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ENERGY EFFICIENCY ANALYSIS OF WATER HEATING SYSTEM GAS CONDENSING BOILERS

Г. Лужанська, Г. Дьяченко, Ю. Бессатьян, О. Тарасюк, І. Сергеєв. **Аналіз енерогоефективності роботи газових конденсаційних котлів системи водяного опалення.** Питання застосування енергозберігаючих технологій стають дедалі актуальнішими. Це пов'язано із збільшенням споживання енергоносіїв, запаси яких обмежені. Значну роль споживанні тепла в теплоенергетичної області займає система теплопостачання. Основним споживачем теплової енергії із системи теплопостачання є система водяного опалення. Будь-яка система опалення складається з трьох основних елементів: джерела тепла, трубопроводів і нагрівальних приладів. У приватному житловому будинку, найбільш часто використовується в якості джерела тепла газовий опалювальний котел, де внаслідок спалювання палива здійснюється нагрівання теплоносія. Згідно з нормами, прийнятими для визначення ККД котлів, вважається, що максимально можлива теплопродуктивність котла дорівнює нижчій теплоті згоряння палива. Причиною такого положення була відсутність технічної можливості використання прихованої теплоти конденсату без шкоди для конструкції котла. У 80-ті роки минулого століття почала розвиватися кондесаційна котлова техніка. Конденсаційні котли здатні досягати додаткової ефективності, використовуючи енергію конденсації атмосферної вологи в димових газах. Таким чином, поява конденсаційної техніки вплинула на зміну норми розрахунку ККД і склала більше 100%. Конструкція конденсаційних котлів із застосуванням додаткового теплообмінника та відведенням конденсату дозволяє отримати додаткову теплову енергію, що вивільняється при фазовому переході. На відміну від звичайних котлів, в конденсаційних агрегатах застосовується більшість прихованої теплоти пароутворення. Для ефективної роботи використовується не нижча, а найвища теплота згоряння, яка для газу вище на 10…11 %. Ефективність використання палива конденсаційними котлами буде вищою під час роботи в конденсаційному режимі. Цей режим можливий при нагріванні теплоносія до температури не вище 57 °C. Якщо температура теплоносія, що нагрівається, буде вищою, то водяна пара не буде конденсуватися з продуктів згоряння і ефективність роботи конденсаційного котла знизиться. Таким чином, максимальна ефективність роботи конденсаційного котла досягається при режимі низькотемпературного опалення. При використанні даного котла в режимі 80…60 °C (нормальний режим водяного опалення) період експлуатації становить лише трохи більше 30% опалювального сезону – ККД значно знижується, для підвищення ефективності роботи застосовують бойлери непрямого нагріву або пластинчасті теплообмінники та баки-акумулятори. Однак, при такому режимі експлуатації площа поверхні опалювальних приладів збільшується у 2 рази. Економія газового палива під час роботи конденсатного котла проти традиційного на 1 кВт теплової енергії становить 0,023 м^3/год, що становить на 19% менше споживання газу.
Ключові слова: газовий конденсаційний котел, теплота згоряння палива, система водяного опалення, підвищення ККД, енергоефективність, енергозбереження

