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Estimation of radiation efficiency of cylindrical porous reactor for combustion of lean premixed methane-air mixture

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Abstract. Aim of this study was to estimate the radiation efficiency inside of a cylindrical porous reactor developed by the authors, using combustion of a lean premixed methane-air mixture using flow calorimetry technique. It was found that the heat flux absorbed by water does not depend on the volume flow rate of the water. It was revealed in the experiment that lower combustible mixture flow rate leads to the maximum radiative efficiency.

Keywords: experiment, porous media, combustion, lean mixture, radiative efficiency, radiative heat flux, methane-air mixture.

1. Introduction

The process of combustion in porous media allows generating more powerful radiative heat flux in comparison to combustion in open flame [1]. In addition, combustion in a porous media has an extensive advantage, such as stabilization of the combustion wave at high combustion rates, possibility of power regulation in a wide range, combustion of lean gas mixtures, and low NOx emission [2–4]. Radiative porous burners are a promising tool for creating thermal radiation sources with controlled distribution of power, spectrum and radiation density. Such burners can potentially be used for non-contact heating of various materials in industrial processes instead of electrical heat sources.

A sintering furnace, in which the furnace chamber is completely packed with a ceramic spheres, and the premixed flame of natural gas with atmospheric air and oxygen as an energy source was experimentally studied in paper [5]. The furnace design allows usage of two combustion modes: (i) filtration combustion, when the narrow reaction front (combustion wave) freely propagates through the packed bed, and (ii) jet-stabilized combustion when the reaction front is stabilized near gas inlet nozzles used for fresh mixture supply into the packed bed. The configuration of high-temperature cylindrical porous reactor with axial gas supply for non-contact heating was proposed in paper [6]. Spectral and power characteristics of thermal radiation from a cylindrical porous burner with filtration gas combustion are experimentally studied in paper [7].

The purpose of this study was to estimate the radiation efficiency inside of a cylindrical porous reactor developed by the authors, using combustion of a lean premixed methane-air mixture.

2. Experiment

Infrared porous burner consisted of two vertical coaxial quartz tubes with outer diameters of 92 mm and 46 mm, wall thickness of both quarts tubes was 3 mm. Double layer porous media was formed by the ZrO_2 balls which filled the space between quarts tubes. The bottom 28 cm layer was formed by 2 mm ZrO_2 balls, the upper 6 cm layer was formed by 5 mm ZrO_2 balls. Outer cylindrical surface of the porous burner was covered by double layer heat insulation to reduce radiative and convective heat loss from the outer surface. The inner layer of insulation consisted of 1 mm stainless steel sheet to reflect the radiative heat flux back to the porous media. The outer layer was formed by 25 mm high-temperature Cerablanket heat insulation (Russia). The scheme of the experimental setup is presented in Fig. 1.

Methane (~ 99% purity) and air mixture was supplied from the bottom end of the porous burner. Pre-calibrated Bronkhorst El-Flow Series mass flow controllers (Netherland) were used to manage the gas flows. Mixture was ignited from the open upper end using the external heat source. Filtration combustion wave propagated against the fresh mixture flow and stabilized at the border line between the balls of a different diameter in a wide range of flow rates and equivalence ratios.

