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JUSTIFICATION OF THE POSSIBILITY OF BUILDING AN INTEGRATED ULTRASONIC MEASURING TRANSDUCER OF NATURAL GAS CONSUMPTION

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Abstract. *The paper establishes the feasibility of constructing an integrated ultrasonic measuring transducer for measuring natural gas consumption. Various schemes for combining ultrasonic transducers with flow conditioning devices, along with several natural gas parameter measuring transducers, were analyzed. The design of an integrated ultrasonic meter that eliminates the need for a standard straight pipeline section and external jet straightener was explored. Simulations of 4-beam ultrasonic meters with known local resistances and the integrated ultrasonic meter were conducted using SolidWorks. The comparative analysis revealed the advantages of the proposed integrated ultrasonic meter.*

Keywords: integrated ultrasonic measuring transducer, flow conditioner, straight pipeline section

UZASADNIENIE MOŻLIWOŚCI STWORZENIA ZINTEGROWANEGO ULTRADŹWIĘKOWEGO PRZETWORNIKA DO POMIARU ZUŻYCIA GAZU ZIEMNEGO

Streszczenie. *W niniejszej pracy przedstawiono uzasadnienie możliwości stworzenia zintegrowanego ultradźwiękowego przetwornika do pomiaru zużycia gazu ziemnego. Dokonano analizy różnych schematów łączenia przetworników ultradźwiękowych z urządzeniami do przygotowania przepływu, a także przeanalizowano szereg przetworników mierzących parametry gazu ziemnego. Opisano konstrukcję zintegrowanego miernika ultradźwiękowego, który nie wymaga standardowego prostego odcinka rurociągu ani zewnętrznej prostownicy strumieniowej. Przeprowadzono symulację 4-wiązkowych liczników ultradźwiękowych o znanych rezystancjach lokalnych oraz zintegrowanego licznika ultradźwiękowego w środowisku SolidWork. Analiza porównawcza wykazała zalety proponowanego zintegrowanego miernika ultradźwiękowego.*

Słowa kluczowe: zintegrowany ultradźwiękowy przetwornik pomiarowy, prostownica strumieniowa, prosty odcinek rurociągu

Introduction

Ensuring comprehensive and transparent accounting of natural gas, as well as all fuel and energy resources, is a key priority outlined in Ukraine's current energy strategy [8].

The accuracy of natural gas consumption measurement relies on the operational and metrological characteristics of the gas accounting unit, which constitutes a complex information and measurement system for monitoring natural gas consumption. Typically, such a system includes a meter, a gas volume corrector, a set of straight pipeline sections of a specific length, and a range of sensors measuring pressure, temperature, and gas density. Additionally, a chromatograph may be used [1] for analysis.

1. Research results

Currently, one of the most advanced technologies for natural gas flow measurement is the use of ultrasonic primary transducers. These ultrasonic flow meters account for over 10% of the global market share for flow measurement devices across various energy carriers. Ultrasonic flow meters offer several key advantages, including a wide dynamic measurement range, absence of pressure loss, no moving parts resulting in increased reliability, low energy consumption, and the ability to be installed without interrupting the process flow (for clamp-on meters). Moreover, they maintain their technical and operational characteristics over time with a typical relative error of 1–1.5%. However, it's important to note some drawbacks associated with these systems. Ultrasonic flow meters can be sensitive to deviations in flow profile during operation compared to their calibration profile. Additionally, they may experience signal distortion with asymmetric velocity profiles and require ongoing monitoring of the physicochemical properties of the measured medium [2, 5].

Today, there are two primary methods for addressing these challenges. One approach involves using flow conditioning devices, such as a straight section of pipeline of a specific length placed upstream of the ultrasonic meter, or specialized flow conditioners. These devices are designed to minimize flow disturbance and reduce deformation of the gas velocity profile within the pipeline [7]. However, using a straight pipeline section typically requires a length of at least ten pipeline diameters, leading to increased complexity and size of the overall flow measurement system. Therefore, a novel design approach has been proposed, which integrates ultrasonic measuring transducers with the flow conditioning system. This integrated design eliminates the need for a straight pipeline section, significantly reducing the system's dimensions and overall cost.