G. Luzhanska, G. Diachenko, Y. Bessatyan, O. Tarasiuk, I. Sergeiev. **Energy efficiency analysis of water heating system gas condensing boilers.** Increasingly relevant is the issue of using energy-saving technologies. This is due to the increase in the consumption of energy carriers, which reserves are limited. The heat supply system plays a significant role in heat consumption in the heat energy sector. The main consumer of thermal energy from the heat supply system is the water heating system. Any heating system consists of three main elements: a heat source, pipelines and heating devices. In a private residential building, a gas heating boiler is most often used as a heat source, where the coolant heating results from the fuel combustion. According to the standards adopted for determining the efficiency of boilers, admitted is that the boiler's maximum possible heat output is equal to the lower heat of fuel combustion. The reason for this situation was the lack of technical possibility to use the latent heat of condensate without harm to the boiler design. In the 1980s, condensing boiler technology began to develop. Condensing boilers are able to achieve additional efficiency by using the energy of atmospheric moisture condensation in flue gases. Thus, the emergence of condensing technology influenced the change in the efficiency calculation rate and amounted to more than 100%. The design of condensing boilers with the use of an additional heat exchanger and condensate removal allows to obtain additional thermal energy released during the phase transition. Unlike conventional boilers, condensing units use most of the latent heat of vaporization. For efficient operation, not the lowest, but the highest heat of combustion is used, which is 10…11% higher for gas. The fuel efficiency in condensing boilers will be higher when operating in condensing mode. This mode is possible when the coolant is heated to a temperature never exceeding 57 °C. If the heated coolant temperature is higher, the water vapor will not condense from the combustion products and the condensing boiler efficiency will decrease. Thus, the condensing boiler maximum efficiency is achieved in the low-temperature heating mode. When this boiler operated in the 80…60 °C mode (normal water heating mode), the operation period is just slightly more than 30% of this one in the heating season: the efficiency is significantly reduced, to increase the efficiency of operation, indirect heating boilers or plastic heat exchangers and accumulator tanks are used. However, with this operating mode, the heating devices surface area increases by 2 times. The gas fuel economy during the operation of a condensing boiler compared to a traditional one per 1 kW of thermal energy is 0.023 m^3/h, that is it allows 19% less gas consumption.
Keywords: gas condensing boiler, fuel combustion heat, water heating system, efficiency increase, energy efficiency, energy saving

Introduction

The energy conservation problem is becoming increasingly relevant nowadays. With the constant growth of the population and the development of technologies, energy consumption has increased sig-

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nificantly, but natural resources remain limited. Therefore, effective energy conservation is becoming an urgent necessity [1, 2, 3]. The main driving factor of modern energy industry throughout the world is fuel economy, maximum efficiency of energy resources operation and use [4, 5]. A significant role in heat consumption is played by the heat supply system. Energy conservation in heat supply systems is the process of optimal use of energy resources in order to minimize losses and reduce energy costs. The most significant consumer of thermal energy in the heat supply system is the water heating system.

Whichever heating system be, it consists of three main elements: a heat source, pipelines and heating devices. In private residential buildings, most often a gas heating boiler is used as a heat source, where the coolant is heated as a result of fuel combustion.

Analysis of reference sources and problem statement

A conventional gas boiler includes the following elements: a burner, a heat exchanger, a heat-insulated casing, a hydraulic unit, and several safety and control devices. Many modern boilers are equipped with built-in pumps for forced water circulation. The heat exchanger represents a three-dimensional structure with tubes, between which plates are located to increase the usable area and accelerate the liquid heating. Water moves inside the tubes, heated up from the walls. The heat exchanger is located above the burner, and when the boiler is ignited, it is heated by its flame, transferring thermal energy to the coolant circulating through it. Inside the metal casing there is a coil through which water for heating circulates. The heat exchanger can be made of steel, cast iron, copper, because the reliability and durability of the boiler depends on the material used. Apart of the heat exchanger, another important element of gas boilers is the burner, designed to burn natural gas and continuously distributing the energy released to the heat exchange circuit. The hot flue gases removal is provided by the chimney.

In a traditional gas boiler, the combustion products, which are a mixture of dry flue gases (CO_2; N_2, excess air) and water vapor (from the combustion of hydrogen, from fuel moisture and air supplied for combustion), coming from the combustion zone, pass through heat exchange surfaces in the firebox and the boiler's convective part, where they give off the main part of the coolant's thermal energy, ensuring its heating. After passing through the gas path of the boiler, the flue gases are emitted into the atmosphere through the chimney. At the same time, some heat is lost with the exhaust gases, since their temperature is higher than the environmental one; they contain water vapor, formed during the combustion of hydrogen and the evaporation of moisture contained in the fuel. The boiler water temperature is above the dew point, this is provided so that condensation of water vapor from the exhaust gases in contact with the heating surfaces of the boiler does not occur, and as a result, protection against corrosion is provided. The boiler efficiency directly depends on the lower heat of combustion of the gas, i.e. without taking into account the energy of steam condensation, and it is on this value that engineering calculations are carried out.

