Computer-Aided System for Designing the Thermal Energy Metering Devices

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Abstract

The paper presents the developed computer-aided design (CAD) system of thermal energy metering devices, which includes flowmeters with standard primary devices. Theoretical bases for CAD developing are considered, in particular, algorithms for determining the thermal energy amount that are developed by the authors, complete mathematical model of differential pressure flowmeter, realized by taking into account the limitations of standards DSTU GOST 8.586.1-5:2009, IAPWS methods for determining water and steam properties, a method for calculating the isentropic exponent of steam, a method for estimating the uncertainty of measurement result of thermal energy amount, developed by the authors, as well as new approaches to the computer-aided design of thermal energy metering systems proposed by the authors. The main characteristics of subsystem for entering and validating the input data are presented. The CAD dialog box for entering the characteristics of measuring instruments of pressure, differential pressure, temperature, which are the components of thermal energy metering system, as well as the dialog box for entering the characteristics of measuring pipe. The basics of the developed technique for estimating the uncertainty of thermal energy amount that is implemented in CAD are presented. The structure of protocol of designing a thermal energy metering system is considered.

Keywords: computer-aided design system; amount of thermal energy; uncertainty of measurement result; differential pressure flowmeter.

1. Definition of the problem to be solved

Establishing an accurate metering of thermal energy is a necessary condition for its efficient and economical use. Accurate metering of thermal energy amount is performed using modern systems based on microprocessor controllers, which are able to implement complex algorithms for calculating the thermal energy amount using the measured values of the heat carrier parameters. The process of designing and calculating such systems is difficult and laborious, therefore, in order to improve its efficiency it is necessary to develop a computer-aided design (CAD) system for automating the design process.

2. Analysis of publications and research

Computer-aided design systems are software packages for creating, editing and optimizing design and technological documentation. Implementing the software packages for automating the design processes provides the increase of calculations accuracy, quality of technological documentation as well as allows reducing the design process.

The analysis of the information technology market showed that ANSYS, SolidWorks, FlowVision, Mathcad and Maple are the common software packages for designing, modeling and engineering calculations, as well as AutoCAD, KOMPAS and others are the current applications for graphic design [1]. Using these powerful software packages makes it possible to solve a wide range of modeling and design problems. However, such software packages

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do not take into account a number of limitations imposed by current regulations on the design and operating conditions of thermal energy metering systems. Therefore during their application a designer must personally control a large number of such limitations.

CAD "Raskhod-RU", which was developed with the authors' participation, is used for designing the variable pressure flowmeters in Ukraine [2]. This CAD is provided with interactive facilities, so that each user step is analyzed during the process of flowmeter calculating and designing. In case of error or any incorrect actions, CAD gives the user the appropriate tips or recommendations. The interactivity of CAD also involves the recommendations for the flowmeters design, the implementation of which will provide the ability to design a flowmeter according to the requirements of DSTU GOST 8.586.1-5:2009 and, in addition, reduce the uncertainty of measurement result. The recommendations proposed by the program should be implemented by appropriate correction of input data and their subsequent entering. Thus, CAD allows us to automate the process of calculation and design of differential pressure flowmeters and to perform all necessary checks of the conditions of application of differential pressure method according to the requirements of DSTU GOST 8.586.1-5:2009.

Program "Arian ISO-5167 Flow CAD software" of the company "Arian Control & Instrumentation" is the other program with characteristics similar to the CAD "Raskhod-RU" [3]. Arian Flow CAD software allows designing differential pressure flow measurement system based on standard primary devices (such as orifice plates, nozzles and Venturi tubes) according to the requirements of ISO 5167.

However, these CAD systems are not intended for designing the thermal energy metering systems. So today there are no specialized software packages for designing the thermal energy metering systems. Therefore, the development of such CAD systems is a very important task.

3. The purpose of the study

The purpose of the study is to develop a computer-aided system for designing the thermal energy metering devices, which include differential pressure flowmeters with standard primary devices for metering the heat carrier flowrate.

