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NUMERICAL MODELING OF STABILIZATION OF THE HEAT OUTPUT OF A STEAM BOILER DURING COMBUSTION OF ASSOCIATED PETROLEUM GAS

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Abstract: *The composition of gaseous fuel can vary widely, depending on the source, time and stage of development of a particular field. Changes in composition lead to a change in thermophysical characteristics of fuel, which affects the stability of operation of boiler units. This article presents the results of numerical simulation of stabilization of heat output and the completeness of combustion of associated petroleum gas (APG) in the event of prolonged, continuous change in its composition. The simulation was carried out using the previously developed algorithm for optimizing the combustion process of the hydrocarbon fuel (HCF) of variable composition. The simulation results showed that with a slow continuous change in fuel low heating value with a relative rate of change of 1 % during the time of thermal inertia, the stabilization of operation of the boiler according to the proposed algorithm allows maintaining the steam temperature at the outlet within 10 % of the required one.*

Keywords: *heat power engineering, industrial boiler, combustion optimization, variable fuel composition, heat engineering, associated petroleum gas*

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Introduction

According to the Decree of the President of the Russian Federation No. 899 dated 07.07.2011, priority direction of science, technology, and engineering development is “Energy Efficiency, Energy Saving, Nuclear Energy”, and one of the critical technologies of the Russian Federation development is “Energy Efficient Production Technologies and Energy Conversion Using Organic Fuels" [1]. Also in the Energy Strategy of Russia for the period until 2030, priority areas for energy development are the reduction of specific fuel costs in the production and consumption of energy resources through the use of energy-saving technologies and equipment [2]. One of the ways to reduce the consumption of traditional energy is the use of alternative fuels, such as biogas, synthesis gas and industrial gaseous waste. For the Russian Federation, the use of associated petroleum gas (APG) is more relevant.

In 2009, the Government of the Russian Federation adopted Resolution No. 7 of January 8 “On Measures to Promote the Reduction of Atmospheric Air Pollution by Products of Associated Petroleum Gas Burning in Flares” which laid down the requirement to increase the level of rational use of associated gas to 95 % [4]. The United States also notes the importance of the rational use of hydrocarbon wastes, so the US Environmental Protection Agency, since 2008, considers any gas generated at a refinery to be used as fuel [5]. At present, the following methods of rational utilization of APG are used [10–14]:

1. Processing at a gas processing plant.
2. Injection into the reservoir (cycling process, "gas lift").
3. Processing of APG using GTL technology (gas to liquid) or liquefaction in LPG (liquefied petroleum gas).
4. Injection to seasonal underground storage.
5. The use of APG as an alternative fuel for generation of electric and thermal energy in power plants.

Unlike traditional fuels, the component content of associated petroleum gas can vary widely depending on the source, time and stage of field development. In the oil reservoir, associated petroleum gas is dissolved in oil or is located above the oil in a “gas cap”. The composition of gases in the “gas cap” can be very different from the composition of gases dissolved in oil. The composition of gases depends on conditions of sampling, its pressure in the well, proportion of free gas in a sample from the reservoir and proportion of gas released from the oil during its rise in the borehole. In this regard, the content and composition of heavy hydrocarbons in gases selected in the same area show significant fluctuations.

A characteristic feature of APG composition is the presence in them not only methane (CH4), ethane (C2H6), propane (C3H8), butane (C4H10), but also vapor of heavier hydrocarbons. APG has a high calorific value, which varies from 37673 to 62788 kJ/m^3 due to the instability of its composition [3].

These changes lead to thermal effect instability of the combustion process, which can lead to negative consequences [4, 5]. There is a probability of blowout (flame going deep into the furnace space), flashback (flame propagation inside the burner), combustion instability (pressure pulsations), self-ignition (ignition of the gas-air mixture in the mixture-forming space), local surface overheating.

The available methods for optimizing a boiler operation, based on controlling the composition of flue gases, calculating the thermal efficiency, and measuring the combustion temperature, are not perfect. The common disadvantages of these methods are high labor intensity, constructive complexity of execution and, most importantly, the inability to quickly respond to random changes in the composition of the combusted fuel. This situation is a consequence of the insufficient knowledge of the thermodynamic characteristics of the hydrocarbon fuels combustion process during periods of changes in its composition, the lack of scientifically based methods for stabilizing the thermal effect of combustion and the heat flux transferred to the coolant. All of the above indicates the relevance of this topic.