According to the standards adopted for determining the boilers efficiency, the maximum possible heat output of a boiler is considered equal to the lower heat of the fuel combustion. The efficiency of a boiler is 100%. Such situation reason was the lack of technical possibility for using the latent heat of condensate without harm to the boiler design.

In the 1980s condensing boiler technology began to develop. Condensing boilers are able to achieve additional efficiency by using the energy of atmospheric moisture condensation in exhaust gases [6, 7, 8]. Thus, the emergence of condensing technology influenced the change in the efficiency calculation rate, and amounted to more than 100%.

Present time, in a number of European countries (Great Britain, the Netherlands, Belgium, Switzerland, Portugal, etc.) prohibited is the use of any gas boilers except condensing ones, which are able to obtain the maximum amount of heat from combustion products, that allows reducing fuel consumption and significantly increases the boiler efficiency.

In all cases of condensing heat-generating equipment use, the technical solution energy efficiency is ensured due to the fuel component in operating costs, despite the increase in capital investments in installations. Support by many countries at the state level of energy-saving technologies and concern for environmental protection contribute to the active introduction of innovative equipment that meets all standards [9, 10]. The priority task therefore is to increase the efficiency and improve the environmental performance of heat supply systems. Due to that fact, in Europe, gas condensing boilers, specific with high demanded characteristics, hold leading positions among heating systems equipment [11].

The design of condensing boilers which includes an additional heat exchanger and condensate removal allows obtaining additional thermal energy, which is released during the phase transition.

The main difference between a condensing boiler and a conventional one is the combustion technology.

Unlike conventional boilers, condensing units use most of the latent heat of vaporization. For efficient operation, not the lowest, but the highest heat of combustion is used, which for gas is 10…11% higher. This amount of additional heat can be obtained if the combustion products temperature is reduced to the dew point, using the exhaust gases heat [12, 13].

In a condensing boiler, gas is supplied to the burner from below, during combustion, heat is distributed through the heat exchanger tubes, which design specific feature is that the input temperature is near the cold wall and the output temperature is near the hot wall. As a result of fuel combustion, the water vapor formed passes through the heat exchanger. In this case, heat is removed in the first part of the heat exchanger, and the not completely cooled vapor passes through the heat exchanger again, including through the tubes, going to the exhaust system. In compliance with the laws of physics, the continuous passage of exhaust gases through the tubes when the supply temperature parameter is 50°C and the return temperature is 25…30 °C, leads to the formation of condensate, further removed from the boiler through a special condensate drain. As a result of this boiler design, vapor from the flue gases condenses on the heat exchanger tube, transferring additional heat from the moisture contained in the gases to the tube. Due to the fact that moisture in the form of condensate returns to the boiler and gives off its heat, there is an increase in efficiency. Flue gases are also removed through the tube. Moreover, if in a conventional boiler the exhaust gas temperature is 150…170°C, then in a condensing boiler it is one hundred degrees lower (Fig. 1) [14].

