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HEAT EXCHANGE IN COOLED COMBUSTION CHAMBERS OF LOW-CAPACITY HEAT GENERATORS

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ABSTRACT: Investigation into heat exchange in cooled combustion chambers and its influence on the intensity of various factors is an urgent and challenging task. On the basis of analysis of theoretical and experimental data on heat exchange, it can be concluded that the existing methods do not consider for peculiarities of heat exchange in small-sized combustion chambers and cannot be applied directly for their thermal design. This article presents data on field experiments and their generalization using criterion equation which is very important for the analysis of heat transfer and thermal design of cooled combustion chambers of low-capacity heat generators. Using generalizing dependence, the contribution of radiation and convection constituents into complex heat exchange for combustion chambers of low-capacity is estimated. Qualitative and quantitative dependence of integral radiation and convection heat exchange on the main process variables of small-sized combustion chambers has been determined.

Keywords: Heat exchange, Low-capacity heat generator, Combustion chamber, Efficiency.

1. INTRODUCTION

Heat transfer in combustion chambers resulted from irradiating flow of combustion products is determined by the intensity of convective, molecular, and irradiating transfer depending on conditions of injection, ignition and burning of the air-fuel mixture, variation of physicochemical properties of the environment, hydrodynamic conditions of the process and other factors. Convective heat exchange, radiation and molecular heat conductance as a constituent of complex heat transfer depending on the course of the process make a quantitative contribution to overall heat transfer. Neglecting any of these constituents can lead to distortion of a physical pattern of heat transfer and, hence, to incorrect quantitative relations in this process. Such result is confirmed by analysis of individual contribution of each constituent without their interaction [1; 2].

2. FORMULATION OF THE PROBLEM

Analysis of heat transfer by convection, molecular and turbulent heat conductance and radiation in gas flow leads to a set of differential and integral equations which should be solved jointly. Mathematical difficulties related to a solution of this system is required for an approximate solution. The main assumption is related to the exclusion of integral terms from the equation of energy transfer added as a consequence of radiation. The exclusion is convenient in ultimate cases of the optical thickness of irradiating layer: maximum and minimum.

The intensity of heat transfer by radiation in small-sized combustion chambers, steam generators and furnaces can be different even under similar thermal conditions since optical properties of the layer of radiating combustion products in combustion chambers of large and small sizes vary significantly. In this regard in small-sized combustion chambers upon the formulation of the problem of heat transfer, peculiar attention should be paid to the range of optical properties of combustion medium because it is known that physical model of energy transfer by radiation and final results depend significantly on the optical density of the medium.

The investigation into optical properties of the medium [2; 3] in small-sized combustion chambers demonstrated that irrespectively of calculation methods of averaged absorption coefficient the radiating medium is neither optically thin nor optically thick.

In order to reveal regularities of the process at intermediate optical thicknesses of radiating layer, additional experiments are required since in some cases it is possible to use absorption coefficient averaged according to Plank (approximation of optically thin layer) or according to Rosseland (approximation of optically thick layer) [3; 4].

Analysis of experimental data demonstrated that in the considered range of optical thicknesses generalization of experimental data obtained on the facility described below could be based on absorption coefficients generalized according to Rosseland.

Integral heat exchange can be determined by functional number of integral heat transfer:

$$K_{\mathrm{H}} = \frac{I_{\mathrm{theor}} - I_{\mathrm{ex}}}{I_{\mathrm{theor}} - I_{\mathrm{w}}},$$

where I_{theor} is the enthalpy of combustion products at theoretical combustion temperature, kJ/kg; I_{ex} is the enthalpy of combustion products at the temperature of exhaust gases, kJ/kg; I_{w} is the enthalpy of combustion products at the wall temperature, kJ/kg.

In this case K_{H} determines efficiency of combustion chamber and is a function of heat exchange between moving radiating gas flow and heating surface of combustion chamber [2].

Heat transfer from the space of combustion chamber to its walls is carried out via boundary layer due to radiation and turbulent diffusion (molecular transfer in the considered case can be neglected).

At the interface between boundary layer and wall heat transfer to wall is carried out by molecular heat conductance and resulting radiation of medium to heating surface.