In this study, we conduct simulations of ultrasonic measuring transducer operations and perform a comparative analysis involving established designs, such as those featuring straight sections, single and double elbows, and a configuration incorporating two elbows with 'half-moon plate', alongside our proposed system design.

The simulation was carried out in the SOLIDWORKS Flow Simulation environment, which is a convenient computational fluid dynamics (CFD) environment built into SOLIDWORKS 3D CAD. It allows to simulate fluid and gas flows to calculate the performance characteristics and capabilities of the tool used. Thanks to this approach, it is possible to set up experiments with minimal time and financial investment. In addition, in some cases, this method of obtaining information is almost the only possibility of detecting the effects of the complex interaction of the measured medium with sensitive elements of the flow converters [6].

The simulation was conducted to assess the impact of local resistances on flow profiles according to ISO17089 standards. This evaluation included an ultrasonic meter positioned at a distance of 10 pipe diameters (DN), along with 90º elbows, two elbows in different planes, and two elbows in different planes with a "half-moon plate". Additionally, a conventional 4-beam ultrasonic meter was employed, preceded by a flow conditioner (refer to Fig. 1). Beyond a specified distance from the flow conditioner, it was possible to achieve an undistorted symmetric gas velocity profile.

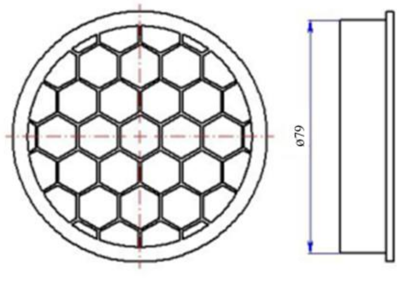

Fig. 1. Honeycomb flow conditioner

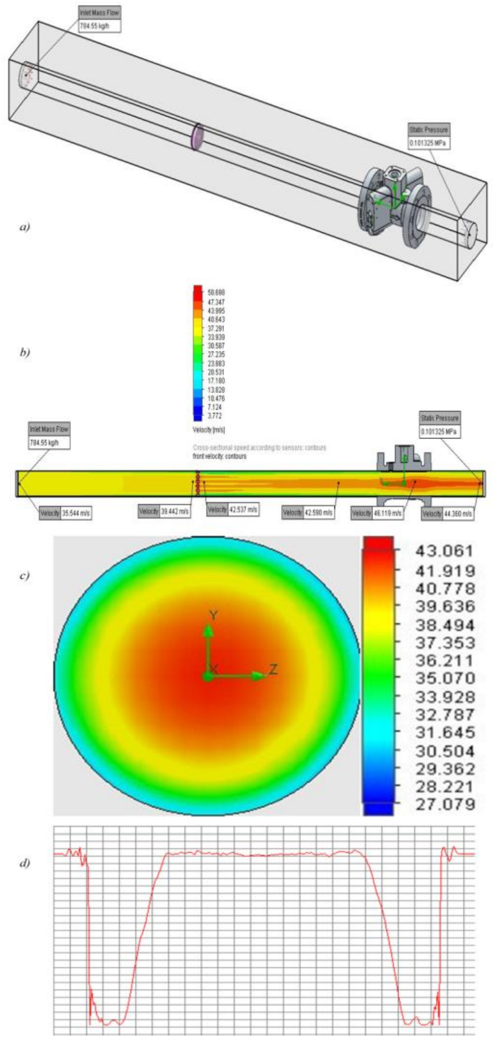

Fig. 2. 4 beam ultrasonic meter in the SolidWork environment: a) appearance; b), c) simulation results – flow velocity distribution, d) graph of the flow rate of the first chord channel