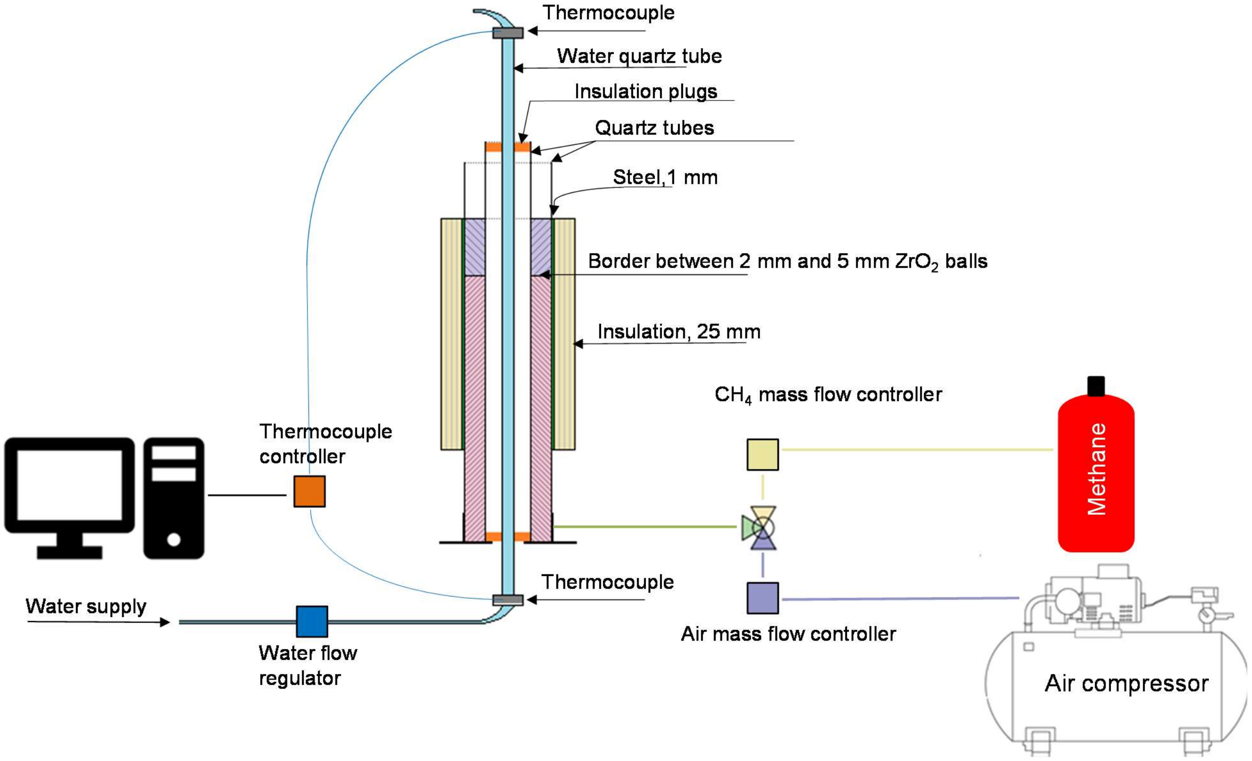

Fig. 1. Scheme of experimental setup.

To estimate the radiative heat flux inside the porous reactor, continuous flow calorimetry method was used. Quartz tube (1 m length) with two K-type thermocouples installed at its ends, was mounted vertically at the axis of the porous reactor using two plugs made of thermal insulation material. Thus, inner volume of porous reactor was isolated from atmosphere. Water from the supply system passed through the tube from the bottom to the top, absorbed the radiative heat flux, and heated up. To register the water temperature, thermocouples were connected to the Thermodat 29M6 controller (Russia). Water flow was controlled by Camozzi manual needle valve (Italy). Water flow was measured by filling of a graduated cylinder to a certain level over a specific amount of time. Obtained data reliability was ensured by a repeated flow measurement (5 times or more), followed by averaging of the obtained values. The heat flux absorbed by the liquid was calculated from the flow rate and the temperature difference at the ends of the tube, according to the formula:

$$Q' = c \cdot V \cdot \Delta \mathrm{T} \cdot \rho, \tag{1}$$

where: c – water specific heat [J/kg·K]; V – average water volume flow, measured inside of central tube [m^3/s]; ΔT – average temperature difference between input and output values of the thermocouples [K]; ρ – water density [kg/m^3].

Heat power obtained from the mixture burning was calculated according to the formula:

$$Q = B \cdot q, \tag{2}$$

where B is methane volume flow rate [m^3/s] and q is methane lower heating value [J/m^3]

Radiative efficiency of porous reactor was calculated according to the formula:

$$\eta = Q'/Q*100, \% \quad (3)$$

where Q' is water heating power [W] and Q is burning power [W].

Lean methane-air mixture with the equivalence ratio $\phi = 0.6$ was used in the experiments. Experiments were conducted in the wide range of mixture flow rates from 12.4 l/min to 74.4 l/min, that match to the inlet gas velocity range from 10 cm/s to 35 cm/s. The lower mixture flow rate led to the flame quenching and the higher one – to downstream flame front propagation. Quartz tubes with various diameters were used in calorimetry to measure the radiative heat flux absorbed by water from emitted porous media. Detail characteristics of the quartz tubes used in the experiments are listed in Table 1.