Equation of heat balance on surface area corresponding to unit length of cylindrical chamber using diffusion approximation for energy transfer by radiation is described as follows:

$$-D_{\mathrm{turb}} \cdot \frac{d(\rho c_p T)}{d_{\mathrm{b}}} - \lambda_{\mathrm{irr}} \frac{dT}{d_{\mathrm{b}}} = \frac{\sigma_o n^2 (T_{\mathrm{c}}^4 - T_{\mathrm{em}}^4)}{\frac{1}{\delta_{\mathrm{em}}} - \frac{1}{2}} - \lambda_{\mathrm{mol}} \frac{dT}{d_{\mathrm{b}}}, \qquad (1)$$

where D_{turb} is the coefficient of turbulent diffusion, m^2/s; r is the chamber radius, m; c_p is the isobar heat capacity of combustion products, kJ/(kg·K); ρ is the density of combustion products, kg/m^3; λ_{rad} is the coefficient of irradiative heat conductance according to Rosseland, W/(m·K); σ_0 is the Stefan–Boltzmann –constant, $W/(m^2 \cdot K^4)$; n is the refractive index of medium; δ_{emm} is the surface emissivity factor; λ_{mol} is the coefficient of molecular heat conductance, W/(m·k); d_{b} is the burner diameter, m.

Equation (1) is given for surfaces obeying the Kirchhoff law.

On the basis of the obtained equation of heat balance at the interface between wall and boundary layer, it is possible to arrange the following criteria:
1. Criterion of radiation similarity:

$$K_{\mathrm{rad}} = \frac{k \cdot d_{\mathrm{ch}}}{\frac{1}{\delta_{\mathrm{em}}} - \frac{1}{2}} \left[1 + \frac{T_{\mathrm{em}}}{T} + \left(\frac{T_{\mathrm{em}}}{T} \right)^2 + \ldots + \left(\frac{T_{\mathrm{em}}}{T} \right)^n \right], \qquad (2)$$

where k is the absorption coefficient; d_{b} is the burner diameter, m.

On the basis of analysis of variables in Eq. (2) with accounting for features of heat transfer in small-sized combustion chambers, the criterion of radiation similarity can be rewritten as follows:

$$K_{\mathrm{rad}} = f(k \cdot d, \alpha) = f(\tau_{\mathrm{o}}, \alpha),$$

where α is the coefficient of air exces; $\tau_{\mathrm{o}} = k \cdot d$ is the optical thickness, m.

2. Criterion of turbulent molecular transfer:

$$K_{\mathrm{t\text{-}m}} = \frac{D_{\mathrm{turb}} \cdot \rho (I_{\mathrm{theor}} - I_{\mathrm{em}})}{\lambda_{\mathrm{mol}} (T_{\mathrm{theor}} - T_{\mathrm{em}})},$$

which in the considered case can be rewritten as follows:

$$K_{\mathrm{t\text{-}m}} = f_1 \left(\mathrm{Re}_{\mathrm{N}}; \frac{d_{\mathrm{b}}}{d_{\mathrm{ch}}}; \frac{l}{d_{\mathrm{ch}}} \right),$$

where Re_{N} is the Reynolds number; l is the chamber length, m.

3. Criterion of irradiative-molecular transfer:

$$K_{\mathrm{irr\text{-}m}} = \frac{\sigma_{\mathrm{o}} n^2 T^3}{k \lambda_{\mathrm{mol}}}.$$

In the considered case $K_{\mathrm{irr\text{-}m}}$ does not influence on heat exchange in combustion chamber.

For homogeneous combustion reactions the influence of reaction kinetic factors on heat exchange can be neglected [5; 6] or they can be considered identical for such combustion chambers with similar injection conditions of reacting substances.

Therefore, the similarity equation for detection of heat exchange for this case can be presented as follows:

$$K_H = \Phi \left(\mathrm{Re}_N; \tau_0; \alpha; \frac{d_{\mathrm{b}}}{d_{\mathrm{ch}}}; \frac{l}{d_{\mathrm{ch}}} \right). \qquad (3)$$

Functional dependence of integral transfer number on criterion arguments can be reliably determined on the basis of experimental study of complex heat exchange on models and field facilities.

3. EXPERIMENTAL STUDY

Experimental studies of complex irradiative-convective heat exchange were carried out on full-scale heat adjustable combustion chambers (Fig. 1). The facility was comprised of water-cooled sectional combustion chambers 1, liquid and gaseous fuel burners for various modes of injection and combustion of air-fuel mixture 2, devices for supply and flow adjustment of air, fuel and cooling water as well as instrumentation for metering of pressure, water flow rate, temperature and composition of fuel and combustion products.