4. Presentation and discussion of the research results

For successful application of computer-aided design system of thermal energy metering devices, this CAD must meet the following requirements:

- to identify automatically the best design solutions in all cases where optimization tasks can be formalized;

- to check automatically the correctness of the input data, taking into account their dimensionality; to generate interactive messages if it is necessary to correct the input data;

- to check automatically the compatibility of decisions made on different parts of the designed system and to adjust incompatible decisions (if it is possible);

- to generate automatically intermediate results in the form familiar to the designer;

- to give to the designer the opportunity to adjust the decisions made by the software package, taking into account the limitations imposed by the physical nature of the process and the requirements of regulatory documents;

- to form interactively the expert recommendations for correcting failed decisions and improving technical or metrological characteristics of the designed devices;

- to form the design results in the documents of a certain form by designer choice;

- to be suitable for improvement without its radical changing.

The authors have developed a computer-aided system for designing the thermal energy metering devices, in which the differential pressure flowmeters with standard primary devices are used for metering the heat carrier flowrate. The theoretical basis for CAD development are the equations for calculating the thermal energy amount and algorithms for determining the thermal energy amount developed by the authors [4], a complete mathematical model of differential pressure flowmeter [5], methods for determining the properties of water and steam [6], technique for calculating isentropic exponent of steam developed by the authors [7], technique for evaluating the uncertainty of the enthalpy of water and steam [8], technique for evaluating the uncertainty of measurement result of thermal energy amount [9], new approaches to computer-aided design of thermal energy metering systems proposed by the authors.

Thermal energy metering system should take into account the parameters of all available flows of heat carrier, the number of which depends on the structure of the heat supply system. The generalized equation, which makes it possible to calculate the thermal energy amount for different structures, has the form [4]:

$$W = \sum_{i=1}^{a} \int_{t_0}^{t_k} q_{1i}h_{1i}dt - \sum_{j=1}^{b} \int_{t_0}^{t_k} q_{2j}h_{2j}dt - \sum_{p=1}^{m} \int_{t_0}^{t_k} q_{fp}h_{cwp}dt \tag{1}$$

where q_{1i}, q_{2j} are the mass flowrates of heat carrier in each supply and return pipelines respectively; q_{fp} is the mass flowrate of heat carrier, used for feeding the system in each p-th feeding pipeline; h_{1i}, h_{2j} are the specific enthalpies of the heat carrier in each supply and return pipelines; h_{cwp} is the specific enthalpy of cold water used for feeding the system; t_k, t_0 are the limits of time interval for calculating the thermal energy amount; a is the number of supply pipelines; b is the number of return pipelines; m is the number of feeding pipelines.

We have considered eight thermal energy metering systems that are most common in the exploitation practice of heat supply networks [4] and the equations of which can be obtained from (1). Particularly, for thermal energy metering system with two flowmeters installed in the supply and return pipelines equation (1) has the form:

$$W = \int_{t_0}^{t_k} q_1 h_1 dt - \int_{t_0}^{t_k} q_2 h_2 dt \cdot \tag{2}$$

The field "Variant of thermal energy metering system" in CAD provides choosing of the appropriate scheme of thermal energy metering system and implementing the corresponding equation for calculating the thermal energy amount. In particular, number 2 in this field corresponds to thermal energy metering system with two flowmeters in supply and return pipelines (see Fig.1).