Below are the simulation results obtained using a 4-channel ultrasonic measuring transducer and under the under the specified modeling conditions:

- task type: internal,
- the diameter of the pipeline DN is 80 mm,
- the length of the straight section from the jet rectifier to the meter is 10 DN,
- the length from the local resistance to the jet rectifier is 10 DN
- flow conditioner type – honeycomb (Fig. 1),
- flow at the entrance: 650 m^3/h,
- media pressure at the outlet: 0.101325 MPa,
- temperature conditions: adiabatic wall,
- type of medium: air (air, gases),
- roughness: 0 microns,
- turbulence model: k-ε,
- level of initial mesh: 6.

The velocity distribution flow profile from the first ultrasonic measuring transducer was utilized to compare the characteristics of the structures being studied, as it experiences the most significant distortion in the flow velocity profile at its location.

Figure 2 depicts the simulation of a 4-beam ultrasonic meter with a straight section positioned at a distance of 10 pipe diameters (DN). The simulation results revealed that the flow rate graph of the first channel is symmetrical and serves as a reference for comparison. Moving forward, this flow rate graph will be compared with the profiles of the flow rate from the analyzed structures.

Figure 3 shows the simulation results of a 4-beam ultrasonic meter with local resistance from a single 90º elbow. The graph in Figure 4d illustrates a distortion in the flow velocity profile, indicating the presence of measurement error that requires correction for accurate measurement results.

Figure 4 illustrates a simulation of a 4x beam ultrasonic meter with a local resistance with two elbows. The presence of two elbows compared to one, leads to additional distortion in the flow velocity profile as shown in Fig. 4d.

Figure 5 presents the simulation of a 4-beam ultrasonic meter with a local resistance with two elbows and "half-moon plate". As shown in the graph (Fig. 5d), there is noticeable distortion of the flow velocity profile.

While this approach resolves the measurement accuracy issue through data correction, it comes with drawbacks such as increased pressure drop and overall system dimensions due to the inclusion of a straight pipeline section and multiple ultrasonic measurement channels. Consequently, these factors contribute to higher system costs overall.

In this study, an innovative approach involves utilizing an ultrasonic measuring transducer housed within a specialized chamber equipped with a built-in flow conditioner to mix and redirect the flow [4]. This integrated design enables a compact structure, with all components seamlessly integrated into a unified whole (refer to Fig. 6).

