UDC 62-62

CALCULATION OF HEAT TRANSFER INTENSITY OF GAS FUEL COMBUSTION PRODUCTS

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The relevance of the research is determined by the modern trend in the field of thermal power engineering and heat engineering for the transition from traditional gaseous fuel (methane) to the use of hydrogen, methane-hydrogen mixtures, as well as thermochemical conversion gases. Switching to new non-design fuel is justified by considerations of reducing the negative impact on the environment and increasing the thermal efficiency of fuel combustion plants. In this case, the use of fuels with a composition different from the design one will affect the heat transfer processes.
The main aim: carrying out a comparative analysis of indicators of the intensity of radiant and convective heat transfer of combustion products of non-design fuels, such as hydrogen, methane-hydrogen mixture and thermochemical conversion gases. As an assumption in the formulation of the problem and objectives of the study, the constancy of the heat release power in the apparatus due to changes in the amount of fuel burned was taken.
Objects: heat exchange surface of a fire-tube hot water boiler.
Methods: carrying out numerical calculation using traditional approaches to determine the indicators of the intensity of heat transfer in the system «combustion products – metal wall of the pipe of thermal power plants». We also used the relations tested earlier by other authors to calculate the thermophysical parameters of gas mixtures.
Results. According to the results of the performed comparative calculations, we can conclude that the transition from the use of conventional fuel (natural gas/methane) to its thermochemical conversion gases under the considered conditions has almost no effect on the integral heat transfer performance. To a greater extent, this transition is caused by changes in the intensity of heat transfer for products of combustion of hydrogen and methane-hydrogen mixture, which will affect the operation of thermal power and heat technological installations. At the same time, it is necessary to conduct additional research on the combustion kinetics of thermochemical methane conversion gases, their thermophysical properties, etc., because the hardware design, type of the catalyst used and operating parameters of the process will affect the composition of obtained synthesis gas.

Key words:
conversion, hydrogen, methane, thermochemical regeneration, hot water boiler,
catalyzator, synthesis gas, combustion products, temperature.

Introduction

In today's realities in the field of heat power and heat engineering the question of environmental safety or even carbon neutrality of production processes, as well as increasing their fuel efficiency in terms of reducing the cost of primary fuel for the output of finished products or services is acute.

One of the directions to improve the environmental efficiency of fuel-using units is their conversion to hydrogen combustion. This development vector of industrial thermal power engineering and thermal power plants is reflected in modern research [1]. However, the work with pure hydrogen imposes certain features on the systems of safe storage, supply and end-use of hydrogen. At the same time, the transition to the use of pure hydrogen as fuel will require a significant modernization of the entire gas transportation infrastructure in Russia. In papers of domestic authors it is noted that with hydrogen content up to 40 % in the mixture with natural gas the existing systems of pipeline transport of such gas practically do not require modernization [2].

Recently there have been a number of papers devoted not so much to the regenerative use of thermal secondary energy sources for heating air, and in some cases fuel [3], as to thermochemical regeneration. Its essence is to use the heat of waste flue gases for preliminary endothermic processing of the original fuel [4–8]. As a result of such conversion fuel gets a larger amount of chemically bound energy in the form of increased calorific value. Ethanol, methanol [9, 10] can be used as a feedstock for steam reforming, along with methane [11], and in some cases even the possibility of pre-gasification of solid fuel by steam [12], obtained from the heat of flue gases, and a steam-gas mixture, representing inherently combustion products, i. e. using direct contact between the gasifying agent and the feed fuel is considered. A similar approach is considered in [13], where thermochemical heat recovery on the basis of methane steam conversion with addition of flue gases, and in [14] the possibility of methane reforming by products of complete combustion with application of nickel catalysts is evaluated on the basis of experimental studies.

There have appeared works not only of a theoretical nature on the study of the processes of thermochemical heat recovery of waste combustion products [15, 16], but also of an experimental plan [17–19]. Such works have been carried out for internal combustion engines [20–22], gas turbines [15, 23], industrial furnaces for various purposes [16, 17, 24], and other fuel-using thermal power and heat engineering installations. A variety of application areas for the technology of thermochemical heat recovery of combustion products shows the promise of this method of improving the energy efficiency of existing and developed equipment.