The combustion chambers were comprised of vertical cylindrical heat exchangers with diameter d_{ch} – 0.18; 0.24; 0.3; 0.36 m assembled of section of various length aiming at obtaining of average regional heat flows on surface areas corresponding to relative section length $\frac{l}{d_{ch}} = \frac{1}{3}$ based on measurements of temperature and heat carrier in the points "B".

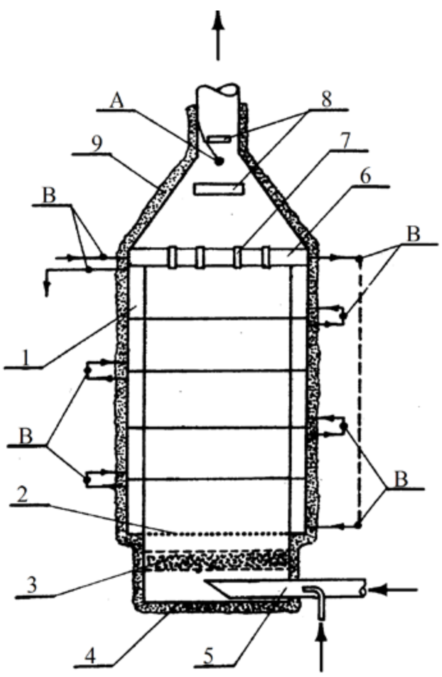

Fig.1 Experimental facility

The influence of chamber length on heat exchange at constant heat intensities of combustion space q_v was determined on the basis of experimental integral heat transfer in chambers with the length $\frac{l}{d_{ch}} = 1; 1\frac{1}{3}; 2; 2\frac{1}{3}$.

The upper portion of combustion chamber was equipped with outlet calorimeter in the form of hollow water-cooled disk with flue tubes 7 distributed over the surface so that the ratio of the surface area of transversal cross section of combustion chamber to the surface area of outlet cross section of flue tubes was constant for chambers of various diameter.

Temperature of combustion products at the outlet from cylindrical part was determined by gas temperatures in the point "A" located between the screens 8 and by heat absorption of the outlet calorimeter.

In one experimental series the combustion chambers were equipped with a burner of complete preliminary mixing of air and natural gas. The burner was comprised of the body 4, the mixer 5, the layer of ceramic chips 3 intended for equalization of velocity field of air-fuel mixture and heating of this mixture, the nichrome grid 2 for kinetic combustion of gas with the coefficient of air excess α = 1.05 – 2.0.

On the basis of generalization of experimental data, the obtained Eq. (3) makes it possible to analyze the influence of mode and geometry factors as well as the properties of absorbing medium on heat exchange in cooled combustion chamber upon identical conditions of injection.

The studies in this article and in [6] demonstrate that the absorption coefficient of combustion products k based on the Rosseland diffusion approximation is inversely proportional to the coefficient of air excess. In this case the criterion of irradiative similarity can be presented as follows:

$$K_{rad} = \frac{k \cdot d_{ch}}{\alpha}.$$

The absorption coefficient of combustion products art α = 1.0 is k_0 = 3.34 m^{-1} for natural gas and k_0 = 3.92 m^{-1} for fuel oil.

The coefficient of air excess influences differently on individual constituents of complex heat flow [7; 8].

With increase in the coefficient of air excess, the convective heat transfer is intensified due to increase in the criterion Re.

At the same time theoretical temperature of fuel burning and partial pressures of triatomic gases increase, that is, the coefficient of air excess influences optical thickness of medium.

The coefficient of air excess as an argument does not exclude from consideration the criterion Re despite the existing dependence of this criterion on α . This can be attributed to the fact that at constant α and $\frac{l}{d_k}$ variation of Re determines the flow mode of irradiating medium, that is, determines the intensity of convective heat transfer. Simultaneously this criterion is a function of heat stress of the combustion chamber.

The coefficient of air excess at steady Re and $\frac{l}{d_{ch}}$ but at various specific energy releases in the chamber characterizes the variation of an irradiative constituent in complex heat exchange.

Experimental data were processed according to the procedure permitting determination of irradiative and convective constituents as a function of the coefficient of air excess.