The CAD includes a subsystem for entering the input data, which automatically checks the correctness of the input data taking into account the dimension selected by the user, generates interactive messages if it is necessary to correct the input data. Particularly, Fig. 1 presents a dialog box for entering the parameters of heat carrier for thermal energy metering system with two flowmeters. The dialog box provides the ability to choose the type of fluid (heat carrier), according to which the appropriate methods for calculating its parameters (density, viscosity and enthalpy) are chosen. CAD realizes calculation of parameters for two fluid types: water and steam. Density and enthalpy are calculated according to the methods of IAPWS [6], isentropic exponent is calculated according to the technique developed by the authors [7].
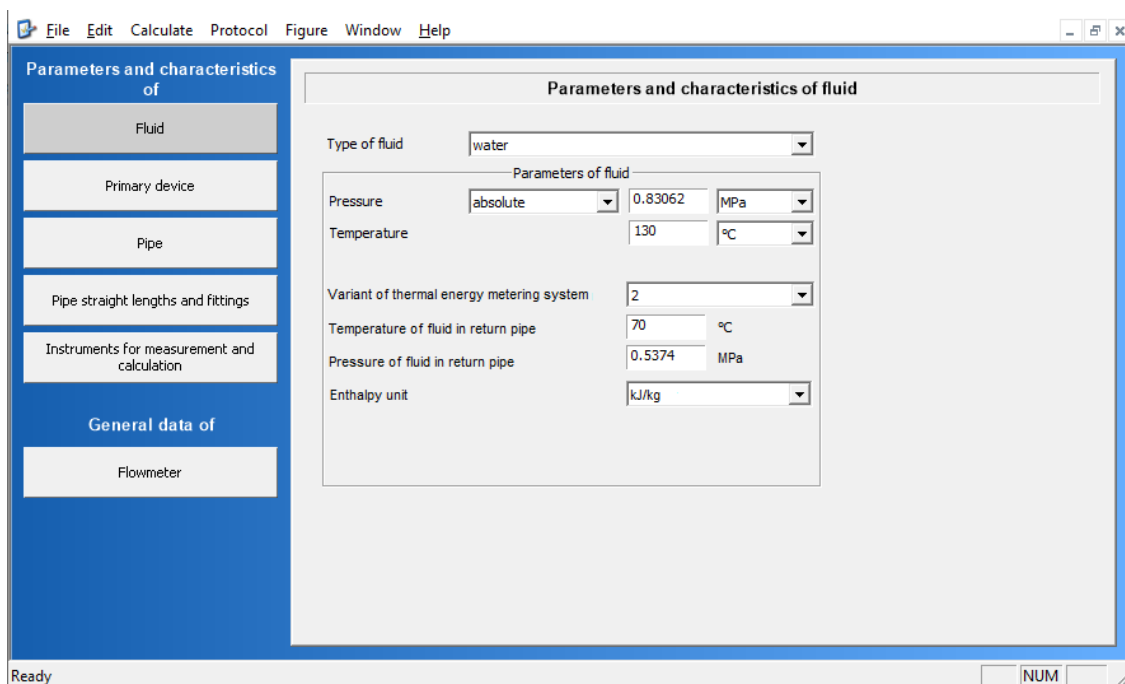

Fig.1. Dialog box for entering the parameters of heat carrier for thermal energy metering system with two flowmeters.

In order to implement the equation (1) and its variants, it is necessary to calculate the value of heat carrier flowrate in supply, return and feeding pipelines, depending on the selected configuration of thermal energy metering system. The developed CAD provides application of differential pressure flowmeters based on standard primary devices at all pipelines. The calculation of the flowrate based on the measuring results of heat carrier parameters, as well as the designing the flowmeters is realized on the basis of a complete model of differential pressure flowmeter, which was developed in [5]. The complete flowmeter model consists of:

- system of equations for calculating the values of: volume and volume or mass flowrate of the fluid, reduced to standard conditions; coefficients of flowrate equation; fluid parameters;

- system of equations for evaluating the uncertainty of: coefficients of flowrate equation; the result of measurement of the fluid flowrate; the result of measurement of the fluid amount;

- system of application conditions and limitations of the flowmeter with the standard primary device:

$$\begin{cases} \dfrac{\Delta p}{p} \leq 0{,}25; \\ d \geq d_{min}; \\ D_{min} \leq D \leq D_{max}; \\ \beta_{min} \leq \beta \leq \beta_{max}; \\ Re_{min} \leq Re \leq Re_{max}, \end{cases} \tag{3}$$

where d_{min} is the minimum allowable diameter of the orifice plate opening at operating temperature; D_{min}, D_{max}, β_{min}, β_{max}, Re_{min}, Re_{max} are the minimum and the maximum values of the inner diameter of measuring pipeline at operating temperature, the relative diameter of the orifice plate and the Reynolds number, respectively.