The transition from combustion of the project fuel – natural gas (methane), should affect the thermal regime of heat power and thermo-technical equipment. Heat transfer coefficients, temperatures of gases and heat exchange surfaces, their heat absorption, combustion processes, aerodynamics of the gas-air duct and, of course, thermal efficiency of the unit as a whole should be expected to change.

Methods

Based on the notion of high-temperature thermal secondary energy sources formation in the form of flue gases and the highest priority of their use as a source of thermal energy for the reactions of thermochemical conversion of the original fuel and its subsequent combustion, we can note the importance and need for a comparative analysis of indicators of intensity of heat exchange of their combustion products. Thus, it is necessary to select the fuels that we will consider in the framework of this work. First of all, these will be methane and methane-hydrogen mixture (MHM), as well as pure hydrogen and thermochemical conversion gases, for which works on numerical and experimental determination of combustion kinetics were performed [25].

The main thermotechnical characteristic of combustion products of combustible gases that allow us to perform a comparative analysis is the intensity of heat transfer, defined by the corresponding coefficients of radiant and convective heat transfer.

By analogy with the works of professor Yu.Ya. Pechenegov [26], as well as taking into account the ratios presented in [27] for the case of intra-channel movement of heat carriers with a slight change in physical properties across the channel, the following parameters, $W/(m^2 \cdot K)$ are taken as indicators of heat transfer intensity:

$$P_l = \frac{5.67 \cdot \varepsilon_g \cdot ((T/100)^4 - 55.5)}{T - 273}$$

and

$$P_c = \frac{\lambda}{d} \cdot 0.023 \cdot \left(\frac{w \cdot d}{v}\right)^{0.8} \cdot Pr^{0.4} \cdot \varepsilon_L, \qquad (1)$$

where ε_g is the degree of blackness of the combustion products; T is the design temperature, K; λ is the heat conductivity coefficient of the combustion products, $W/(m \cdot K)$; d is the determining size (for the case of movement of combustion products inside the pipes, it is taken equal to the inner diameter), m; w is the speed of the combustion products, m/s; v is the kinematic viscosity

coefficient of the combustion products, m^2/s; Pr is the criterion of thermophysical properties of a mixture of gases (Prandtl criterion); ε_L is the correction taking into account the ratio of the length of the pipe L to its inner diameter d.

Similarly to the approach described in [26], the calculated temperature T can be defined as half of the adiabatic combustion temperature of the fuel.

The expression for P_l is an expression for calculating the heat transfer coefficient by radiation obtained from the Stefan–Boltzmann equation; P_c is obtained on the basis of the well-known criterion relationship between the Nusselt and Reynolds numbers under the assumption of a turbulent gas flow regime, which makes it possible to correctly compare heat transfer from combustion products of different composition to the heat exchange surface.

During calculations according to the additivity rule, the molecular mass, density and volumetric heat capacity of the products of combustion (mixture of gases) are determined. The additivity rule cannot be fully extended to multicomponent mixtures. For a binary mixture, the error in determining the thermophysical properties by the additivity rule can reach 20–40 %, which is not in the methods offered in [28]. The dynamic viscosity coefficient of a gas mixture consisting of n components at low pressure (up to 1 MPa) is determined according to the Chapman–Enskog kinetic theory by the Sutherland–Thiesen formula [28, 29], Pa·s:

$$\mu_{mix} = \sum_{v=1}^{V} \frac{r_v \cdot \mu_v}{\sum_{w=1}^{W} r_w \cdot \Phi_{vw}}, \qquad (2)$$

where r_v and r_w are the molar fractions of the v-th and w-th components; μ_v is the dynamic viscosity of the pure v-th component, Pa·s;

$$\Phi_{vw} = \frac{[1 + (\mu_v/\mu_w)^{0.5} \cdot (M_w/M_v)^{0.25}]^2}{[8 \cdot (1 + (M_v/M_w)]^{0.5}}$$

is the Wilke multiplier-function of the ratio of viscosities μ and molecular masses M of the v-th component by all other w-th components in the mixture.

