных в эксплуатации средств, которые стимулируют совершенствование технологий и вовлечение в их разработку мировых приборостроительных корпораций, при этом растущая интеллектуализация измерений положительно сказывается на безопасности и эффективности работы промышленности.

Проведенное численное исследование согласуется с данными натурных измерений и показывает общую закономерность влияния скорости потока на погрешность неинтрузивных измерений температуры. Показано, что проведение измерений после верхнего или нижнего колена компенсатора позволяет снизить погрешность измерений в диапазоне чисел Рейнольдса (Re) примерно 1000–7000, что характерно для начала турбулентного течения жидкости. Показано также, что гравитация отрицательно влияет на точность измерений, поэтому предпочтение надо отдать горизонтально расположенным компенсаторам.

Обнаружено, что течение потока по трубопроводу при сравнительно больших числах Рейнольдса определяет наибольшее изменение температуры в пристеночной области трубы, а при малых числах Re – по оси трубопровода. Это в сочетании с особенностями течения в компенсаторе меняет характер распределения температур и изменения погрешности в зависимости от скорости течения потока в трубопроводе. В частности, этот эффект определяет уменьшение погрешности измерения температуры в компенсаторе при малых числах Re.

Существующие накладные датчики температуры, имеющие коррекцию поверхностных измерений температуры в температуру потока, требуют доработки для работы на потоках с числами Re, изменяющимися в широком диапазоне, при этом привязка таких измерений к трубопроводным компенсаторам может повысить качество измерений за счет сглаживания и, в том числе, флуктуационных тепловых и гидродинамических воздействий.

Ключевые слова: давление, расход, температура, неинтрузивное измерение, погрешность, число Рейнольдса, трубопроводный компенсатор, моделирование течения, распределение температур.

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