UDC 53.02:006.91 DOI:

A portable calorimeter for measuring the calorific value of natural gas

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Abstract

Natural gas quality assessment is a relevant issue. A critical analysis of calorimeter designs for measuring the calorific value of natural gas was carried out. The most common methods for determining the calorific value of natural gas are as follows: direct by gas calorimeters; indirect by gas chromatographs; indirect, based on correlations. The advantages of isoperibolic calorimeters of measuring calorific value of natural gas directly in the consumer's conditions are substantiated. The design of a portable calorimeter containing a thermostated shell, calorimetric tank, Peltier element with tank, circulating pump, gas burner, thermostat systems, metered supply of natural gas and air, fuel ignition, sensors, combustion analyzer and control and measurement unit, was developed. The geometric dimensions of the calorimetric tank are optimized, materials and technologies of manufacturing parts are specified. The metrological analysis of the developed portable calorimeter was carried out. A method for measuring the calorific value of natural gas directly in the conditions of household consumers and transport enterprises was developed. The results of testing the prototype calorimeter in the laboratory confirmed its high performance and metrological characteristics, and the deviation of the measurement of the calorific value of natural gas from that determined using a gas chromatograph was 0.6%.

Keywords: isoperibolic calorimeter; calorific value of natural gas; uncertainty; error; automated control system.

Received: 12.07.2021 Edited: 16.08.2021 Approved for publication: 25.08.2021

1. Introduction

European gas market deregulation and natural gas pricing based on its energy value (rather than volume) has sharply escalated the attention of natural gas suppliers and consumers to specification of gas energy characteristics. In Ukraine, on January 26, 2017, the Resolution No 84 "On Approval of Amendments to Certain Resolutions of the National Commission for Regulation of Economic Competition on the Introduction of Units of Energy on the Natural Gas Market" came into force. It obliges operators of local gas distribution networks in addition to the volume of natural gas to indicate the value of the weighted average calorific value of gas for the calculation period. Methods of reproduction and transfer of the units of calorific value and density of natural gas are presented in [1].

2. Analysis of the issue and problem statement

Determination of natural gas calorific value in Ukraine is carried out according to the recommendations of DSTU (State Standard) ISO 15971:2014, using the following measurement methods: direct with gas calorimeters; indirect with gas chromatographs; and indirect based on correlations.

The calculation method to determine natural gas calorific value is also used in regional gas distribution organizations. Accordingly, final gas consumers for industrial or household needs do not have the opportunity to verify the assigned gas calorific value of for the calculation period.

Currently, the main number of gas energy measurements performance is carried out by chromatographs of high cost, large size and weight, duration of preparation for analysis, the need for special carrier gases, as well as increased requirements for microclimate in the workplace. This eliminates the possibility of using chromatographs for regular monitoring of gas performance directly by consumers.

The work [2] describes methods to determine the natural gas calorific value and specifies methods in addition to gas calorimetry providing procedure of gas sample burning. They are analytical methods based on gas sample analysis; correlation methods to calculate calorific value ability as a function of physical measured values; stoichiometric methods that use an almost linear correlation between the amount of oxygen required for fuel combustion and calorific value by gas supply network offline modelling.

The works [1, 3] present results of theoretical and experimental studies in the field of natural gas calorimetry and note that the absence of restrictions on the component composition and physicochemical characteristics of gas is a significant advantage for the use of direct combustion calorimeters. The work [3] describes the design of direct natural gas adiabatic calorimeter and the method of determining the calorific value. Due to its bulkiness and inertia, this device has limited use in the national economy.

In various countries, works have intensified to create new devices for monitoring the energy performance of gas and to improve existing methods and devices to minimize measurement uncertainty. The EU PTB laboratories have developed reference calorimeters with an uncertainty of 0.05% and 0.06%, respectively [4]. It can be argued that in the EU the basis of metrology in the field of calorimetry is chosen direct measurement methods.