The thermal conductivity coefficient of the gas mixture can be determined by Vasilyeva formula [28, 29], $W/(m \cdot K)$:

$$\lambda_{mix} = \sum_{v=1}^{V} \frac{r_v \cdot \lambda_v}{\sum_{w=1}^{W} r_w \cdot A_{vw}}, \qquad (3)$$

where λ_v is the thermal conductivity coefficient of the pure v-th component, $W/(m \cdot K)$;

$$A_{vw} = \frac{[1 + (\lambda_v/\lambda_w)^{0.5} \cdot (M_v/M_w)^{0.25}]^2}{[8 \cdot (1 + (M_v/M_w)]^{0.5}}$$

is the Mason–Sachsen multiplier-function of the ratio of thermal conductivity and molecular masses of the v-th component by all other w-th components in the mixture.

Numerical values of properties of individual components in formulas (2), (3) are taken at the temperature for which the corresponding property is determined.

When calculating the indicator of the intensity of convective heat transfer of combustion products P_c according to expression (1), the correction value ε_L can be taken equal to unity for pipe lengths greater than 50 pipe inner diameters. This condition is satisfied for most gas-tube hot water boilers, including the one considered later in our work. The Prandtl number, taking into account the recommendations of [28], in the framework of this work is determined by the expression:

$$\mathrm{Pr} = \frac{c_{p,m}}{1.204 \cdot c_{p,m} + 6.155},$$

where $c_{p,m}$ is the heat capacity of combustion products per 1 kmol, kJ/(kmol·K).

In general, the degree of emissivity of combustion products depends on many factors: chemical composition and combustion conditions of the fuel, design of the burner, and other individual features, and most of them are rather problematic to take into account theoretically. It is known that only triatomic gases and gases of high atomicity have appreciable radiation. Therefore, the degree of blackness of combustion products, provided that there are no dust particles and black carbon in their composition, can be determined by the expression [30]

$$\varepsilon_g = \varepsilon_{CO_2} + \beta \cdot \varepsilon_{H_2O},$$

where ε_{CO_2}, ε_{H_2O} is the degree of blackness of carbon dioxide and water vapor in the composition of the combustion products, determined according to the recommendations [30] depending on the temperature of the combustion products; β is the correction factor for partial pressure of water vapor.

When determining the average beam length in this work, we used the dependence obtained for the radiation of an equivalent gas hemisphere [30]

$$l = 0{,}9 \cdot d.$$

The using parameters P_l and P_c in the comparative analysis of combustion products of nonproject fuels makes it possible to identify those of them that provide the greatest intensity of heat exchange of combustion products, and allows establishing the possibility of their use in standard power and heat engineering installations without making significant changes in the design.

Results and discussion

When determining the conditional velocity of the combustion products w for calculation P_c, it is necessary to select the geometric and linear dimensions of the heat exchange surface.

Based on the hypothesis of continuity (continuity), taking into account their temperature, the velocity of combustion products is calculated by the expression, m/s:

$$w = \frac{\upsilon \cdot B}{f} \cdot \frac{T}{273},$$

where υ the volume of combustion products determined according to the method [30] based on the composition of the initial fuel, m³/m³; B is the fuel consumption, m³/s; f is the cross-sectional area provided for the passage of combustion products, m².

It is suggested to consider a flame and smoke tube boiler of KSV-2.0, as a heat engineering installation in which any of the considered fuels will be used. The nominal heat output of the boiler is 2,0 MW, the boiler's inlet/outlet water temperature is 70/115 °C, the maximum operating water pressure is 0,6 MPa, boiler volume is 5,31 m³.

In this paper the movement of combustion products is considered on the example of chimney pipes with an internal diameter of 52 mm and the number of pipes of 36 pcs. In addition to the chosen geometry of the tube bundle, which ensures the passage of combustion products, the total thermal power of the boiler at the level of 2,0 MW, provided by gaseous fuels of different calorific value, is chosen as a constant value, which undoubtedly causes a change in the volumetric flow rates of fuel and the resulting combustion products. In addition, in the calculations it was accepted: η=92,5 % is the boiler efficiency; q_3=0,5 % is the heat loss with chemical unburning; q_4=0 % is the heat loss with mechanical unburning; q_5=0,5 % is the heat loss to the environment.

The composition of thermochemical conversion gases (TCG) is taken on the basis of experimental data presented in [31] for reaction temperature 1200 K and composition CH_4:H_2O:CO_2=1:1.3:0.7.