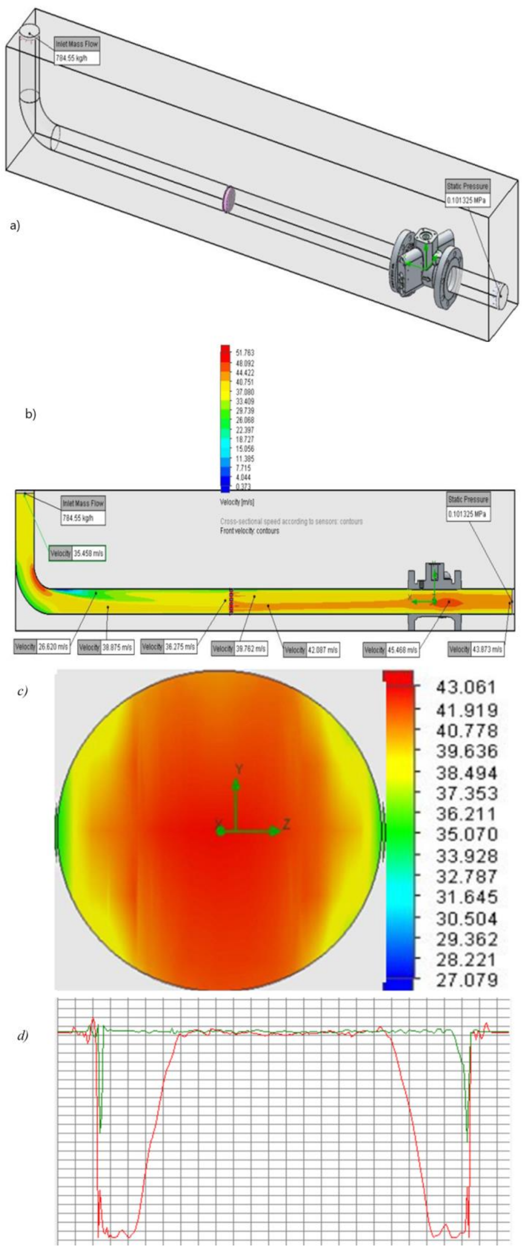

Fig. 3. 4 beam ultrasonic meter with local resistance 90° elbow in the SolidWork environment: a) appearance; b), c) simulation results – flow velocity distribution, d) graph of the flow rate of the first chord channel

Rather than incorporating a straight section equivalent to 10 pipe diameters (DN), the meter features a dedicated measuring channel 4, accompanied by inlet flow conditioner 6 and internal flow conditioner 5, as well as a flow fairing 3. These elements work collectively to establish a symmetrical gas velocity profile within the measuring channel 4. As shown in Fig. 6, this entire structure, together with ultrasonic transducers, is located in a special chamber 1.

Figure 7 displays the simulation results of a 4-beam integrated ultrasonic meter.

Figure 8 presents the simulation results of another 4-beam integrated ultrasonic meter.

The preliminary simulation results have demonstrated the feasibility of developing an integrated natural gas flow measurement system capable of achieving a symmetrical, undistorted gas velocity profile (see Fig. 8a).

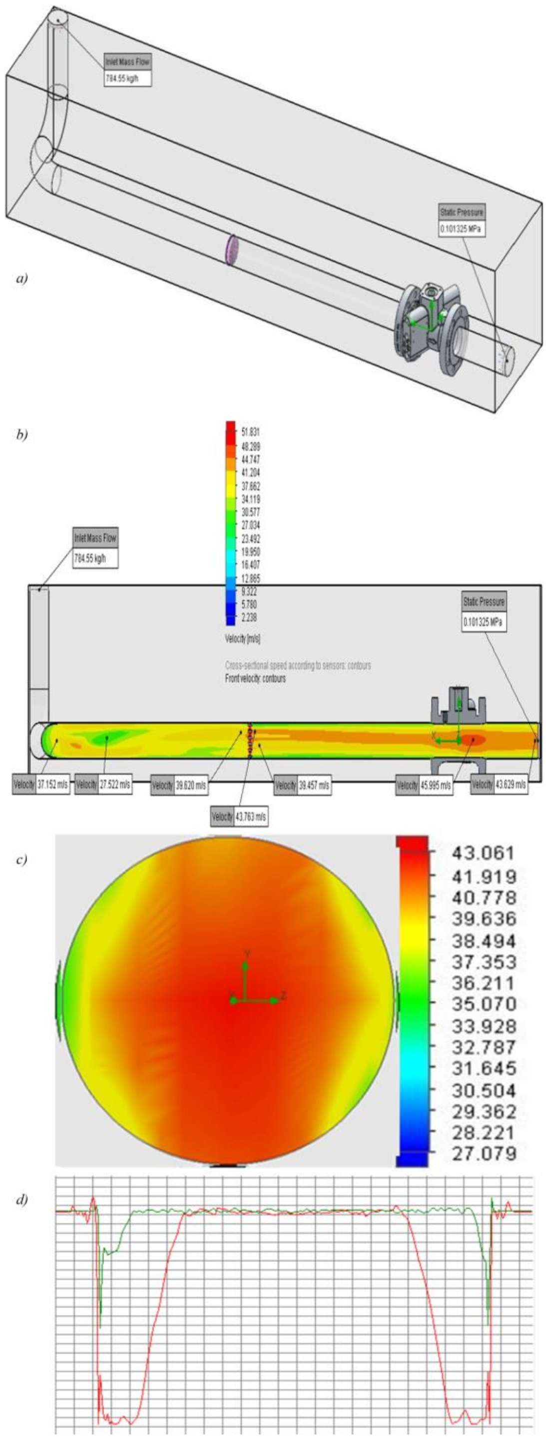

Fig. 4. 4 beam ultrasonic meter with local resistance two elbows in the SolidWork environment: a) appearance; b), c) simulation results – flow velocity distribution, d) graph of the flow rate of the first chord channel