Requirements for designing the flowmeter with standard primary device, its application conditions, particularly, the limit values of diameter of an orifice plate opening, of pipe diameter, of Reynolds number are defined for each type of primary device in the relevant parts of standards DSTU GOST 8.586.1-5:2009. Therefore the conditions and limitations of these standards were taken into account during implementing the mathematical model of differential pressure flowmeter. So, the CAD system performs designing the flowmeter as well as calculating the fluid flowrate for all pipelines of metering system in accordance with the requirements of standards DSTU GOST 8.586.1-5:2009.

If the heat carrier parameters or the characteristics of the flowmeter components do not meet the requirements of DSTU GOST 8.586.1-5:2009, CAD generates a message or expert recommendations for eliminating the unconformity. Fig.2. presents an example of CAD message about violating the requirements to the relative diameter of the orifice plate (a) and a message with recommendations for eliminating the unconformity of the pipe straight lengths upstream the orifice plate.
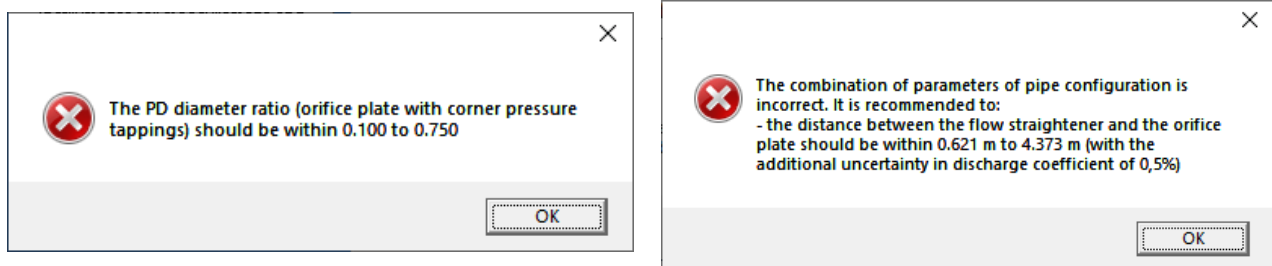
a)   b)

Fig.2. Dialog messages of CAD system of thermal energy metering devices:
a) notification about violating the condition $\beta_{min} \leq \beta \leq \beta_{max}$; b) expert recommendation on adjusting the characteristics of the measuring pipeline.

The choice of flowmeter configuration is also realized in CAD, in particular, the configuration "with calculator of fluid flowrate and amount" or "with measuring complex" can be selected. Depending on the selected configuration, the CAD modifies the tabs to enter the characteristics of the measuring instruments of differential pressure, pressure, temperature, and also implements an appropriate method for calculating the uncertainty of measured flowrate.