Theoretical studies, as well as systematic analysis of calorimeter designs have shown that the most effective is the isoperibolic principle of natural gas calorific value measuring, which allows to perform measurements of higher calorific value with the lowest possible uncertainty [4]. The isoperibolic principle of measurement envisages the most exact account of heat losses as an integral of a difference of temperatures between a calorimetric capacity and a cover with known temperature. In an isoperibolic calorimeter, the shell temperature is maintained at a constant level and the temperature of the calorimetric measuring system changes. Since heat transfer depends on the temperature difference and the shell temperature is stable, the heat flux is only a function of the temperature of the calorimetric system. This dependence is linear and can be determined during calibration. In addition, it is necessary to take into account external sources of thermal energy – energy for mixing calorimetric liquid and self-heating of temperature sensors. Algorithms for accounting for these heat fluxes are described in [4–6]. The designs of most modern calorimeters [4, 5, 7] are practically a modified design of the Rossini calorimeter [6] and are intended for use in laboratories. Their main unit is the combustion chamber with the output of combustion products through a helical tube. Since these devices are not equipped with a system of forced cooling of the calorimetric liquid, they are characterized by high thermal inertia. The preparation time for the first and subsequent measurements can be tens of hours.

Therefore, there is a need to develop a portable gas calorimeter, which uses the isoperibolic principle of natural gas calorific value to measure it directly in the household and CNG gas station consumer conditions.

The study aims at development of a portable gas calorimeter design to implement the isoperibolic principle of natural gas calorific value for household and CNG gas station conditions providing relative error of no more than 1%, significantly reduced calorimeter preparation time, and metrological analysis.

3. Research results

Design of a portable gas calorimeter. The main energy indicator of natural gas is its higher calorific value, which differs from the lower by the amount of heat condensation of water vapor caused by combustion: for higher calorific value water is in the liquid state, and for the lower – in the gaseous state.

A significant factor that complicates the design of direct combustion calorimeter is the flue gas temperature, which should not exceed 30 °C to meet the conditions of condensation. Because the flue gas temperature is always higher than the temperature of the coolant to provide heat is transfer, the upper value of the coolant temperature, for example, in the LNE calorimeter [4] is selected at 26 °C. As far as laboratory devices operate in ambient temperature 20 ± 2 °C, it imposes significant restrictions on the lower temperature of the coolant, which is 23 °C for the LNE calorimeter [4]. Thus, the change in temperature in typical designs of isoperibolic calorimeters is only 3 °C, and the accuracy of measuring this temperature, as well as the uniformity of its distribution in the volume of the coolant is decisive for this calorimeter. Thus, the error of temperature measurement of only 0.1 °C, or non-uniform distribution of temperature by the same value, causes an increase in the deviation of the results of measuring the calorific value by 3%. The LNE calorimeter uses thermistors with an accuracy of 0.02 °C, and 18 thermistors are used simultaneously to increase accuracy. This combination provides a standard deviation of the temperature measurement results at 0.0009 °C. This technical solution is acceptable only for reference devices.

Analysis of ways to reduce requirements of temperature measurement accuracy while maintaining full condensation of water vapor, showed that heating initial temperature reducing can significantly reduce the requirements for the accuracy of temperature measurement with little effect on other characteristics of the calorimeter. The introduction of a calorimetric liquid cooling system into the design of the device allows reducing the lower temperature from 23 °C to 15 °C. This preserved thermal resistance between the calorimetric system and the thermostated shell [8]. When the upper temperature is set at 25 °C, the temperature range is 10 °C, or 3.33 times more. The requirements for the accuracy of temperature measurement reduces the same way, and, the uneven distribution of temperature in the volume of the calorimetric liquid reduces the same