Table 1. Parameters of quartz tubes used in the experiments.

№	Outer diameter, mm	Wall thickness, mm
1	5	1.05
2	10	2
3	15	1.45
4	20	1.95
5	25	2.6

All experiments were conducted according to the following procedure. After switching on the water supply and mixture ignition, filtration combustion wave propagated upstream through the porous media formed by 5 mm balls. Depending on mixture flow rate combustion wave stabilized on the border line between 2 mm and 5 mm ZrO_2 balls in approximately 20–40 minutes. After flame front stabilization, we set a water flow rate to satisfy the condition of minimal temperature difference (~ 20 K) between upper and bottom thermocouples mounted on the quartz tube, using the needle valve. This condition was necessary to reduce errors in measurement. After the water flow has been set, we waited around 30 minutes for the full thermal stabilization of the experimental setup.

The calorimetric measurement involved evaluating the water flow rate and calculating the temperature difference between cold and heated water. The water flow rate measurement method described above; flow rate was measured at least 5 times for each given flow rate. During the water flow measurement, thermocouple readings were recorded simultaneously. After completing the flow measurement, the recording of temperature values stopped. Next, the collected data was analyzed, and the average water flow rate and the average temperature difference were calculated. These average values were substituted into equation (1) to determine the heat flow. At the experimental setup, a new, lower flow rate was set, with obtaining constant values of the cold and heated water temperature, and the procedure was repeated. This algorithm was performed for various liquid flow rates with constant parameters of mixture flow rate and equivalence ratio.

3. Results and discussion

Fig. 2 shows the results of preliminary calorimetric measurements at a fresh mixture flow rate of 35 cm/s, an equivalence ratio of $\phi = 0.8$, in a tube with a diameter of 5 mm. The reactor's outer surface did not have any thermal insulation during the preliminary experiment. Fig. 2 illustrates the results, with the vertical axis displaying the measured heat flow received by the water from the radiating porous media. The horizontal axes represent the volumetric flow rate of the water (lower axis) and the corresponding flow rate of the water into the tubes (upper axis). The red markers on the graph indicate the average values of the measured heat flow, while the horizontal error bars represent the standard deviation. The green horizontal line indicates the average value of the measured heat flux over the entire range of water flow rates. From the graph, it is evident that the heat flux absorbed by the water due to passing through the hot zone of the porous reactor does not depend on the water velocity. Based on this conclusion, we decided to focus on measuring the average heat flow at five different water flow rates in the subsequent experiments.

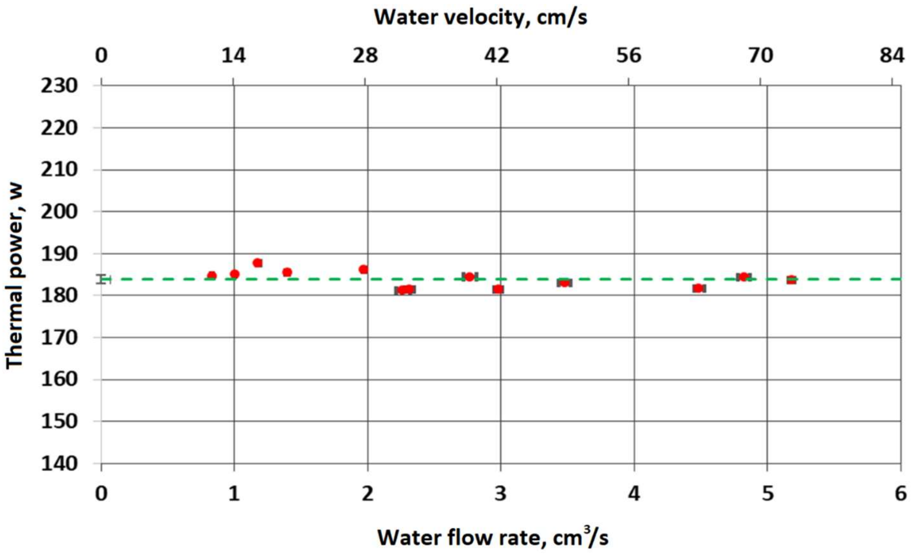

Fig. 2. Dependency of measured heat flux on water flow rate. Tube №1, ϕ = 0.8, mixture velocity 35 cm/s.