The aim of this work was to numerically simulate the stabilization of heat output and the complete combustion of purified associated petroleum gas according to the algorithm developed earlier in the event of a long continuous change in its composition.

Methods

The authors had previously developed a quasistationary model of stabilizing the heat release rate during combustion of a mixture of methane hydrocarbon fuels with air, ensuring complete combustion of fuel in the event of short-term and long-term changes in its calorific value [6–9], and allowing one to stabilize the heat release of the boiler when burning the methane hydrocarbon fuels variable composition with ensuring its complete combustion. According to the algorithm, when the outlet temperature of the heat carrier decreases, caused by a decrease in the fuel calorific value, it is necessary to begin a gradual increase in the fuel flow rate without changing the air flow rate until the heat carrier temperature becomes initial. In case of a constant temperature, the burning mode is specified by a one-time reduction in fuel consumption. A sharp decrease in temperature indicates the optimal combustion mode, and, according to the algorithm, it is necessary to return to the previous value of fuel flow rate and back to the optimum mode. The constancy of the temperature after a single reduction in the fuel flow rate indicates that an increase in specific heat of combustion has begun, which compensates fuel underburning because the air flow rate has not changed. Therefore, it is necessary to continue a further reduction in fuel flow rate until the temperature starts to decrease. After that, it is necessary to return the previous value of fuel flow rate which corresponds to the initial constant temperature.

Numerical simulation was carried out according to the developed algorithm using the standard method of thermal calculation of boilers [12].

Calculation conditions

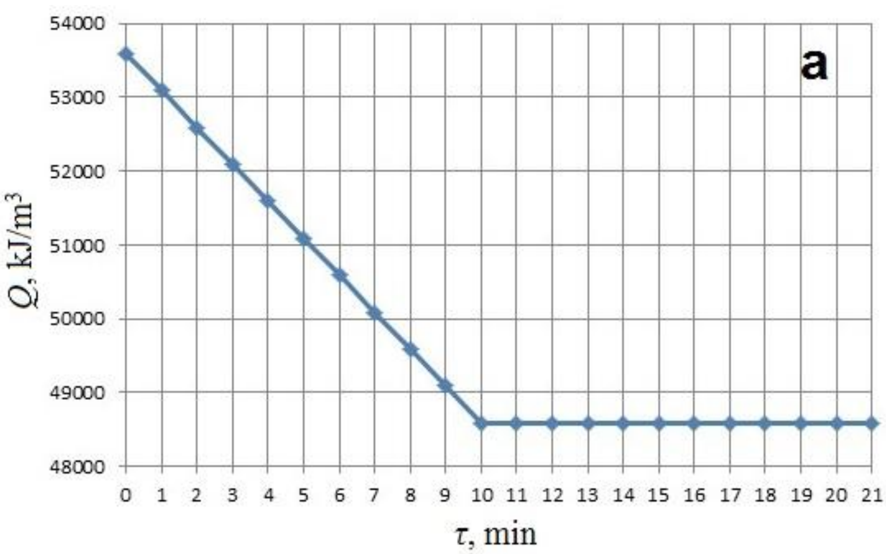
For the calculation we selected steam boiler DE 10-14. The parameters of the boiler operation are shown in the table.