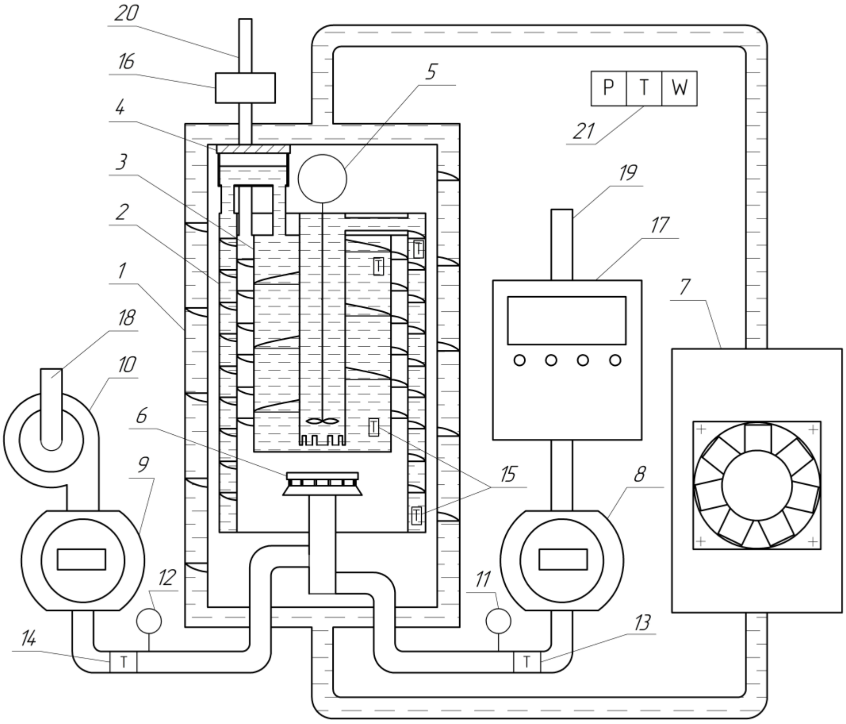

Fig. 1. Scheme of the portable calorimeter: 1 – thermostated shell; 2 – external calorimetric tank; 3 – internal calorimetric tank; 4 – Peltier element with a tank; 5 – circulating pump; 6 – gas burner with ignition unit; 7 – thermostat; 8 – natural gas volume meter; 9 – air volume meter; 10 – air blower; 11 – sensor of excess gas pressure; 12 – sensor of excess air pressure; 13 – gas temperature sensor; 14 – air temperature sensor; 15 – liquid temperature sensor; 16 – analyser of combustion products; 17 – control and measurement unit; 18 – inlet pipe for air; 19 – inlet pipe for natural gas; 20 – outlet pipe for combustion products; 21 – sensors of pressure, temperature and humidity of the environment

too. The change in heat capacity of the calorimetric liquid from temperature does not affect the accuracy of the device, because the range of temperature changes is always the same, and the average heat capacity is set when calibrating the calorimeter using pure gases.

The metrological analysis of the direct combustion calorimeter showed that main contribution to the accuracy of measurement is made by two components: the accuracy of gas volume measurement and the accuracy of measuring the average temperature of the calorimetric tank. The accuracy of measuring the average temperature is significantly affected by the efficiency of heat transfer. During the work on the LNE calorimeter [4], the identified problems with the uniformity of the temperature field and fluid flow rates inside the calorimetric tank were separately noted.

Therefore, when designing the portable calorimeter, special attention was paid to the use of technical solutions that would provide an effective solution to these problems, namely – helical flow of liquids and gaseous combustion products, and measuring time reducing (Fig. 1). The design and geometric parameters of the calorimeter are optimized using numerical-analytical methods for calculating inhomogeneous shell structures [9–11], pipes [12] and vibration protection [13]. The results of computer simulations of heat transfer using numerical methods have shown that the temperature difference between the liquid and the combustion products does not exceed 1 °C. Various technologies of hardening and coating by microarc oxidation and chromium plating [14–16], as well as soldering [17] were used during the production of parts. At the same time, special attention was paid to the accuracy of the formation of notches to ensure the tightness of pipelines [18, 19] and the rational choice of process equipment [20].

Flexible branch pipes are used to connect the portable calorimeter to a house gas network for household measurement and to a gas filling station through gas reducer (not shown).