A dialog box for entering the characteristics of measuring and calculating instruments is shown in Fig. 3, particularly a tab of the characteristics of measuring instrument of pressure drop on the primary device for the flowmeter configuration "with measuring complex". The tab shows the parameters of metering complex with two accuracy-normalized measurement ranges of differential pressure. Standardization of the error of metering complex for several measurement ranges of differential pressure makes it possible to expand the measurement range of the fluid flowrate. This tab also has a field for entering the measured value of differential pressure of return flow of heat carrier in thermal energy metering system, which implements equation (2).
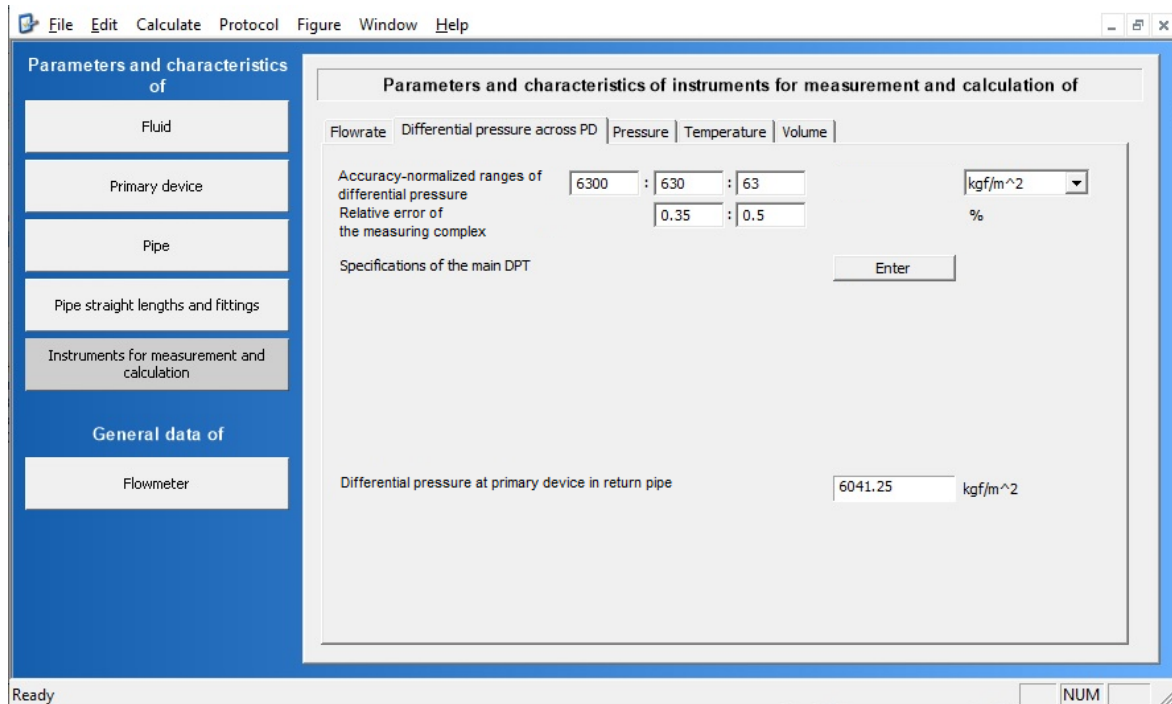

Fig.3. Dialog box for entering the characteristics of measuring and calculating instruments.

An important task to be solved when designing metering systems based on differential pressure flowmeters is to design the configuration of measuring pipeline and pipe straight lengths between the fittings. The configuration and geometric dimensions of measuring pipeline should be designed to provide forming the undisturbed symmetrical flow upstream the primary device. In order to do this the requirements to measuring pipeline should be implemented according to the relevant parts of standards DSTU GOST 8.586.1-5:2009. In particular, the requirements to measuring pipeline with a primary device of the type "orifice plate" are defined in DSTU GOST 8.586.2:2009.

Automation of the design process of the measuring pipeline is performed on the basis of the following approaches:

• types of fittings and their location relative to the primary device are determined by the designer;

• the pipe straight lengths between the fittings are determined on the basis of tabular data of DSTU GOST 8.586.1-5:2009; the interpolation method is used to calculate the values between the "nodes" of the table;

• when choosing the values of the pipe straight lengths, the values of lengths according to option A (see table 4 of DSTU GOST 8.586.2:2009), which provide flow measurement without additional component of uncertainty, have the highest priority.

While designing the measuring pipeline in accordance with the requirements of DSTU GOST 8.586.1-5:2009 it is necessary to determine the design characteristics of the following elements and equipment of measuring pipeline:

• types and sizes of fittings, their location, pipe straight lengths between them;

• location of flow straightener or flow conditioner devices;

• sizes and location of the thermometer;

• sizes of steps and differences between the diameters of sections of measuring pipelines, their location (if available).