Table

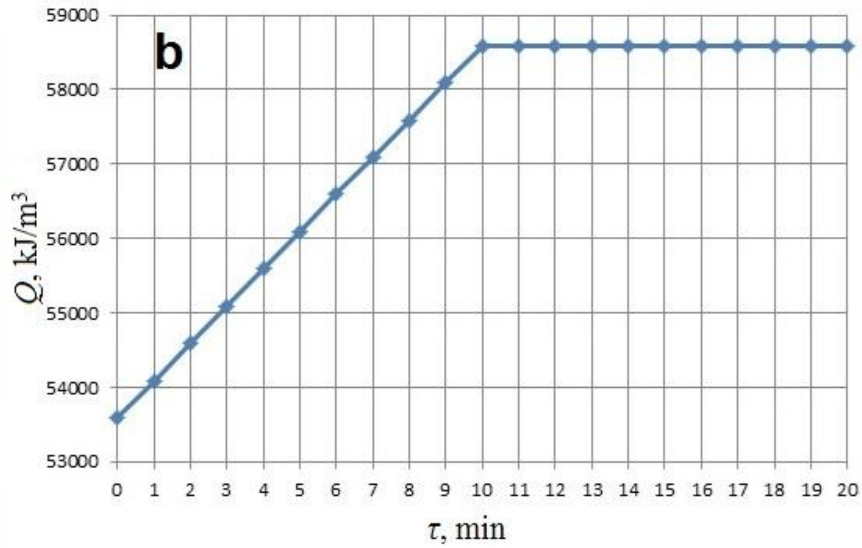
Parameters of the boiler operation

№	Parameter	Value
1.	Boiler steam output *D*, kg/h	6097
2.	Saturated-steam temperature t_s, ^{0}C	172,1
3.	Saturated-steam enthalpy H_s, kJ/kg	2770
4.	Entering water temperature t_w, ^{0}C	100
5.	Entering water enthalpy H_w, kJ/kg	508
6.	Exhaust gases temperature ϑ, ^{0}C	125
7.	Air temperature at the boiler inlet t_{ina}, ^{0}C	27
8.	Thermal inertia time τ_{ti}, min	1

As an example of a hydrocarbon fuel of variable composition, purified associated petroleum gas (i.e., only the hydrocarbon composition of the gas was taken into account) was taken. Two cases were considered: a prolonged decrease and increase in the fuel calorific value (Fig. 1).



a)



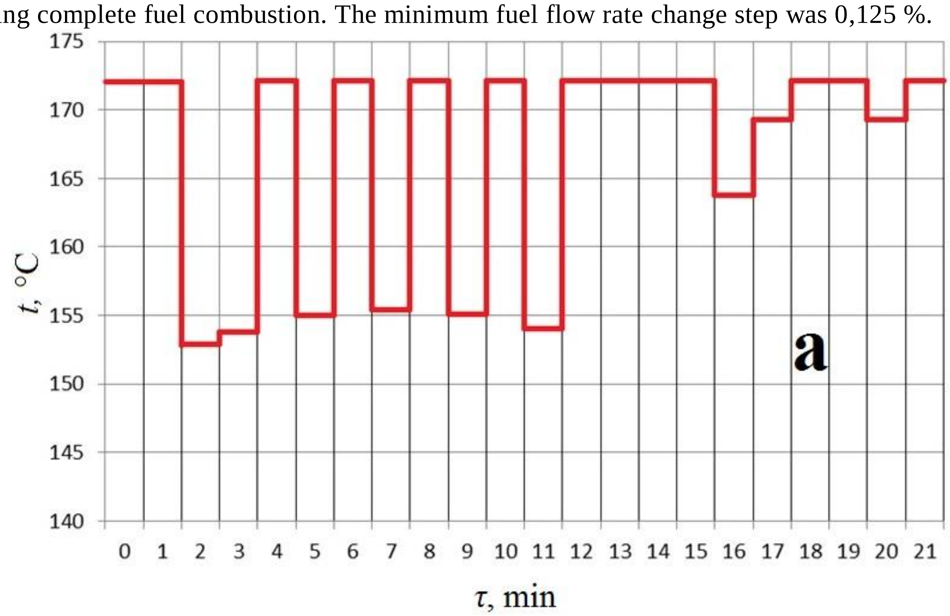
b)

Fig. 1. Prolonged decrease (a) and increase (b) of the fuel calorific value over time

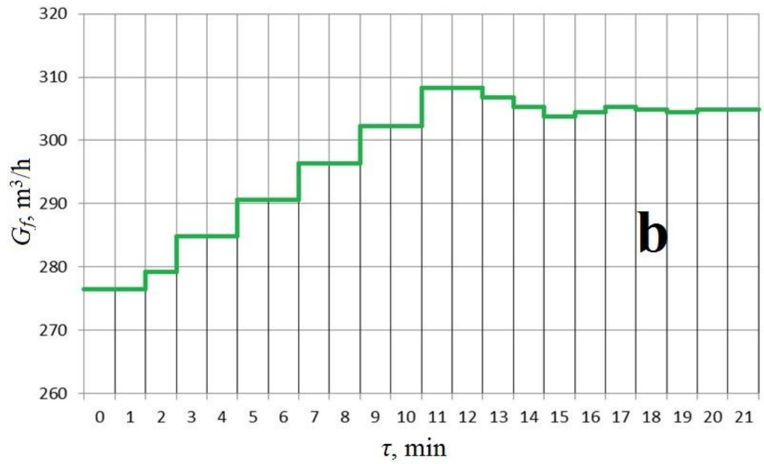
The rate of fuel calorific value change is λ_q=500 kJ/min·m^3, initial fuel flow rate G_f=276,5 m^3/h, gross efficiency η=0,931. The analysis was performed in a quasistationary approximation. This means that in the time interval equal to the time of the boiler's thermal inertia, the enthalpy of steam remains constant. At the end of the time interval, the enthalpy quickly takes on the value corresponding to fuel calorific value, which was at the beginning of the interval, so $H_s(\tau)$ is considered a function of $Q_n^r(\tau-\tau_{ti})$.

