Gas using efficiency in heating boilers for individual consumers

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Abstract. Gas boilers for heating of individual consumers is used in all regions of Russia. Gas boilers are characterized by higher efficiency unlike on other types of organic fuels. Using dry natural gas reduces the polluting emissions into the atmosphere. A significant variety of gas boilers for individual heat supply meets the needs of consumers. The main requirements for individual heat supply from gas boilers are safety, economy, high efficiency, ease of use. These requirements are met by using gas with specified properties that meets standards. The required gas parameters for the consumer are provided due to the availability and functioning of the gas distribution system in the settlements. For the safety and efficiency of gas boilers, proper organization of air exchange in the room is necessary. To determine the efficiency of domestic gas boilers, the influence of the temperature of the air used in the combustion process is considered. Boilers with open the combustion chamber use internal air. Outside air is used in boilers with a closed combustion chamber. The study determines how the efficiency of a gas boiler changes at different temperatures outside air during the heating period. Losses of flue gases and chemical incomplete burning were taken into account when calculating the efficiency of gas boilers. The calculation was made taking into account the physical heat introduced by the air for burning. The study considered gas boilers with a heating capacity of 20, 30, 50, 100 kW at a nominal operating mode. The annual effect of gas fuel saving is presented for natural dry gas with a calorific value of 34 MJ/cub m.

1. Introduction

Natural dried gas for individual heating systems is widely used in Russia for different climatic conditions. The gasification program for the development of regions provides a qualitative improvement in the living conditions of the population [1]. The object of the research is gas-fired hot water boilers. Domestic gas boilers and low-power boilers for heating systems for individual consumers differ in their nominal thermal performance, efficiency and cost [2]. The cost and efficiency depend on the design of the gas boiler. Water heating systems for individual consumers for different climatic conditions are diverse in design, location and construction of a gas boiler [3]. The purpose of this study is to determine the influence of the temperature of the air supplied during the combustion of gas fuel on the efficiency of the boiler. Operating conditions are accepted for the city of Perm. As a result of the research, the following tasks were solved: a mathematical model was developed taking into account the theoretical foundations of gas combustion in a boiler for the purpose of heating; the analysis of the methodology for calculating the efficiency was carried out and the main criteria were adopted; factors that affect the efficiency of household boilers are considered; the conditions for installing gas boilers at subscribers are analysed, and heat losses with flue gases at the
nominal operating mode of boilers are determined. The economic assessment of the change in the efficiency at different temperatures of the air supplied for combustion is equivalent to the cost of gas fuel.

2. Materials and methods
The consumption of gas by residential and public buildings for the needs of heat supply is associated with the trends of reducing the length of heating networks and reducing losses during the transportation of heat energy. This is due to the desire of consumers to reduce the cost of heat supply, the emergence of a wide variety of heat-generating equipment, and the technical ability to connect subscribers to gas distribution networks. Gas-fired boilers for heating individual consumers provide high combustion efficiency with low environmental emissions. Therefore, the placement of gas boilers in the residential area and directly at the consumer provides sanitary and hygienic air standards. Calculation of sanitary and hygienic parameters of emissions depends significantly on the installed capacity of gas-using equipment. The modern regulatory framework expands the boundaries of the use of gas-fired boilers for individual and multi-apartment buildings.

The use of gas for domestic purposes and for heating is efficient and safe, firstly, due to the modern structure of the gas distribution system. The reliability of the gas distribution system, to which the subscribers’ equipment is directly connected, determines the stability and safety of the gas-using equipment operation within the specified parameters. The development of the gas distribution system of territories provides an integrated and balanced approach to heat supply, taking into account the interests of consumers, climatic conditions and economic factors [1-4].

Secondly, the composition of the gas fuel determines the amount of heat that can be produced by the operation of the heating boiler. The composition of natural combustible gas entering the gas distribution network changes during the operational period. Thus, the properties of natural combustible gas during operation differ from the passport data within the specified limits. Gas properties for gas distribution systems are regulated by the state standard (GOST 5542-2014. Combustible natural gases for industrial and municipal purposes. Technical conditions). The composition and density of natural combustible gas are not standardized. Gas properties are determined when designing gas distribution and gas-consuming networks, using an analytical method for calculating the technical and economic indicators of a gas supply system. The net calorific value of gas under standard conditions must be at least 31.8MJ/cub m, the range of values of the Wobbe number (Wo) is limited from 41.2MJ/cub m to 54.5MJ/cub m. Gas-using equipment ensures safe and reliable operation while meeting the quality requirements for natural combustible gas. In accordance with the normative data, the study adopted the value of the lowest working heat of combustion equal to 34MJ/cub m. Thirdly, reliable operation of gas-using equipment is ensured within the framework of regulatory requirements in the design of internal gas supply systems, ventilation systems and heating systems.