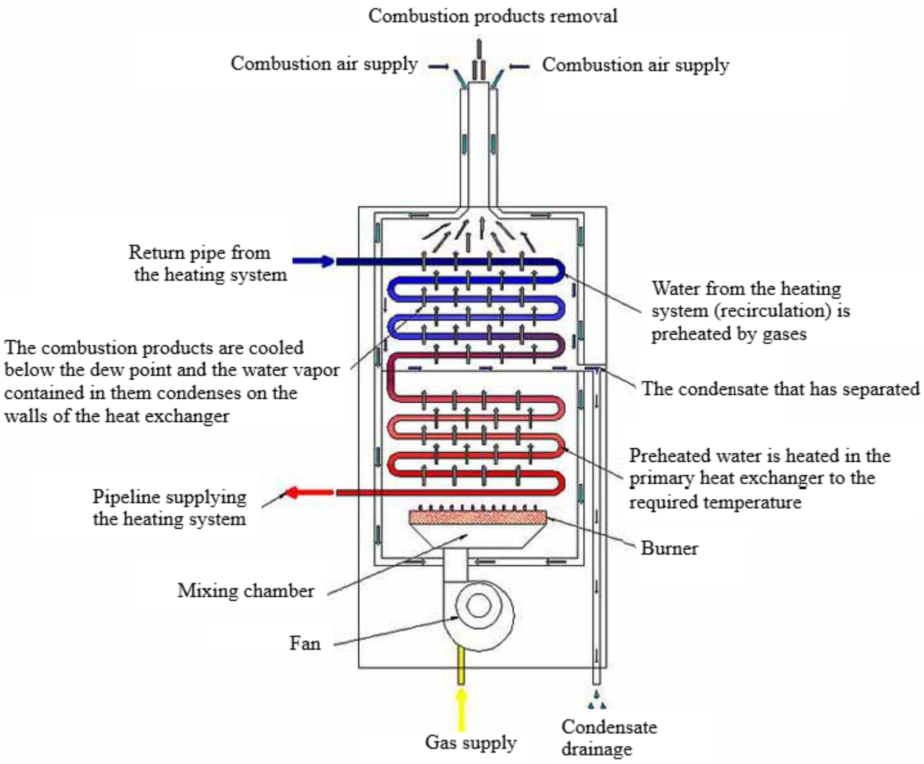

Fig. 1. The principle of condensing boiler's operation

Research objective

Research on the gas condensing boilers energy efficiency in order to identify the optimal long-term period for ensuring maximum thermal energy economy in water heating systems at different coolant modes during the heating season, as well as the influence of the condensing and non-condensing boiler operation modes on the selection of heating devices.

To achieve the goal set, it is necessary to solve the following tasks:

– analyze the influence of the coolant temperature in the heating system return line on the condensing boiler efficiency;

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– determine the gas fuel use efficiency assessment;

– investigate the energy-efficient period of operation of the condensing boiler when using different coolant temperature modes of the water heating system during the heating season.

Materials and research methods

The use of water vapor condensation heat from combustion products is especially beneficial for fuels with a high hydrogen content [15] on the fuel mass and fuel moisture.

The possible amount of water vapor condensation heat Q_{H_2O} available for use from the volume of combustion products can be determined by the formula:

$$Q_{H_2O} = 24.62(9.84H^{w} + W^{w}), \quad (1)$$

where: H^{w} – hydrogen content in fuel, W^{w} – water vapor content in fuel.

The total heat obtained by condensation technology is equal to the sum of the lower combustion heat of combustion Q_L^w and the latent condensation heat Q_{H_2O} and is called the highest heat of combustion Q_H^w:

$$Q_H^w = Q_L^w + Q_{H_2O}. \quad (2)$$

At that, the amount of condensate formed in boilers burning natural gas will be approximately 0.16 kg/kWh. The amount of condensed steam will be determined by the circulating water temperature, and the increase in efficiency in turn will be determined by the amount of condensate formed. Thus, the efficiency of condensing boilers at a certain temperature regime is more than 100% and can even reach up to 111% (Fig. 2) [16].