The measurements described above, were conducted using tubes of various sizes listed in Table 1, with fresh mixture flow rates ranging from 12.4 l/min to 74.4 l/min. Fig. 3 demonstrates the relationship between the radiation efficiency, calculated using formula (3), and the internal diameter of the tubes used in the calorimetric experiment. The different marker colors represent different flow rates of the fresh mixture. Each marker in Fig. 3 represents an average value based on five measurements. Vertical error bars indicate standard deviations, and thin black lines represent logarithmic trend lines. The graph demonstrates that a change in radiation efficiency occurs based on both the diameter of the quartz tube and the flow rate of the combustible mixture. An increase in radiation efficiency was observed when using larger diameter quartz tubes, as well as when reducing the speed of the combustible mixture. In the first case, the surface area of the water column, which absorbs radiation, increases. In the second case, as the velocity of the mixture decreases, the proportion of convective heat loss also decreases. The maximum radiation efficiency was achieved using a quartz tube with an outer diameter of 25 mm, at a velocity of the combustible mixture of 10 cm/s. The diameter of the quartz tube in calorimetry is limited by the design of the porous reactor. In the limiting case, the diameter of the water column must be equal to the internal diameter of the porous reactor. By using trend line equations, we extrapolated the experimental data to the scenario where the entire internal space of the reactor is filled with water and the velocity of the fresh mixture is minimal. Under such conditions, the maximum possible radiation efficiency was estimated to be around 40%. It's important to note that this value is a low estimate, as water absorbs only a portion of the radiation generated by the porous media, suggesting that the actual radiation efficiency of a porous reactor is likely higher.

The temperature distribution along the axis of the porous reactor was studied in addition to calorimetric measurements. The measurements were conducted for a mixture with an equivalence ratio ϕ = 0.6 and combustion mixture flow rates of 54.3 l/min and 76 l/min, corresponding to mixture velocities at the burner inlet of 25 cm/sec and 35 cm/sec. A K-type thermocouple enclosed in a ceramic Al_2O_3 casing was used for the temperature measurements. The thermocouple was installed on the reactor axis using a coordinate table with a 130 mm stroke along the axis, and the tip of the thermocouple was leveled at the upper border line of the 5 mm ZrO_2 balls porous layer. The measurements were taken from the lowest position of the coordinate table after the porous reactor was brought to a stationary mode. The thermocouple readings were recorded for 10 seconds, averaged, and then the thermocouple was moved to the next measurement point. The displacement step of the thermocouple ranged from 5 mm near the flame front to 10 mm far from the zone of combustion wave stabilization.

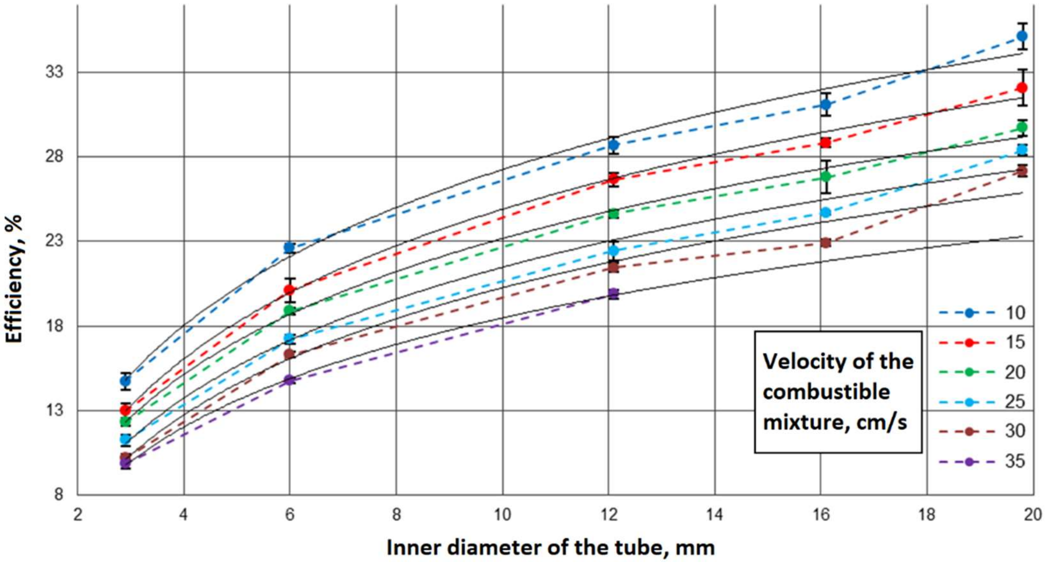

Fig. 3. Dependency of the porous reactor efficiency on water tube diameter.

