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Modeling of the Construction for the Combustion Chamber of the Gas Calorimeter in the Aspect of Exhaust Gas Homogenization in the Measuring Space

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Abstract. The assessment of the physicochemical parameters of fuels is particularly important in energy generation processes implemented using combustion processes. The calorific value of the fuels used is important in these processes. The calorific value of fuel is the basic parameter from which the mass of fuel necessary to generate a certain amount of energy results. Calorimeters are used to determine the calorific value of fuels. The subject of analyzes is the conceptual design of the calorimeter for gaseous fuel testing. A special element in the construction of the calorimeter is the combustion chamber. In its initial part, the gaseous fuel oxidation process is carried out, and in the final part, the required parameters are measured. In order to obtain high accuracy in the measurement of selected thermodynamic parameters, it is necessary to ensure homogeneity of the exhaust gases flowing in the measurement space. For this purpose, the construction of the combustion chamber was developed and simulation tests aimed at homogenization of exhaust gases in the chamber measuring space were carried out. An example of the construction and the tests carried out are provided in this article.

1 Introduction

The energy demand of modern civilization along with the need to protect the natural environment prompts the search for new ways to generate energy directed at sources other than conventional fossil fuels. Technologies related to the use of biogas, synthesis gas obtained in biomass or waste gasification processes are being introduced. The use of these fuels in industrial processes of generating heat and electricity requires caloric stability of the fuel. The caloric stability of the fuel is necessary to ensure the stability of thermal energy conversion processes that translate directly into the set values of generated electricity using electric machines. One way to assess the energy quality of a fuel is to measure its calorific value. There are several methods for determining the calorific value of fuel.

The calorific value can be determined on the basis of knowledge of the chemical composition of the fuel. This method is based on the assumption that the calorific value of the fuel is equal to the sum of the product of the individual components in the compound calorific value and their percentage content in the fuel. This method allows obtaining an approximate value, because it was assumed that the elements appear as single ones and does not take into account the fact that they occur in the fuel in the form of chemical compounds that have their heat of creation affecting the value of the calorific value [1, 3-10, 12]. These methods obtain the highest accuracy of calorific value determination for hard coal. For gaseous fuels, the calorific value (W_{op}) can be determined from approximate formulas [MJ/m^3],

$$W_{op} = \sum_{i=1}^{n} \left[\left(W_{op} \right)_i \cdot \mu_i \right] \quad (1)$$

where:
$(W_{op})_i$ – calorific value of the i-th gas component,
μ_i – volume share of the i-th gas component.

The calorific value of gas can be determined using a Junkers calorimeter. It is a flow device, mainly used to determine the heat of combustion and the calorific value of gaseous fuels. Combustion takes place at a constant pressure equal to the atmospheric pressure. The measurement is carried out under steady-state conditions of the combustion gas flow, with a constant cooling water flow rate. Under steady-state conditions, the calorimeter's internal energy and temperatures at individual points on the calorimeter are constant. The method consists in determining the heat released during the combustion of a certain amount of gaseous fuel in the calorimeter. The heat released is picked up by the water flowing through the calorimeter. The indicated measurement guidelines cannot be met in the case of measurements carried out in industrial conditions outside the laboratory. Therefore, the concept of an industrial calorimeter has been developed that can meet the conditions for obtaining a satisfactory measurement result with small requirements for the conditions of measurement.

The concept of measurement with a gas calorimeter dedicated to gaseous fuels is described in more detail in the authors' article, which also presents a schematic diagram of the structure (Fig. 1).

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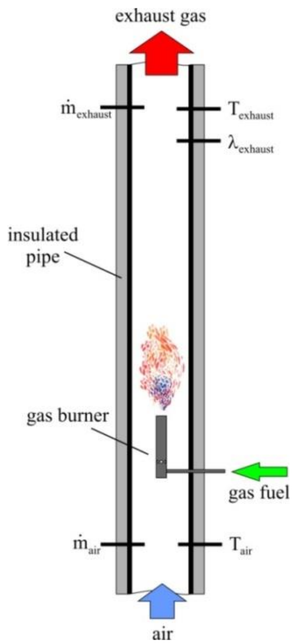


Fig. 1. Diagram of the gas calorimeter concept.

The flow-through combustion chamber is a thermally insulated circular pipe. A burner was placed inside, supplied from the outside with analyzed gas fuel and supplied with air flowing inside the pipe. The amount of air flowing inside the burner and the space of the flame-covered pipe should be adequate to ensure a stoichiometric process of fuel combustion. The assessment of the calorific value of gas in the proposed concept consists in the analysis of the amount of heat supplied to the air flowing in a thermally insulated pipe. The calculation algorithm presented in the article concerns theoretical conditions and requires experimental verification both in the field of simulation with the use of numerical tools and in instrumental research. This article proposes the design of the combustion chamber and subjected it to numerical analysis aimed at assessing the conditions of gas flow inside the chamber.