The air blower is a centrifugal fan. The volume and air flow rate are measured by a rotary counter. The air is supplied to a gas burner installed inside the thermostated shell and equipped by burning unit, where it mixes with natural gas, which enters through the inlet pipe and the rotary gas meter, forming a combustible mixture. Combustion products fall into the gap between the cylindrical walls of the outer and inner calorimetric tanks, in which hollow helical shells are formed, and move up the two-west helical channels, pass through the combustion products analyser.

The outer and inner calorimetric tanks are jointed through reservoir of the Peltier element and are filled with liquid (e.g., distilled water), which is pumped to the lower part of the inner calorimetric tank, passes through a two-way screw channel to its upper part, and from there through the pipe located at the top, the calorimeter enters the outer part. The first channel of the two-way helical channel directs the liquid down, and from there on the second helical channel, this liquid moves in the opposite direction, and enters the reservoir of the Peltier element. The distance from the surface of the liquid in the tank to the lower surface of the Peltier element corresponds to the size of the gap between the outer calorimetric tank and the thermostated shell. The thermostated shell also includes a helical channel to direct the flow of fluid and ensure the same temperature throughout the shell. The temperature of the thermostated shell is maintained at a constant level of 20 °C by the thermostat.

The control-measurement unit provides constant temperature control inside the outer and inner calorimetric tanks (by 4 temperature sensors); air and gas volume measurement; combustion stoichiometric ratio calculation; combustion product composition control by combustion product analyser signals; combustion stoichiometric mode by automatically adjusting the performance of the air supercharger, controlling all calorimeter processes (exposure, ignition, combustion, temperature stabilization, preparation for repeated measurements); and calculation and display the results of natural gas calorific value measuring. There is also a calorimeter calibration mode using pure gases as a reference fuel. The control and measurement unit is based on the Atmel microcontroller and allows to control the operation of the device in accordance with the requirements by changing the software.

The maximum value of the natural gas calorific value of is achieved for the stoichiometric ratio of gas and oxygen. The excess oxygen coefficient is determined from the ratio of the actual amount of air and gas burned, to the theoretical amount of these components which provide stoichiometric combustion of the mixture:

$$\lambda = \left(V_O / V_G\right) / \left(V_{OST} / V_{GST}\right),$$

where V_O and V_G are the volumes of oxygen and natural gas used, respectively, m^3; V_{OST} and V_{GST} are the volume of oxygen and the volume of natural gas, respectively, for which stoichiometric combustion is ensured, m^3.

To control the combustion products in the portable calorimeter, a system of automatic regulation of the stoichiometric composition of the mixture is used: natural gas – air with a lambda probe based on ZrO_2 and a controlled air blower, which maintains the optimal combustion mode of the gas burner.

Rapid cooling of the calorimetric liquid to 15 °C is provided by the Peltier element with the tank installed between the outer thermostated shell and the calorimetric volume, which is integrated into the design of the calorimeter and does not change the principle of its operation. To ensure heat transfer parameters at a low level during the measurement and at a high level during forced cooling of the calorimetric tank, it is proposed to control the heat transfer by changing the calorimetric tank vertical position by rotating it at an angle of 90 degrees (horizontal position). In the vertical position of the thermostated shell, the liquid level is lower than the cooling surface of the Peltier element, and in the horizontal position, the liquid completely washes this surface. An additional advantage of the proposed method of heat exchange control is a significant reduction in the preparation time of the portable calorimeter for re-measurement, because the forced cooling of the calorimetric liquid is much faster than during natural cooling.

The main performance of the calorimeter. The amount of energy E required to heat the calorimetric tank is determined by the formula:

$$E = c_W \cdot m_W \cdot (T_{W2} - T_{W1}), \qquad (1)$$

where c_W – the heat capacity of the heated calorimeter components, J/kg·K; m_W – mass of heated calorimeter components, kg; T_{W2} – final internal temperature of the calorimeter, K; T_{W1} – initial internal temperature of the calorimeter, K.