Results

Numerical simulation showed that regulation of the boiler operation according to the proposed algorithm allows maintaining the steam temperature within 10 % of the initial one (Fig. 2, *a*, Fig. 3, *a*) as a result of appropriate control of fuel flow rate (Fig. 2, *b*, Fig. 3, *b*) ensuring complete fuel combustion. The minimum fuel flow rate change step was 0,125 %.



a)



b)

Fig. 2. The change in outlet steam temperature t (*a*) and the optimal fuel flow rate G_f (*b*) over time in the case of a prolonged decrease in fuel calorific value

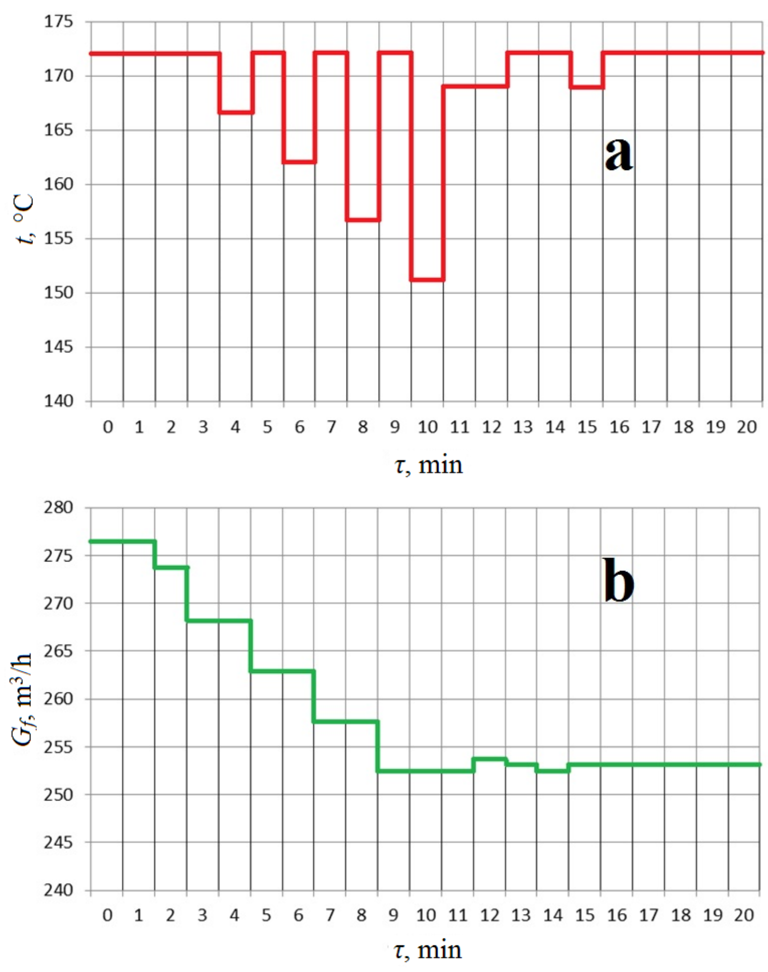


Fig. 3. The change in outlet steam temperature t (*a*) and the optimal fuel flow rate G_f (*b*) over time in the case of a prolonged increase in fuel calorific value

Conclusion

Numerical simulation has shown that with continuous random decrease (or increase) of APG specific calorific value, caused by fluctuations in its composition, the heat output of the steam boiler DE 10-14 with the complete combustion of fuel is stabilized by discrete increases (or decreases) steam temperature in a given control range of 10 %.

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