For district heating boiler houses, the efficiency is one of the main indicators of technical and economic efficiency in determining and justifying the tariff for heat supply. When installing heating boilers for individual consumers, the efficiency is given in the passport data at the nominal operating mode. Various types of boilers are used as heating boilers: capacitive and instantaneous gas water heaters, atmospheric boilers with injection burners, boilers with a closed combustion chamber. Depending on the design features, the efficiency of the equipment can vary significantly. The operating mode of the boilers also has an effect: water temperature, gas pressure in front of the device, temperature of flue gases [5, 6]. Domestic boilers have a limited depth of regulation. It is usually accepted for most devices not lower than 40% of the nominal thermal performance. If the boiler operation mode is regulated by the gas flow rate without changing the air flow rate, then the combustion process is accompanied by a decrease in the efficiency when the temperature deviates from the nominal conditions [7].

Distinguish between direct and reverse methods for determining the efficiency of gas-using equipment. When designing heat supply sources for centralized heat supply systems, the reverse method for calculating the efficiency is the main one. The direct method for determining the efficiency
is used for operational testing. The accuracy of the direct method depends on the test procedure, the accuracy of the instrumentation and the software for processing the results. For individual consumers, the choice of gas-using equipment for heating and hot water supply is carried out according to the required performance of the heat supply system and the technical data of the equipment.

For individual consumers, the choice of heating equipment is carried out according to aggregated indicators. The balance calculation of losses for the design of household heating boilers for individual consumers is carried out for installations with a capacity of 20, 30, 50, 100kW. The study of the efficiency was carried out on the basis of the reverse method at different temperatures of the air supplied for the combustion process. The efficiency of heating boilers depends on the design, the type of gas burner devices, the amount and temperature of the air entering the combustion, the temperature of the outgoing combustion products. The composition of natural combustible gas determines the main physical and chemical properties, affects the amount of air required for complete combustion of the gas. In heating boilers, natural draft (atmospheric burners) and forced draft by means of a fan are used. The gas-burner device provides mixing of gas and air, supply of the gas-air mixture to the combustion chamber and gas combustion. When installing equipment in a room for the operation of atmospheric burners, the supply of internal air for combustion is provided. Therefore, the temperature of the air supplied to the combustion can be taken constant, equal to the temperature of the air inside the room during the heating period. With this method of installing heating boilers, it is necessary to ensure a constant flow of air into the room in the amount necessary for gas combustion. For heated rooms, it is required to provide for the heat consumption for heating the air in the air-heat balance of the room (or in adjacent rooms).

When air is supplied by a fan for boilers with a closed combustion chamber, the air supplied to the combustion does not communicate with the internal air of the room. Therefore, in the air-heat balance of the room, the volume of air for the combustion process is not taken into account. The heat generated as a result of combustion is expended to heat the gas-air mixture to the autoignition temperature, at which the combustion reaction of the combustible components of the gas fuel takes place. Autoignition temperature depends on the homogeneity of the gas-air mixture, pressure, and the presence of catalytic active substances in the reaction zone. For methane, the autoignition temperature is taken to be 650°C. Combustion products heat the heat carrier-water. At the exit from the equipment, the temperature of the combustion products is taken equal to 170°C according to the data of the passport of a household heating boiler. Hot water boilers equipped with atmospheric burners have a lower efficiency in comparison with boilers operating on forced draft (GOST 20548-87 Hot water heating boilers with a heating capacity of up to 100kW. General specifications (with Amendment No.1)). Practical research shows that under variable conditions of a real object, the efficiency of boilers with a closed combustion chamber is 7-10% less than the value indicated in the passport under the nominal mode during bench tests [7]. Condensing boilers are not considered in the study.

The determination of the efficiency is based on the heat balance of the gas boiler:

$$\eta = 100 - (q_2 + q_3 + q_4 + q_5 + q_6)$$

where:

- $\eta$ is coefficient of efficiency (%).
- $q_2$ is heat loss with flue gases (%).
- $q_3$ is heat loss from chemical incompleteness of fuel combustion (%).
- $q_4$ is heat loss from mechanical incompleteness of fuel combustion (%).
- $q_5$ is heat loss from the equipment to the environment (%).
- $q_6$ is heat loss with the physical heat of the ash (%).