The window of the developed CAD system containing tabs for entering the characteristics of all elements and equipment of measuring pipelines is shown in Fig.4.
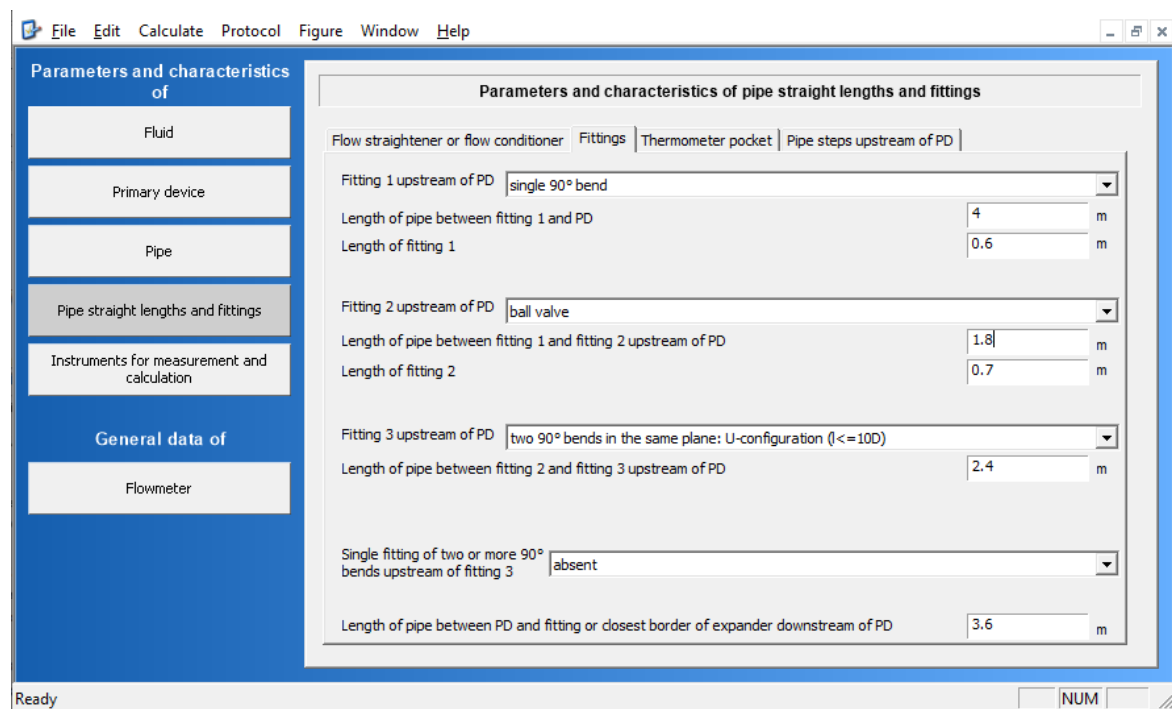

Fig.4. Dialog box for entering the characteristics of measuring pipe.

A window with the main calculation results was implemented in CAD in order to acquaint the designer with the main calculation results of parameters and characteristics of thermal energy metering system. A view of this window during designing the thermal energy metering system that implements equation (2) is shown in Fig.5. The window presents the parameters of heat carrier in supply and return pipelines, the main characteristics of the flowmeter placed at the supply pipeline and the flowmeter placed at the return pipeline, as well as the amount of thermal energy in heat supply systems.

The results of thermal energy amount metering are the subject of commercial relations between its supplier and consumer. Accordingly, it is important to obtain not only the measured value of thermal energy amount, but also the characteristic of the uncertainty (error) of this value. Therefore, it is also necessary to obtain the uncertainty of the result of thermal energy metering according to the results of designing the thermal energy metering system.

The authors developed a technique for estimating the uncertainty of the measured value of the thermal energy amount using the principles described in [10]. Particularly, for the thermal energy metering system based on differential pressure flowmeters, which realizes equation (2), the technique is implemented in the following sequence:

1) to calculate the uncertainty of measurement result of heat carrier flowrate in supply u'_{q1} and return u'_{q2} pipelines, respectively, according to the equations (10.35), (10.36) of DSTU GOST 8.586.5:2009;

2) to calculate the uncertainty of enthalpy of heat carrier, respectively, in the supply u'_{h1} and return u'_{h2} pipelines by the formula [8]

$$u'_h = \left[u'^2_{Mh} + \left(C_{hT} u'_T \right)^2 + \left(C_{hp} u'_p \right)^2 \right]^{0,5}, \tag{4}$$

where u'_{Mh} is the methodological uncertainty of dependence $h=F(p, T)$, $u'_{Mh} = 0,15\%$ [8]; C_{hT} is the relative influence coefficient of the uncertainty of measured value of water (steam) temperature on enthalpy uncertainty; C_{hp} is the relative influence coefficient of the uncertainty of measured value of water (steam) pressure on enthalpy uncertainty; u'_T is the relative standard uncertainty of measured value of water (steam) temperature; u'_p is the relative standard uncertainty of measured value of water (steam) pressure.