Expressing energy as the product of combustion power N at combustion time t:

$$E = N \cdot t$$

and using expression (1), for the selected parameters: c_W = 4180 J/(kg·K); m_W = 4 kg, $(T_{W2} - T_{W1}) = 10$ K; N = 2000 W, and determined the heating time t of the developed calorimeter, s:

$$t = c_W \cdot m_W \cdot (T_{W2} - T_{W1}) / N = 4180 \cdot 4 \cdot 10 / 2000 = 86.3\ \text{s}.$$

Gas consumption Q for the average calorific value of natural gas in Ukraine H = 32.73 MJ/m^3 and burner combustion power N = 2000 W is:

$$Q = N / H = 2000 / (32.73 \cdot 10^6) = 0.00006116\ \text{m}^3/\text{s}.$$

The volume of gas used was defined as the product of the consumption of natural gas at the time of combustion:

$$V_G = Q \cdot t = 0.00006116 \cdot 83.6 = 0.005113\ \text{m}^3.$$

Metrological analysis of the developed calorimeter. The calorific value of the studied natural gas, with reduction to standard conditions and taking into account the heating of the components of the device, was determined by the formula:

$$H = \frac{c_W \cdot m_W \cdot (T_{W2} - T_{W1})}{V_G \cdot \left(\dfrac{(P_A + P_G)}{P_A} \cdot \dfrac{T_A}{T_G} \right)}, \qquad (2)$$

where P_A – atmospheric pressure, Pa; P_G – excess pressure of natural gas, Pa; T_A – ambient temperature, K; T_G – temperature of natural gas, K.

Table 1

Calorimeter mode and absolute measurement errors of input parameters

Parameter	Value	Parameter	Value
m_W, kg	4.0	Δm_i, kg	0.001
c_W, J/kg K	4183.0	Δc_W, J/kg K	1.000
T_{W2}, K	298.15	ΔT_{W2}, K	0.05
T_{W1}, K	288.15	ΔT_{W1}, K	0.05
V_G, m^3	5.113×10^{-3}	ΔV_G, m^3	0.00001
P_A, Pa	101325	ΔP_A, Pa	50.0
P_G, Pa	1300.0	ΔP_G, Pa	50.0
T_A, K	293.15	ΔT_A, K	0.1
T_G, K	293.15	ΔT_G, K	0.1

The mass of water is more than 90% of the total mass of the heated calorimeter components, and the heat capacity of water is about 10 times higher than the heat capacity of stainless steel, so the mass of other components was neglected for metrological analysis.

Coefficients of influence on the result of measuring the calorific value of natural gas were defined as partial derivative functions (2):

$$\frac{\partial H}{\partial c_W}=\frac{m_W\cdot(T_{W2}-T_{W1})}{V_G\cdot\left(\frac{(P_A+P_G)}{P_A}\cdot\frac{T_A}{T_G}\right)},\tag{3}$$

$$\frac{\partial H}{\partial m_W}=\frac{c_W\cdot(T_{W2}-T_{W1})}{V_G\cdot\left(\frac{(P_A+P_G)}{P_A}\cdot\frac{T_A}{T_G}\right)},\tag{4}$$

$$\frac{\partial H}{\partial T_{W2}}=\frac{m_W\cdot c_W}{V_G\cdot\left(\frac{(P_A+P_G)}{P_A}\cdot\frac{T_A}{T_G}\right)},\tag{5}$$

$$\frac{\partial H}{\partial T_{W1}}=\frac{-m_W\cdot c_W}{V_G\cdot\left(\frac{(P_A+P_G)}{P_A}\cdot\frac{T_A}{T_G}\right)},\tag{6}$$

$$\frac{\partial H}{\partial V_G}=\frac{-m_W\cdot c_W\cdot(T_{W2}-T_{W1})}{V_G{}^2\cdot\left(\frac{(P_A+P_G)}{P_A}\cdot\frac{T_A}{T_G}\right)},\tag{7}$$