The heat loss with flue gases is determined by the equation:

$$q_2 = \frac{(l_{ext} - \alpha_{ext} l_{in,ext}) (100 - q_4)}{Q^{\prime}_w}$$

where:

- $l_{ext}$ is the external heat loss with flue gases.
- $l_{in,ext}$ is the total heat input to the equipment.
- $q_4$ is the heat loss from chemical incompleteness of fuel combustion.
- $Q^{\prime}_w$ is the heat carrier-water.
$J_{\text{ext}}$ is flue gas enthalpy (kJ/cub m).
$
\alpha_{\text{ext}}$

is excess air coefficient.

$J_{\text{ina}}^0$ is enthalpy of incoming combustion air (kJ/cub m).

$Q^w$ is low working a calorific value of fuel (kJ/cub m).

The flue gas enthalpy at the outlet of the boiler is determined by the equation:

$$J_{\text{ext}} = V_{\text{air}} \cdot (c_{\text{air}} \cdot \Theta_{yx})$$  \hspace{1cm} (3)

where:

$V_{\text{air}}$ is air volume (cub m).

c_{\text{air}}$ is specific heat of air (kJ/(cub m $\cdot ^\circ$C)).

$\Theta_{yx}$ is flue gas temperature ($^\circ$C).

The enthalpy of incoming combustion air:

$$J_{\text{ina}}^0 = c_{\text{air}} \cdot t_{\text{in air}} \cdot V_{\text{air}}^0$$ \hspace{1cm} (4)

where:

$t_{\text{in air}}$ is air temperature for combustion ($^\circ$C).

$V_{\text{air}}^0$ is volume of the theoretically required amount of air (cub m of air / cub m of gas).

The heat loss from chemical incompleteness of fuel combustion is due to the velocity of the reaction, and the temperature. When burning gas at a nominal operating mode, the design of heating boilers provides a chemical incompleteness of combustion lower than 0.5% according to regulatory requirements. Heat losses to the environment for stationary heating boilers are taken at 3.5%. The efficiency of using gas in comparison with other types of fossil fuels is explained by the absence of such losses as heat loss from mechanical incompleteness of combustion and loss with the physical heat of the ash.

3. Results and discussion

Technical and environmental indicators of gas boilers for domestic and heating needs, reflected in the technical data sheet, characterize the nominal operating mode. Gas consumption, efficiency, temperature and amount of combustion products under nominal conditions may differ within acceptable limits depending on the operating conditions of the consumer. When deviating from the nominal modes, the following negative factors take place. An increase in harmful components is observed in combustion products, which appear as a result of incomplete combustion of gaseous fuel.

The service life of gas-using devices decreases, efficiency decreases [8–10].

In natural draft boilers equipped with injection burners, a system is provided for the removal of combustion products from the device into a separate chimney. The requirements for the smoke exhaust system are described in the regulatory literature (SP 42-101-2003. General provisions for the design and construction of gas distribution systems from metal and polyethylene pipes). The economic costs of constructing a combustion product removal system for atmospheric boilers depend on its design. The height of the vertical chimney must exceed the level of the roof; the outer part of the chimney requires insulation. Therefore, the cost of the chimney reaches or exceeds the cost of the boiler. Technically and environmentally friendly operation of natural draft boilers is ensured by the correct organization of the combustion products removal system and the general ventilation system in accordance with the established standards.

When installing a pressurized gas boiler, it is possible to use a coaxial chimney (SP 282.1325800.2016. Apartment heating systems based on individual gas heat generators. Design rules and devices). Thanks to this technical solution, the cost of installing a flue gas removal system is reduced. But at the same time, both from the windward and windward sides of the building, the products of incomplete combustion of gas can penetrate into the area of open window openings. Therefore, for individual consumers (private houses) with pressurized boilers, this chimney is recommended, despite the fact that the norms allow not to arrange a vertical channel for the removal
of combustion products, taken out to the level of the roof. The flue gas removal system placed above the roof ensures compliance with air quality standards in all operating modes. During operation, this option should take into account the energy consumption of the fan and the need to prevent the formation of condensate and freezing of the combustion products removal system.