Initial data for calculating the combustion process of fuels are as follows: the excess air ratio is 1,1; the oxygen content in the air is 21 vol. %. Initial data on the composition of the initial fuel, the lower heat of combustion and other calculation results are presented in Table.

The results of calculations to determine the parameters P_l and P_c are shown in Figure.

Analysis of Figure, a shows that the combustion products of the methane-hydrogen mixture are comparable to the products of methane (natural gas) by the radiant heat transfer intensity P_l. Significantly different values P_l for hydrogen combustion products take place – below the corresponding value for natural gas combustion products by 21–22 %, and for thermochemical conversion gases – higher by 38–39 %. The maximum value P_c for flue gases at combustion of thermochemical conversion gases can be explained by the maximum value of the fraction of triatomic gases capable of transferring thermal energy in the form of radiation compared to the values characteristic of methane and methane-hydrogen mixture. The explanation for such small absolute numerical values P_l can be the element of the boiler selected for consideration (the small value of the thickness of the radiating layer, characteristic of the movement of combustion products in the convective heating surfaces). At the same time, the obtained results can be used for a qualitative comparison of the intensity of heat transfer by radiation of combustion products of different gaseous fuels.

When considering the indicator of the intensity of convective heat transfer P_c according to the data of calculations presented in Figure, b, the situation is slightly different. The maximum value P_c corresponds to the combustion products of natural gas and is 44 W/(m²·K), then in the ranking order there are thermochemical conversion gases, hydrogen and the minimum value corresponds to the use of methane-hydrogen mixture as a fuel.

The value of the effective (total) heat transfer intensity factor for methane combustion products is 50 W/(m²·K). The minimum deviation in comparison with the products of natural gas combustion is in the products of combus-tion of gases of thermochemical conversion +3,5 %, while for the methane-hydrogen mixture the deviation is –4,6 %, and for the products of hydrogen combustion it is already –5,8 %.

Table. *Initial data and calculation results*
Таблица. *Исходные данные и результаты расчета*

| Indicator Показатель	Measurement unit Единица измерения	Fuel/Топливо			
		hydrogen водород	methane метан	methane-hydrogen mixture (MXM) метано-водородная смесь (MBC)	thermochemical conversion gases (TCG) газы термохимической конверсии(TXP)
Fuel composition/состав топлива H_2 CH_4 CO_2 CO H_2O	vol. %/об. %	100,00 — — — —	— 100,00 — — —	40,00 60,00 — — —	51,53 0,01 5,56 28,44 14,46
Net calorific value/Низшая теплота сгорания	kJ/m³/кДж/м³	10800	35820	25812	9164
Volume of combustion products Объем продуктов сгорания	m³/m³/м³/м³	3,160	11,641	7,849	2,728
Combustion products composition Состав продуктов сгорания N_2 O_2 CO_2 H_2O	vol. %/об. %	65,44 1,59 — 32,97	71,06 1,73 8,59 18,62	73,78 1,79 7,64 16,79	60,63 1,47 12,46 25,44
Fuel consumption/Расход топлива	m³/s/м³/c	0,200	0,060	0,083	0,236
Design temperature/Расчетная температура	К/К	1309	1212	1278	1251
Kinematic viscosity coefficient of the combustion products Коэффициент кинематической вязкости продуктов сгорания	m²/s/м²/c	218,3·10⁻⁶	169,3·10⁻⁶	185,3·10⁻⁶	181,6·10⁻⁶
Thermal conductivity coefficient of combustion products Коэффициент теплопроводности продуктов сгорания	W/(m·K) Вт/(м·К)	0,073	0,061	0,063	0,066
Rate of combustion products Скорость продуктов сгорания	m/s/м/c	39,87	40,80	40,12	38,22
Average beam length Средняя длина луча	m/м	0,0468	0,0468	0,0468	0,0468
Degree of blackness of combustion products Степень черноты продуктов сгорания	—	0,032	0,048	0,041	0,061
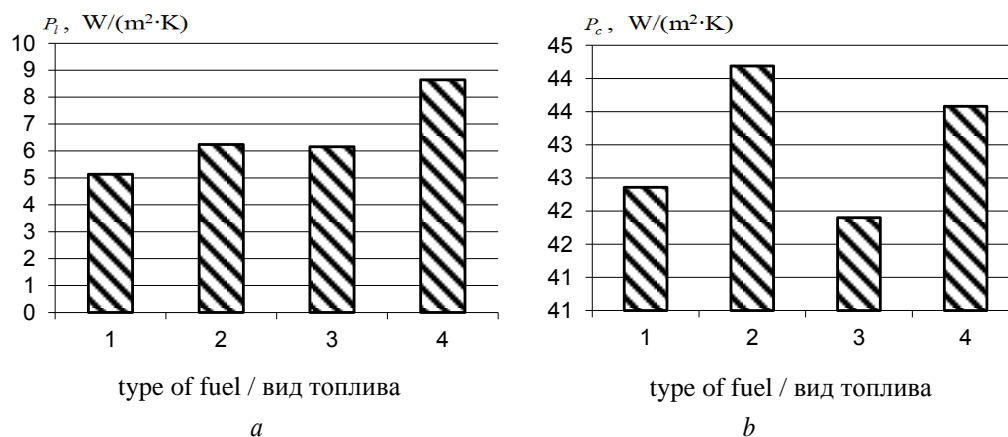
Figure. *Dependence of the parameters of the radiant (a) and convective (b) heat exchange of the combustion products: 1 – hydrogen; 2 – methane; 3 – methane-hydrogen mixture; 4 – thermochemical conversion gases*
Рисунок. *Зависимость параметров лучистого (a) и конвективного (b) теплообмена продуктов сгорания: 1 – водорода; 2 – метана; 3 – метано-водородной смеси; 4 – газов ТХР*