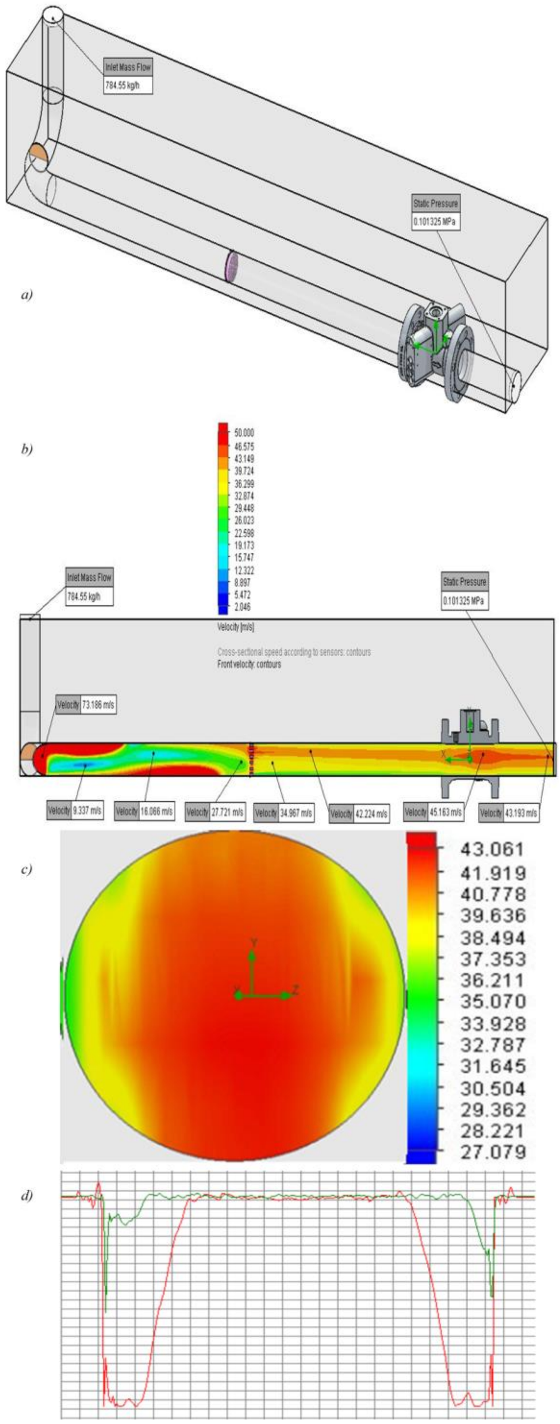

Fig. 5. 4 beam ultrasonic meter with local resistance two elbows and "half-moon plate in the SolidWork environment: a) appearance; b), c) simulation results – flow velocity distribution, d) graph of the flow rate of the first chord channel

Given that the simulation results for the aforementioned ultrasonic transducer designs are presented as images depicting flow velocity distribution across the pipeline cross-section, we utilized the well-established Peak Signal-to-Noise Ratio (PSNR) criterion [3] for quantitative assessment. This criterion is commonly used to measure distortion levels in image compression. The simplest method to calculate PSNR is through Mean Square Error (MSE), which is computed as follows for two monochrome images of size m×n – one considered ideal and the other distorted:

$$PSNR(n,m) = 20Lg\frac{255}{\sqrt{\frac{1}{N}\sum_{i=1...N} d(n_i,m_i)^2}}$$

where is N – the total number of pixels in each image; n_i, m_i – pixels of the two compared images; $d(n_i, m_i)$ – the difference between the colors of the corresponding pixels (for grayscale it is simply the difference in pixel values, and for color images it is the Euclidean distance between pixels in a three-dimensional color space).