2 Methodology

In order to evaluate the flow parameters inside the combustion chamber of the calorimeter, its geometry was defined (Fig. 2) and the basic values of the mass and volume flows of the medium supplied to the chamber in the form of a fuel-air mixture were determined. A combustion chamber with a diameter of 100 mm and a length of 600 mm was adopted. The combustion chamber is open with the exhaust outlet located axially in the upper part of the chamber with a diameter of 50 mm. In the combustion chamber, it is possible to distinguish the flame zone, the heat propagation zone and the flue gas flow zone to which the conducted analysis was directed.

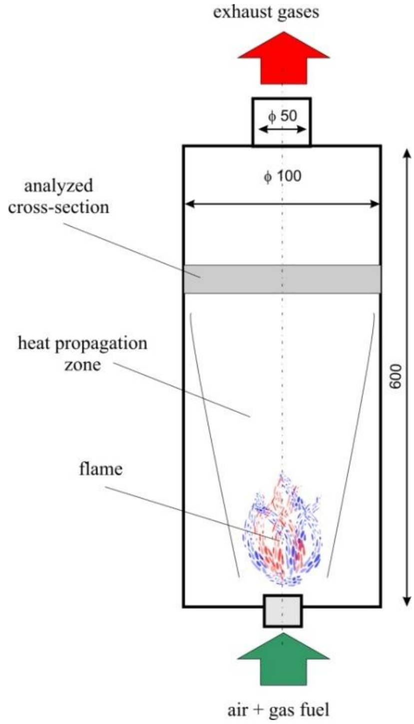


Fig. 2. Diagram of the calorimeter combustion chamber.

Certain process assumptions were also made related to the combustion of gaseous fuel in the calorimeter chamber. The analysis was carried out for the combustion of natural gas containing methane - 96.1%, ethane - 1.2%, propane - 0.4% and nitrogen - 2.3%. It was assumed that the fuel consumption was 0.0007 kg / min. It was assumed that the combustion process takes place with the excess air factor λ = 1.19, therefore it was assumed that the combustion process consumes air in the amount of 0.0113288 kg / min. Together, these values indicate the delivered amount of the fuel-air mixture of 0.0006295146 kg / s. using the equation of state of the gas p · v = m · R · T, the volume flow of the medium flowing through the burner was calculated. Assuming the following values presented in equation (2) respectively:

$$\dot{V}_1 = \frac{\dot{\mathrm{m}}\mathrm{RT}_1}{\mathrm{p}} = \frac{0.0006295146\ kg/s \cdot 287\ J/(kg{\cdot}K) \cdot 293\ K}{101300\ Pa} = 0.00052257\ m^3/s \tag{2}$$

Assuming that there is no mass exchange in the combustion chamber mass flow remains unchanged. On the other hand, the temperature of the heated medium changes as a result of the combustion process. The temperature assumed in the analysis is the temperature in the cross-sectional area of the combustion chamber in which only the heated medium flows in the form of exhaust gases. The temperature in the assumed cross-section was determined to be T2 = 873 K. By following the example above, the equation (3) was obtained:

$$\dot{V}_2 = \frac{\dot{\mathrm{m}}\mathrm{RT}_2}{\mathrm{p}} = \frac{0.0006295146\ kg/s \cdot 287\ J/(kg{\cdot}K) \cdot 873\ K}{101300\ Pa} = 0.001557\ m^3/s \tag{3}$$

It was also assumed that the value of the flow rate of the flowing medium obtained as a result of the heat supplied in the combustion process remains unchanged in the cross-section of the outlet channel of the measuring chamber, therefore $\dot{V}_2 = \dot{V}_3$. On the basis of the obtained results, the flow velocity of the medium in the individual sections of the combustion chamber was calculated using the equation (4), transforming it into equation (5):

$$\dot{V} = \mathrm{v} \cdot \mathrm{S} = v \cdot \frac{\pi d^2}{4} \tag{4}$$

$$v = \frac{4\dot{V}}{\pi d^2} \tag{5}$$

Substituting the data accordingly, the following results were obtained:

$$v_1 = \frac{4\dot{V}_1}{\pi {d_1}^2} = \frac{4 \cdot 0.00052257\, m^3/s}{\pi \cdot (0.042\, m)^2} = 0.377\, m/s$$

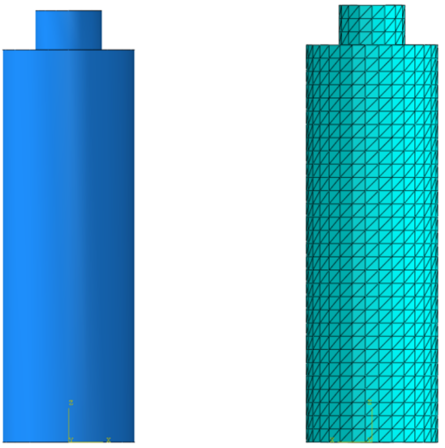
$$v_2 = \frac{4\dot{V}_2}{\pi {d_2}^2} = \frac{4 \cdot 0.001557\, m^3/s}{\pi \cdot (0.1\, m)^2} = 0.198\, m/s$$

$$v_3 = \frac{4\dot{V}_3}{\pi {d_3}^2} = \frac{4 \cdot 0.001557\, m^3/s}{\pi \cdot (0.05\, m)^2} = 0.793\, m/s$$

The obtained values of the flow velocity in individual cross-sections of the calorimeter measuring chamber were verified in the numerical analysis of the flow.