Name of parameter	Value	Unit
Type of fluid	water	
Maximum flowrate of fluid at given parameters of the fluid	162.19	t/h
Minimum flowrate of fluid at given parameters of the fluid	16.276	t/h
Upper limit of differential pressure measurement at PD	6300	kgf/m^2
Absolute pressure of the fluid	0.83062	MPa
Thermodynamic temperature of the fluid	403.15	K
Density of the fluid at operating conditions	935.12	kg/m^3
Dynamic viscosity of the fluid at operating conditions	0.00021304	Pa*sec
Enthalpy of fluid in feeding pipe at operational conditions	546.767	kJ/kg
Pipe internal diameter at operating temperature of the fluid	207.17	mm
Diameter ratio of primary device opening	0.44877	-
Reynolds number at maximum flowrate of fluid	1299662	-
Entrance speed coefficient	1.0209	-
Discharge coefficient at Reynolds number corresponding to the maximum flowrate	0.60231	-
Correction coefficient for taking into account the blunting of orifice plate inlet edge	1.004	-
Correction coefficient for taking into account the roughness of pipe internal surface	1	-
Pressure loss at PD at maximum flowrate of fluid	4916.2	kgf/m^2
Orifice plate opening diameter at operating temperature of the fluid	92.974	mm
Orifice plate opening diameter at temperature of 20°C	92.8	mm
Thermal energy flow in feeding pipe	319244740	kJ/h
----------- FLUID IN RETURN PIPE -----------		
Maximum flowrate of fluid at given parameters of the fluid	162.19	t/h
Minimum flowrate of fluid at given parameters of the fluid	16.2712	t/h
Upper limit of differential pressure measurement at PD	6041.25	kgf/m^2
Absolute pressure of the fluid	0.5374	MPa
Thermodynamic temperature of the fluid	343.15	K
Density of the fluid at operating conditions	977.971	kg/m^3
Dynamic viscosity of the fluid at operating conditions	0.00040367	Pa*sec
Enthalpy of fluid in return pipe at operational conditions	293.432	kJ/kg
Pipe internal diameter at operating temperature of the fluid	207.02	mm
Diameter ratio of primary device opening	0.448639	-
Reynolds number at maximum flowrate of fluid	686371	-
Entrance speed coefficient	1.02089	-
Discharge coefficient at Reynolds number corresponding to the maximum flowrate	0.602671	-
Correction coefficient for taking into account the blunting of orifice plate inlet edge	1.00396	-
Correction coefficient for taking into account the roughness of pipe internal surface	1	-
Pressure loss at PD at maximum flowrate of fluid	4714.3	kgf/m^2
Orifice plate opening diameter at operating temperature of the fluid	92.8773	mm
Orifice plate opening diameter at temperature of 20°C	92.8	mm
Thermal energy flow in return pipe	171316907	kJ/h
Amount of thermal energy in heat supply systems	147927834	kJ/h

Fig.5. Window of calculation results of parameters and characteristics of thermal energy metering system.

The simplified dependences $C_{hT} = F_1(T)$ and $C_{hp} = F_2(p, T)$, developed by the authors, have the form:

$$C_{hT} = 1.3471\theta^3 - 19.8754\theta^2 + 96.8585\theta - 158.4162 , \qquad (5)$$

$$C_{hp} = 0.06p(-0.0265\theta^3 + 0.3695\theta^2 - 1.7163\theta - 2.6647), \theta = T/100, \qquad (6)$$

where p, T are the absolute pressure and temperature of fluid (heat carrier).