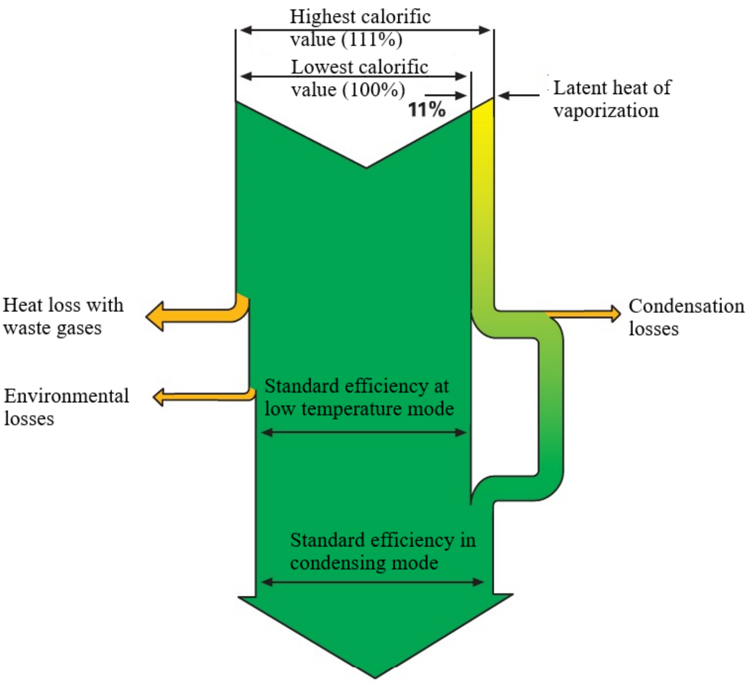

Fig. 2. Increasing the efficiency of a condensing boiler by using waste gas heat

The actual gas temperatures are above the dew point temperature for the combustion products composition, i.e. the combustion products are not saturated, although there is active condensation of water vapor in the heating surfaces, at their temperature below the flue gases dew point [17]. This can be explained by the incompleteness of the process of moisture condensation from the combustion products and the mixing behind the boiler condensation surfaces (at the outlet) of some of the dried combustion products deeply cooled to saturation parameters and some of the transit flue gases.

So, the lower the condensing boiler temperature is, the higher is its efficiency. The steam that turns into moisture releases the energy transferred further to the water inside the heat exchanger, and thus generating additional efficiency.

One of the main parameters, key to the effective operation of condensing boilers and their efficiency increasing efficiency, are the modes of the heating system coolant use, namely the temperature in the return line. To ensure condensation, the water temperature at the boiler inlet should be 10…15 °C below the dew point temperature and for natural gas it is 57 °C.

Let's consider the efficiency of a gas condensing boiler when heating system operates in different temperature modes: low-temperature (fan coils, underfloor heating, radiators with an increased heating surface) and normal mode 80…60 °C.

Analyzing the graphical dependencies in Figure 3, it is clearly seen that the maximum efficiency of the condensing boiler is achieved in the low-temperature heating mode.

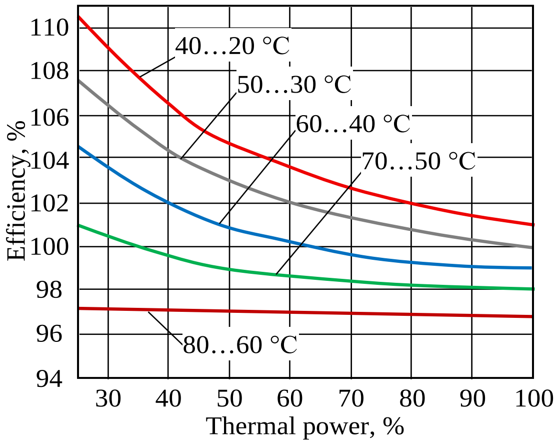

Fig. 3. Efficiency of the condensing boiler at different temperature regimes of the heating system

When using the boiler in the 80…60 °C mode, the efficiency makes on average 97%. To increase the operation efficiency, indirect heating boilers or plastic heat exchangers and accumulator tanks are used.

The boilers effective operation depends on the thermal power. A decrease in power relative to the nominal value leads to an increase in the boiler's efficiency, and the lower the coolant temperature, the more pronounced is this effect. The explanation refers to the fact that when the boiler power decreases, the volume of combustion products decreases, which, with a constant heat exchange area, allows for greater cooling of the flue gases.

In real conditions, it is not possible to ensure the maximum possible efficiency throughout the entire boiler operating season, since traditional water heating systems operate on a quality control schedule when 80…60°C, although this temperature regime is achieved only at significantly low outdoor temperatures, lasting several days or a little more, while to ensure the internal microclimate, heating devices must have a large heating area.