4. RESULTS AND DISCUSSION

After data processing the following dependencies were obtained describing the influence of coefficient of air excess α on heat exchange in the combustion chamber:

$$K_H = A\left(\frac{k \cdot d_{ch}}{\alpha}\right)^{0.47} \quad \text{at} \quad \text{Re} = \text{const}; \quad \frac{l}{d_{ch}} = \text{const}$$

$$K_H = B\,\text{Re}_N^{-0.33} \quad \text{at} \quad \alpha = \text{const}; \quad \frac{l}{d_{ch}} = \text{const}. \qquad (4)$$

The determining velocity of gases was the velocity normalized to the unit heat absorbance surface; the determining size was the chamber diameter, the determining temperature was the theoretical burning temperature.

Figure 2 illustrates the influence of α on irradiative constituent at constant convective heat transfer. Equation (4) describes the convective constituent of heat transfer as a function of $\text{Re}_N = f(q_v)$ at minor variation of intensity of heat exchange by radiation.

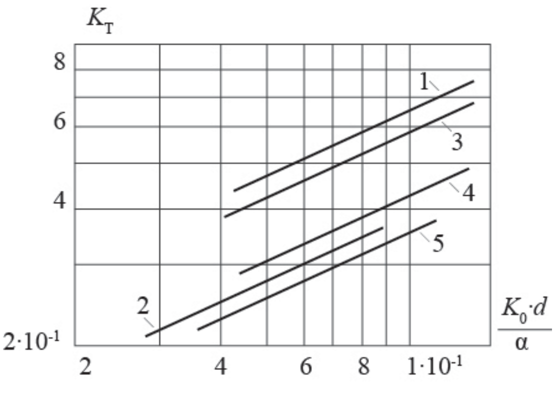

Fig.2 Integral heat transfer number as a function of criterion $\frac{k_0 \cdot d}{\alpha}$

1) $\frac{l}{d_{ch}} = \frac{7}{3}$, $\text{Re}_N = 67.1 - 80.1$;

2) $\frac{l}{d_{ch}} = \frac{7}{3}$, $\text{Re}_N = 299.1 - 315.2$;

3) $\frac{l}{d_{ch}} = \frac{7}{3}$, $\text{Re}_N = 121.1 - 137.4$;

4) $\frac{l}{d_{ch}} = \frac{7}{3}$, $\text{Re}_N = 120.6 - 144.4$;

5) $\frac{l}{d_{ch}} = \frac{4}{3}$, $\text{Re}_N = 189.9 - 211.3$.

Generalizing of the processed experimental data by exponential function made it possible to obtain partial dependences of integral transfer number K_H on criterion numbers and arguments in the equation of similarity (3).

Results of data processing for experiments in the chambers with diameter d = 0.18–0.36 m equipped with burners of complete and incomplete preliminary mixing of air with fuel and distributed along the cross-section injection of the air-fuel mixture were generalized as follows:

$$K_H = \frac{1}{1 + 0.1016 \cdot \text{Re}_N^{0.55} \cdot \left(\frac{k_0 \cdot d}{\alpha}\right)^{-0.86} \cdot \left(\frac{l}{d_k}\right)^{0.75}}. \qquad (5)$$

In the experiments the chamber fuel load varied in the range of $1.5 \cdot 10^{-4}$–$17.5 \cdot 10^{-4}$ kg/s, the coefficient of air excess α = 1.05–2.0, the temperature at chamber outlet into outlet calorimeter T_2 = 1011 – 1752 K, the conventional Reynolds number Re_N = 66–359, the relative chamber length $\frac{l}{d_k} = 1 - 2\frac{1}{3}$, the criterion of irradiative similarity $\frac{k_0 \cdot d}{\alpha}$ = 0.301–1.145, the integral heat transfer number K_H = 0.15–0.67, the specific energy release in the chamber q_y = 0.76–1.73 MW/m^3.

5. CONCLUSIONS

The obtained generalizing criterion dependence (5) makes it possible to estimate the contribution of radiation and convection constituents into complex heat exchange for low-capacity combustion chambers and to reveal qualitative and quantitative dependence of integral radiation and convection heat exchange on main geometrical, physical, and operation factors of small-sized combustion chambers.

Confidence estimation of the obtained experimental data demonstrated that the ultimate mean square error of integral heat transfer number K_H was 3.24%. Correlation estimation of conformity of the generalizing dependence (5) was based on integral heat transfer number K_H and exhaust gas temperature T_2. For all experiments, the deviation of calculations from experiments with a probability of 95% did not exceed the confidence range of ±9.52%.

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