$$\frac{\partial H}{\partial P_A}=\frac{-m_W\cdot c_W\cdot(T_{W2}-T_{W1})}{V_G\cdot(P_A+P_G)^2}\cdot\frac{P_A\cdot T_G}{T_A}+$$
$$+\frac{m_W\cdot c_W\cdot(T_{W2}-T_{W1})\cdot T_G}{V_G\cdot(P_A+P_G)\cdot T_A},\tag{8}$$

$$\frac{\partial H}{\partial P_G}=\frac{-m_W\cdot c_W\cdot(T_{W2}-T_{W1})}{V_G\cdot(P_A+P_G)^2}\cdot\frac{P_A\cdot T_G}{T_A},\tag{9}$$

$$\frac{\partial H}{\partial T_A}=\frac{-m_W\cdot c_W\cdot(T_{W2}-T_{W1})}{V_G\cdot(P_A+P_G)}\cdot\frac{P_A\cdot T_G}{T_A{}^2},\tag{10}$$

$$\frac{\partial H}{\partial T_G}=\frac{m_W\cdot c_W\cdot(T_{W2}-T_{W1})}{V_G\cdot(P_A+P_G)}\cdot\frac{P_A}{T_A}.\tag{11}$$

The absolute error of the measured natural gas calorific value caused by the input parameter measuring was determined due to the absolute error of their measurement (Table 1) and the corresponding coefficients of influence (3) – (11). Table presents the absolute error of the input parameters measured by the available sensors and devices and calorimeter operation modes.

The absolute error of the developed calorimeter was calculated by the formula:

$$\Delta_H=\begin{pmatrix}\left(\frac{\partial H}{\partial m}\Delta m_W\right)^2+\left(\frac{\partial H}{\partial c_W}\Delta c_W\right)^2+\left(\frac{\partial H}{\partial T_{W2}}\Delta T_{W2}\right)^2+\left(\frac{\partial H}{\partial T_{W1}}\Delta T_{W1}\right)^2+\\+\left(\frac{\partial H}{\partial V_G}\Delta V_G\right)^2+\left(\frac{\partial H}{\partial P_A}\Delta P_A\right)^2+\left(\frac{\partial H}{\partial P_G}\Delta P_G\right)^2+\left(\frac{\partial H}{\partial T_A}\Delta T_A\right)^2+\left(\frac{\partial H}{\partial T_G}\Delta T_G\right)^2\end{pmatrix}^{1/2}.\tag{12}$$

Using the numerical values presented in the Table, partial derivatives (3) – (11) were calculated and substituting them in expression (12) the absolute error of natural gas calorific value measurement $\Delta_H = 2.38 \cdot 10^5$ was determined.

The relation (12) to calculate Δ_H shows that the errors in measuring the initial and final temperatures of device parts to be heated contribute maximally in the result of natural gas calorific value measuring as well as the error in measuring the volume of flue gas.

The relative measurement error for the average natural gas calorific value of H = 32.73 MJ/m^3 is:

$$\delta_H = \frac{\Delta_H}{H} \cdot 100\% = \frac{2.38 \cdot 10^5}{32.73 \cdot 10^6} \cdot 100\% = 0.73\% .$$

Thus, the relative error is 0.73%, i.e. it does not exceed 1%. It indicates a sufficiently high accuracy of the developed portable isoperibolic calorimeter. For comparison, having performed similar calculations to change the temperature in the calorimetric tank by 3 °C, as in typical designs of isoperibolic calorimeters, the error of the developed device is 2.2% with the same accuracy of all applied sensors. Tests of calorimeter prototype have confirmed its high operational and metrological characteristics and have shown the calorific value of natural gas of 32.5 MJ/m^3. A Chromatec Crystal 2000M chromatograph determined the same gas calorific value of 32.7 MJ/m^3. Accordingly, the deviation of the measurement result of the chromatograph was 0.6%.

4. Discussion of research results

Researchers in works on energy measuring usually focus on the accuracy of determining the volume of liquid [21] and gaseous hydrocarbons during their accounting [22], but do not always pay due attention to determining their calorific value. In addition, to justify the rational use of alternative fuels in transport and in everyday life [23] it is also necessary to determine their calorific value.