The efficiency of fuel use in condensing boilers will be higher when operating in condensing mode. This mode is possible when the coolant is heated to a temperature never exceeding 57 °C. If the temperature of the heating coolant is higher, then water vapor will not condense from the combustion products and the efficiency of the condensing boiler will decrease.

The condensing boiler efficiency can be assessed by direct or reverse heat balance. In the first case, the efficiency of the heat generating unit is determined by direct calculation of the value of the received useful thermal power in the form of:

$$\eta = \frac{Q_{\text{term}}}{BQ_{\text{c}}^{\text{w}}}, \tag{3}$$

where: Q_{term} – thermal power; B – fuel consumption; Q_{c}^{w} – heat of combustion of the fuel which is equal to the higher heat of combustion.

Let's estimate the gas fuel economy of a condensing boiler compared to a conventional one for 1 kW of thermal energy using the formula:

$$\Delta B = 3.6\frac{Q_{\text{term}}}{Q_{\text{L}}^{\text{w}}\eta_{\text{t}}\eta_{\text{c}}}(\eta_{\text{c}} - \eta_{\text{t}}), \tag{4}$$

where: ΔB – gas fuel economy; $\eta_{\text{c}} = 1.11$ – efficiency of a condensing gas boiler; $\eta_{\text{t}} = 0.9$ – efficiency of a conventional gas boiler; $Q_{\text{L}}^{\text{w}} = 33.5$ MJ/m^3 – lower calorific value of natural gas.

Gas fuel economy when using a condensing boiler per 1 kW of thermal energy at a maximum efficiency of 111% will be:

$$\Delta B = 3.6 \cdot \frac{1 \cdot (1.11 - 0.9)}{33.5 \cdot 0.9 \cdot 1.11} = 0.023 \text{ m}^3\text{/hour.}$$

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Here, the fuel consumption of a conventional boiler will be 0.119 m^3/h, and for a condensing boiler – 0.096 m^3/h. As a result, fuel economy of 0.023 m^3/h were obtained, which is 19% less that the gas consumption by a conventional boiler.

Research results

Let us consider the winter period external temperatures' time intervals when the maximum efficiency of the condensing boiler is achieved. In residential buildings, widely used is the qualitative control, the regulation type when the temperature of the coolant in the heating system depends on the temperature of the outside air. Therefore, the lower the outside air temperature is, the higher the temperature of the coolant will be. When developing a heating system, it is namely the coolant parameters that determine the size of the heating devices, i.e. the heat exchange area.

Now we shall study the operation of a condensing boiler for a building with a rated thermal capacity of 100 kW, located in the central part of the country. The standard coolant in the heating system is water with parameters $T_1 = 80$ °C, $T_2 = 60$ °C. The graphical dependence of the coolant parameters on the outside air temperature is shown in Figure 4.

Analyzing the graph of changes in coolant temperatures with respect to the outside air temperature, and knowing the effective temperature for the boiler to operate in condensation mode, we can conclude that the most effective temperature regime is achieved at an outside air temperature of +8 °C to –5 °C. When the ambient temperature drops below –5 °C it is necessary to exit the condensation mode of the boiler operation to maintain the pre-set temperature regime in the premises. Another solution, as already said, is to have a more developed heating surface of heating devices for operation in condensation mode.

We will determine the duration of standing outside air temperatures using data from regulatory documents for designing heating systems to determine the boiler operating time in energy-saving mode (Fig. 5).