Heat losses with exhaust products of combustion, coefficient of efficiency depending on the temperature of the supply air for gas with the lowest working heat of combustion, equal to 34 MJ/cub m, are shown in table 1.

**Table 1.** Heat losses with exhaust combustion products, efficiency of the heating boiler based on material balance.

| The air temperature for combustion, °C | The enthalpy of incoming combustion air, kJ/cub m | The heat loss with flue gases, % | The coefficient of efficiency, % |
|---------------------------------------|-----------------------------------------------|--------------------------------|---------------------------------|
| 20                                    | 216.4                                         | 3.9                            | 92.1                            |
| 15                                    | 162.3                                         | 4.0                            | 92.0                            |
| 10                                    | 108.2                                         | 4.2                            | 91.8                            |
| 5                                     | 54.1                                          | 4.4                            | 91.6                            |
| 0                                     | 0.0                                           | 4.5                            | 91.5                            |
| -5                                    | -54.1                                         | 4.7                            | 91.3                            |
| -10                                   | -108.2                                        | 4.8                            | 91.2                            |
| -15                                   | -162.3                                        | 5.0                            | 91.0                            |
| -20                                   | -216.4                                        | 5.1                            | 90.9                            |
| -35                                   | -378.8                                        | 5.6                            | 90.4                            |

At a combustion air temperature of plus 20°C, the coefficient of efficiency increases by 1.2% when compared with air intake with a temperature of minus 20°C. An additional effect on the efficiency of hot water boilers is provided by the excess air ratio (Fig. 1).

**Figure 1.** Influence of supply air temperature and excess air ratio on boiler efficiency.

The result of the study shows that an increase in the excess air ratio from 1.2 to 2 at a combustion air temperature from plus 20°C to minus 20°C leads to a decrease in the efficiency by 6.2%.

For domestic gas heating boilers with combustion air at temperatures of minus 5.4°C and 20°C, the annual gas consumption is presented in table 2. In an economic assessment of reducing the cost of gas fuel, the cost of gas is taken as 6 rubles/cub m. The duration of the heating period is assumed to be 250 days.
The calculation of the gas flow rate was carried out at a combustion air excess ratio of 1.2. The temperature of the air entering the combustion when air is supplied from the outside of the room changes during the heating period. When regulating and deviating from the nominal operating modes, the efficiency of the equipment operation decreases.

Table 2. Gas consumption for heating boilers with a capacity of up to 100kW.

| Boiler productivity, kW | 20    | 30    | 50    | 100   |
|-------------------------|-------|-------|-------|-------|
| Annual gas consumption at air temperature 20°C (cub m/year) | 46892 | 70337 | 117229 | 234458 |
| Annual gas consumption at air temperature minus 5.4°C, (cub m/year) | 47300 | 70950 | 118250 | 236501 |
| Relative difference in gas consumption when the air temperature decreases from 20°C to minus 5.4°C (cub m/year) | 409   | 613   | 1021  | 2043  |
| Reduction of costs for the heating period (rubles/year) | 2451  | 3677  | 6128  | 12257 |

4. Summary

When air for combustion with a temperature of minus 35°C is supplied, the efficiency of heating boilers decreases by 1.7% relative to the temperature of air supplied for combustion directly from the room with a temperature of 20 °C. The efficiency of heating boilers with a capacity of up to 100kW decreases by 1%, depending on the combustion air temperature, at an average temperature of the heating period of minus 5.4°C. The decrease in efficiency also occurs with a deviation from the nominal operating modes, for example, with an increase in the excess air ratio, a change in the composition of gas fuel.

When installed a gas boiler with an open combustion chamber, the organization of air exchange promotes heat recovery. The room air exchange for appliances with an open combustion chamber is calculated based on the air heat balance of the room. The safe operation of heating boilers with an open combustion chamber is ensured by meeting the requirements of volumetric planning solutions, the rules of general exchange ventilation, and regulatory requirements for the combustion products removal system. For the safe use of gas for heating domestic consumers, it is recommended to develop standard solutions depending on the power of the boilers.

The design of the closed chamber boilers is characterized by high safety and high efficiency in regulation. In the economic calculations of the efficiency and payback of heating boilers with a closed combustion chamber, it is recommended to take into account a possible decrease in efficiency by 1-2%, which is due to the temperature of the air entering the combustion and the efficiency change when deviating from the nominal operating modes.

5. References

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