Conclusions

On the basis of the performed assessment of the indicators of the intensity of radiant and convective heat ex-change of the combustion products of various gaseous fuels, it can be replaced that the transition to hydrogen or a methane-hydrogen mixture in standard boiler units and other heat engineering and heat power installations is

complicated due to a change in the heat absorption of the corresponding heating surfaces and requires the introduction constructive changes in them or performance degradation. The closest in terms of the resulting heat transfer coefficient are the products of combustion of the products of combustion of gases obtained by the method of thermochemical steam-hydrocarbon conversion.

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РАСЧЕТ ИНТЕНСИВНОСТИ ТЕПЛООБМЕНА ПРОДУКТОВ СГОРАНИЯ ГАЗОВЫХ ТОПЛИВ

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Актуальность исследования обуславливается современным трендом в области теплоэнергетики и теплотехники по переходу с традиционного газообразного топлива (метана) на использование водорода, метано-водородных смесей, а также газов термохимической конверсии. Перевод на новое непроектное топливо обосновывается соображениями снижения негативного воздействия на окружающую среду и повышения тепловой эффективности топливосжигающих установок. При этом использование топлив с составом отличным от проектного повлияет на процессы теплообмена.
Цель: проведение сопоставительного анализа показателей интенсивности лучистого и конвективного теплообмена продуктов сгорания непроектных топлив, таких как водород, метано-водородная смесь и газы термохимической конверсии. В качестве допущения при постановке задачи и целей исследования принято постоянство мощности тепловыделения в аппарате за счет изменения количества сжигаемого топлива.
Объект: теплообменная поверхность жаротрубного водогрейного котла.
Методы: проведение численного расчета с привлечением традиционных подходов по определению показателей интенсивности теплообмена в системе «продукты сгорания – металлическая стенка трубы теплоэнергетических установок». Также использованы апробированные ранее другими авторами соотношения для расчета теплофизических параметров газовых смесей.
Результаты. По результатам выполненных сравнительных расчетов можно заключить, что переход от использования традиционного топлива (природного газа/метана) к газам его термохимической конверсии в рассмотренных условиях практически не влияет на интегральные показатели теплоотдачи. В большей степени такой переход вызывает изменения интенсивности теплоотдачи для продуктов сгорания водорода и метано-водородной смеси, что повлияет на работу теплоэнергетических и теплотехнологических установок. Вместе с тем необходимо проводить дополнительные исследования по кинетике горения газов термохимической конверсии метана, их теплофизическим свойствам и пр., поскольку аппаратурное оформление, тип применяемого катализатора и рабочие параметры процесса будут оказывать воздействие на состав получаемого синтез-газа.

Ключевые слова:
конверсия, водород, метан, термохимическая регенерация, водогрейный котел,
катализатор, синтез-газ, продукты сгорания, температура.

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