3 Results of numerical flow analysis

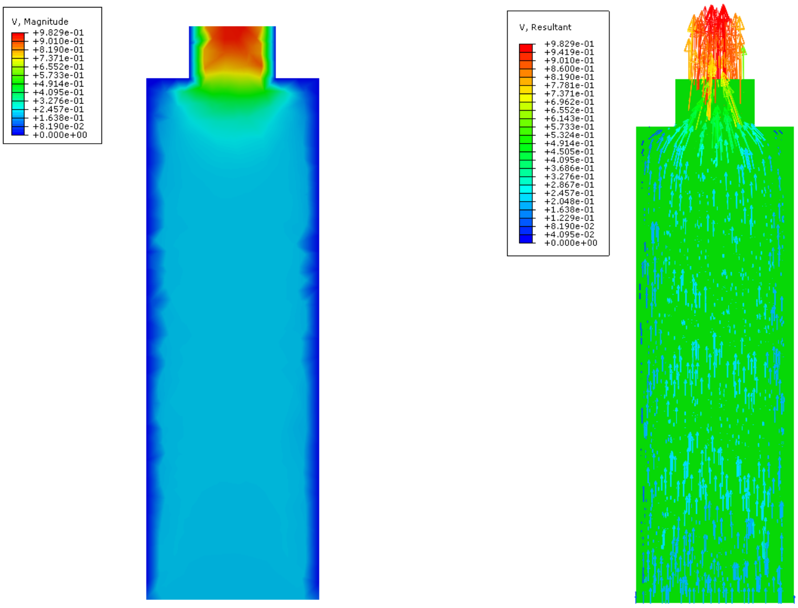
The obtained values of the flow velocity in individual cross-sections of the calorimeter measuring chamber were verified in the numerical analysis of the flow. There are many concepts and individual ways to conduct an analysis in this area [2, 11] and each of them presents the specificity of an approach that can be considered appropriate and at the same time constitutes an individual use of numerical tools. The presented analysis is also the authors' specific approach to solving the problem. In the first step, the solid model of the chamber was defined and then discretized (Fig. 3). During the process of heating the factor, as a result of burning the supplied fuel, heat is suddenly supplied, which is associated with high dynamics of the process. Analyzes of this type are carried out with the use of dedicated software. The subject of the analysis is the flow of the medium in the upper part of the combustion chamber after the heat supply to the medium.



Solid model Discretized model
(FC3D4: A 4-node linear fluid tetrahedron)

Fig. 3. Solid and discretized model of the calorimeter combustion chamber for numerical analysis.

Therefore, adopting the flow criteria, it was assumed that the heat supply has already taken place and the definition of the parameterization of the factor refers to the obtained thermodynamic state. Therefore, the following parameters of the factor were adopted with the values adopted in the calculations presented in chapter 2. The factor is air with pressure parameters of 101,300 Pa, temperature 873 K. The parameterization also uses the value of the factor's volume flow in the analyzed cross-section - diameter of the calorimeter chamber d = 100 mm, which was determined according to earlier calculations at $\dot{V}_2$= 0.001557 m^3/s. A numerical problem with specified parameters was analyzed, which resulted in obtaining the results of the flow value in the analyzed part of the calorimeter chamber (Fig. 4).



Velocity distribution Velocity vectors distribution

Fig. 4. The results of the flow velocity analysis in the upper part of the calorimeter combustion chamber - velocity distribution values in m/s.

The obtained results of the numerical analysis in the range of the maximum values of the flow velocity of the medium in the analyzed sections d_2 = 100 mm were obtained v_2 = 0.28 m/s and in the outlet channel d_3 = 50 mm the obtained were v_3 = 0.98 m/s. Taking into account that these are the maximum values of the flow velocity of the medium in the flow axis in the individual analyzed sections, it is necessary to average these values. After averaging, the obtained results do not differ from the values obtained from the calculations in chapter 2. Therefore, the proposed adopted procedure in the numerical analysis procedure was considered appropriate.

4 Conclusions

Calculations and verification in numerical analysis are associated with the development of mechanisms for the analysis of the processes taking place in the measuring chamber of the calorimeter. These works are closely related to the actions taken to develop a new design of the measuring device. The proposed concept was subjected to detailed elementary analyzes, part of which was presented in terms of the possibility of assessing the values of the flow parameters of the working medium. In the performed numerical tests, the obtained results were similar to those previously performed. This indicates proper use of the numerical tools. The obtained results will be subjected to another experimental verification in real laboratory measurements.

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