The work [24] considered the technical aspects of natural gas calorific value measuring and accounting taking into account the volume of gas consumed, the air temperature around the gas meter and metrological assessment. However, this method has limited functionality.

The developed device has a simple design and allows to determine the calorific value of natural gas directly in consumer conditions with a rather low error. However, it should be noted that this device is intended to perform rapid measurements of the calorific value of natural gas directly by consumers. The results of the research serve as a basis for the industrial production of portable devices.

5. Conclusions

1. Legislative stipulation of natural gas pricing based on its energy value requires developing portable devices to control its calorific value in household or transport conditions.
2. The developed portable isoperibolic calorimeter for calorific value of natural gas provides high-precision results. The control of heat exchange between the calorimetric tank and the thermostated shell using the Peltier element expands the operating temperature range and reduces the preparation time for repeated measurements.
3. Metrological analysis of the calorimeter confirmed the high accuracy in determining the calorific value of natural gas. The relative error of the device is 0.73%. The calorimeter – chromatograph calorific value measuring deviation was 0.6%.

Further research plans to expand the functionality of the calorimeter to determine the Wobbe index for natural gas.

Портативний калориметр для вимірювання теплотворної здатності природного газу

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Анотація

Актуальним питанням є оцінка якості природного газу під час його транспортування, розподілу, постачання, зберігання та споживання, а також розробка пристроїв для вимірювань теплотворної здатності. Проведено критичний аналіз конструкцій калориметрів для вимірювання теплотворної здатності природного газу. Встановлено, що найбільш поширеними методами визначення теплотворної здатності природного газу є: прямий, із використанням калориметрів; непрямий, за допомогою газових хроматографів; опосередкований, на основі кореляційних залежностей. Обґрунтовано переваги калориметрів, у яких використовується ізопериболічний принцип вимірювання теплотворної здатності, для оперативного контролю якості природного газу безпосередньо в умовах споживачів. Розроблено конструкцію портативного калориметра, який містить термостатовану оболонку, калориметричну ємність, елемент Пельтьє з резервуаром, циркуляційний насос, газовий пальник, системи термостатування, дозованої подачі природного газу та повітря, запалювання горючої суміші, давачі, аналізатор продуктів згоряння і блок керування та вимірювання. Оптимізовано геометричні розміри калориметричної ємності, вибрано матеріали та технології виготовлення деталей. Проведено метрологічний аналіз портативного калориметра. Розроблено методику вимірювання теплотворної здатності природного газу безпосередньо в умовах побутових споживачів та транспортних підприємств. Результати тестування прототипу калориметра в лабораторних умовах підтвердили його високі метрологічні характеристики, а відхилення результату вимірювання теплотворної здатності природного газу від визначеної з використанням газового хроматографа становило 0.6%.

Ключові слова: ізопериболічний калориметр; теплотворна здатність природного газу; невизначеність; похибка; система автоматизованого керування.

Портативный калориметр для измерения теплотворной способности природного газа

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Аннотация

Актуальным вопросом является определение теплотворной способности природного газа. Проведен анализ конструкций калориметров. Обоснованы преимущества использования изопериболических калориметров для измерения теплотворной способности природного газа непосредственно в условиях потребителей. Разработанный калориметр содержит термостатированную оболочку, калориметрическую емкость, элемент Пельтье с резервуаром, циркуляционный насос, газовую горелку, системы термостатирования, дозированной подачи природного газа и воздуха, зажигания, датчики, анализатор продуктов сгорания и блок управления и измерения. Оптимизированы геометрические размеры, выбраны материалы и технологии изготовления деталей. Разработана методика измерения. Проведен метрологический анализ калориметра. Отклонение результата измерения теплотворной способности природного газа от определенной с использованием газового хроматографа Хроматэк Кристалл 2000М составило 0.6%.

Ключевые слова: изопериболический калориметр; теплотворная способность; неопределенность; погрешность; система автоматизированного управления.

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