3) to calculate the combined standard uncertainty of thermal energy amount by the equation

$$u_W' = \sqrt{u_\tau'^2 + C_1^2 u_{q1}'^2 + C_2^2 u_{h1}'^2 + C_3^2 u_{q2}'^2 + C_4^2 u_{h2}'^2} , \qquad (7)$$

where u_τ' is the uncertainty of measured value of time interval during which the thermal energy amount is calculated; u_{q1}', u_{q2}' are the uncertainties of measurement results of heat carrier flowrate in supply and return pipelines, respectively; u_{h1}', u_{h2}' are the uncertainties of measurement results of heat carrier enthalpy in supply and return pipelines, respectively; C_1, C_2, C_3, C_4 are the influence coefficients of uncertainty components on the combined standard uncertainty of thermal energy amount, which should be calculated by the formulas presented in [9].

4) the relative expanded uncertainty of measured value of thermal energy amount at the confidence level 95% should be calculated by the formula [10]

$$U_W' = 2u_W' . \qquad (8)$$

Based on the results of calculating and designing the thermal energy metering system CAD generates a protocol in the form of an html-page, which displays information on the following sections:

• parameters and characteristics of the fluid;

• parameters and characteristics of the primary device;

• parameters and characteristics of the measuring pipe;

• parameters and characteristics of the pipe straight lengths and fittings;

• parameters and characteristics of measuring instruments of pressure drop on the primary device;

• parameters and characteristics of pressure measuring instruments;

• parameters and characteristics of temperature measuring instruments;

• complex parameters of flowmeters at the specified values of fluid parameters;

• relative uncertainty of measurement results of flowrate and amount at specified values of fluid parameters;

• relative uncertainty of measurement result of thermal energy amount.

The information presented in protocol of calculating and designing the thermal energy metering system is sufficient to:

• check compliance with the requirements of current regulations of the existing thermal energy metering system;

• check the correctness of algorithms for calculating the thermal energy amount, implemented in microprocessor controllers of metering systems;

• develop design documentation and produce the basic components of the designed thermal energy metering system.

5. Conclusion

The developed computer-aided design system makes it possible to simplify the process of designing the thermal energy metering devices. In addition, during the designing CAD controls the compliance of design solutions with the requirements of regulations on thermal energy metering and on differential pressure flowmeters as well as provides expert recommendation on the adjusting the relevant solutions. Thus, the developed CAD provides an opportunity to design a modern thermal energy metering system, which meets the requirements of current regulations.

In addition, after appropriate certification the developed CAD can become the basis of metrological support of thermal energy metering systems based on differential pressure flowmeters. CAD makes it possible to calculate the thermal energy amount for the specified characteristics of measuring instruments and the flow parameters of heat carrier and to use these values as reference while testing the existing metering systems.

Therefore, the application of the developed CAD will make it possible to improve the quality of designing the thermal energy metering systems, to form their metrological support and to increase the accuracy of thermal energy metering.

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Система автоматизованого проектування засобів вимірювання кількості теплової енергії

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Анотація

В статті представлено розроблену систему автоматизованого проектування (САПР) засобів вимірювання кількості теплової енергії, у складі яких застосовують витратоміри зі стандартними звужувальними пристроями потоку. Розглянуто теоретичні засади для розроблення САПР, зокрема, розроблені авторами алгоритми визначення кількості теплової енергії, повна математична модель витратоміра змінного перепаду тиску, реалізована із врахуванням обмежень стандартів ДСТУ ГОСТ 8.586.1-5:2009, методи IAPWS визначення властивостей води та водяної пари, розроблені авторами методика обчислення показника адіабати водяної пари, методика оцінювання невизначеності результату вимірювання кількості теплової енергії, запропоновані авторами нові підходи щодо автоматизованого проектування систем вимірювання кількості теплової енергії. Представлено основні характеристики підсистеми введення та перевірки коректності вхідних даних. Розглянуто реалізацію вікон САПР для введення характеристик засобів вимірювань тиску, перепаду тиску, температури, що входять до складу системи вимірювання кількості теплової енергії, а також вікна введення характеристик вимірювального трубопроводу витратоміра. Представлено основи розробленої авторами методики оцінювання невизначеності кількості теплової енергії, що реалізована в САПР. Розглянуто структуру протоколу проектування системи вимірювання кількості теплової енергії.

Ключові слова: система автоматизованого проектування; кількість теплової енергії; невизначеність результату вимірювання; витратомір змінного перепаду тиску.