According to the criterion, a higher PSNR value indicates better design quality.

Numerical simulation results are provided in table 1.

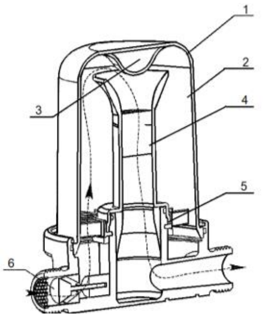

Fig. 6. Design of an integrated ultrasonic measuring transducer

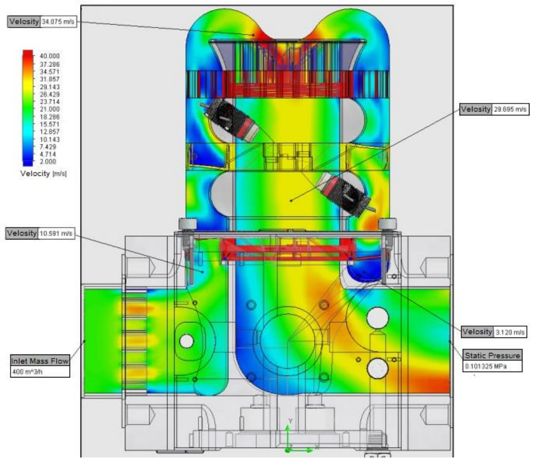

Fig. 7. 4 beams integrated ultrasonic meter in the SolidWork environment

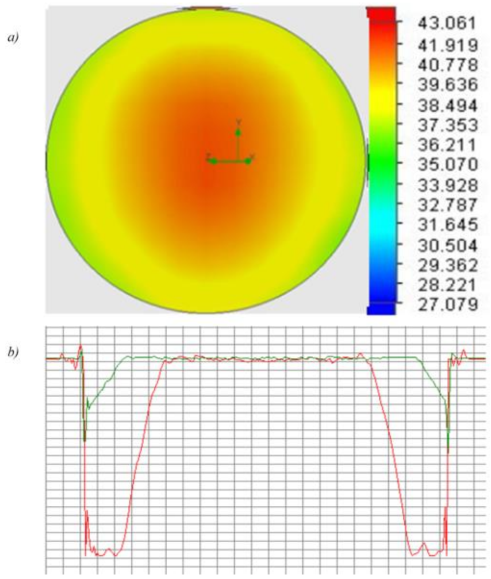

Fig. 8. Simulation results of a 4-beam integrated ultrasonic meter: a) flow velocity distribution; b) graph of the flow rate of the first chord channel

Table 1. Comparative analysis of the performance efficiency of specific ultrasonic meter designs

Design type 4x beam ultrasonic meter	Results of criterion analysis
1. with local resistance (one elbow)	17.895
2. with local resistance (two elbows)	17.747
3. with local resistance (two elbows and "half-moon plate")	17.343
4. integrated ultrasonic meter	18.694

Based on the quantitative analysis conducted on the flow velocity profile images, it can be inferred that there are promising prospects for utilizing an integrated ultrasonic measuring transducer for natural gas flow.

2. Conclusions

The study supports the feasibility of developing an integrated ultrasonic measuring transducer for natural gas flow through modeling and comparative analysis with existing designs. The proposed integrated ultrasonic flow meter eliminates the need for external straight sections and flow conditioners, leading to substantial reductions in system dimensions and overall cost.

The development of this new type of ultrasonic flow meter paves the way for replacing outdated mechanical gas flow meters (such as turbine and rotary meters) with modern ultrasonic technology.

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