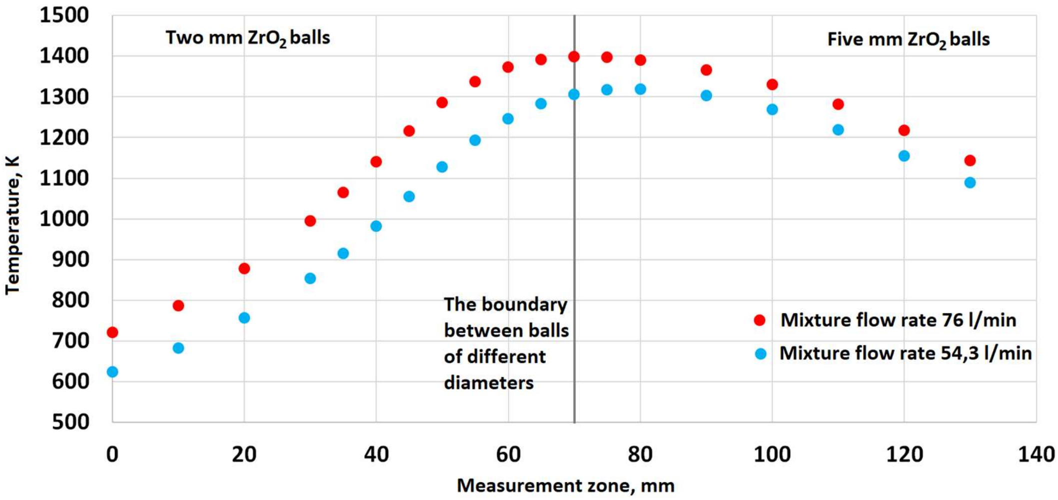

Fig. 4. Temperature profile at the axis of porous reactor.

The temperature profiles measured in the reactor axis for fresh mixture flow rates of 54.3 l/min and 76 l/min at an equivalence ratio of $\phi = 0.6$ are present in Fig. 4. Despite the lean mixture in the center of the reactor, high temperatures up to 1400 K were achieved due to the presence of thermal insulation. The graph shows that the maximum temperature at a flow rate of 54.3 l/min is approximately 100 K lower than at 76 l/min, indicating lower energy release at the lower flow rate. Additionally, there is a noticeable downstream shift of the temperature maximum relative to the interface between two porous media at a flow rate of 54.3 l/min. These results demonstrate that reactors of the proposed design can be utilized for industrial applications. Furthermore, the temperature inside the reactor can be manipulated not only by adjusting the composition and velocity of the mixture but also by varying the thickness of the thermal insulation.

4. Conclusions

In this work, an experimental study was conducted to evaluate the radiative efficiency of a cylindrical porous reactor during the combustion of a lean methane-air premixture. Flow calorimetry technique was used to measure radiative heat. Zirconium dioxide beads with diameters of 2 mm and 5 mm were chosen as packing material to stabilize the filtration combustion wave at the boundary of the two porous media across a range of mixture flow rates from 12.4 to 74.4 l/min. It was found that the radiative heat flux perceived by water does not depend on the volumetric flow rate through the measurement section. Increase in the radiative thermal efficiency was observed when the volumetric flow rate of the fuel mixture decreased, when the area of the water column absorbing the radiation increased, and when the distance between the emitting and receiving media decreased.

The results have potential applications in heat treatment of materials. The use of radiative porous burners can enhance the efficiency of processing operations by eliminating the need for electrical heaters. In addition, the safe combustion of various gaseous fuels in the porous medium is an important advantage of radiative porous heaters usage.

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5. References

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