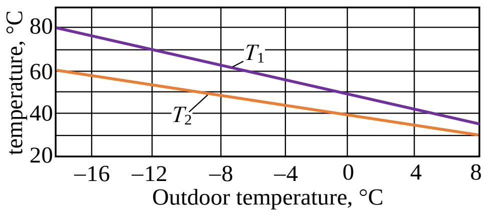

Fig. 4. Dependence of the heating system coolant temperature on the ambient temperature

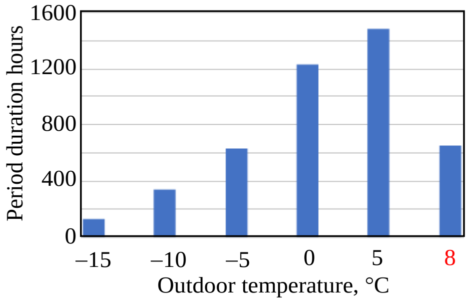

Fig. 5. Number of hours of the corresponding part of the heating period depending on the duration of outdoor temperatures according to regulatory data

However, the actual duration of outdoor temperatures differs significantly from the regulatory values, so using meteorological data [18] we calculate the actual duration of outdoor temperatures.

Therefore, according to Figure 6, the actual operating time of the boiler in condensing mode is significantly higher than the standard values and its use is more efficient practically throughout the entire heating period.

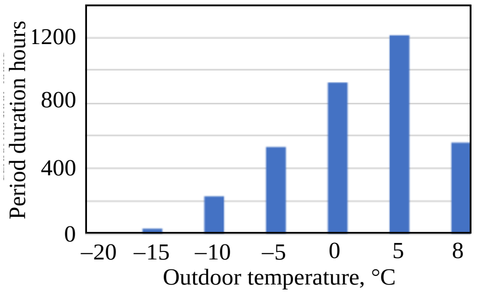

Fig. 6. Number of hours of the corresponding part of the heating period depending on the duration of outdoor air temperatures according to actual data

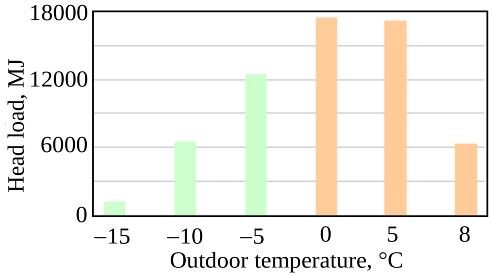

Fig. 7. Change in heat load depending on the temperature intervals of the external environment

Change in heat load depending on the number of hours with the corresponding outdoor air temperature during the operation of the condensing boiler, while in condensing mode the boiler operates up to an outdoor temperature of –5 °C:

$$Q = Q_{\text{c.h}} \cdot \frac{t_{\text{in}} - t_{\text{o}}}{t_{\text{in}} - t_{\text{so}}} \cdot n \cdot 3.6\,, \tag{5}$$

where: Q – change in heat load; $Q_{\text{c.h}}$ – calculated heat load; t_{in} – indoor temperature; t_{o} – outdoor temperature in corresponding temperature period; t_{so} – standard calculated outdoor air temperature for the heating system; n – duration of the corresponding temperature period.

According to the graph in Figure 7, it is clearly visible that the total amount of heat produced by the boiler will be 611981MJ, while in non-condensing mode it works only 33%.

During the conducted research it was established that to ensure the same thermal power of 1 kW of heat for the calculated external air temperature of –18 °C, for the condensation temperature mode, a type 22 radiator of size 700×500 h is required, at the same time, to cover heat losses in the mode of low external air temperatures, for the condensation mode it is necessary to use a type 22 radiator of size 1400×500 h, respectively, i.e. a 2 times larger heating surface of heating devices is required to create and maintain the normalized parameters of the premises' internal air.

Conclusions

During the conducted research of the gas condensing boiler and comparison of its operation with a conventional boiler, it was obtained the following results:

– when burning 1 m^3 of natural gas, 2 m^3 of water vapor (or ~1.6 kg of water) is formed, which, upon complete condensation, provides heat input of up to 11% of additional thermal energy, thereby increasing the efficiency of the condensing boiler;

– the condensing boiler efficiency is affected by the temperature of the coolant in the return line, the lower it is, the higher the efficiency is;

– the economy of gas fuel during the condensing boiler operation compared to the conventional one per 1 kW of thermal energy is 0.023 m^3/year, which renders 19% less gas consumption;

– when operating a condensing boiler for water heating systems in low-temperature mode (fan coils, underfloor heating), the efficiency of fuel use will be significantly higher, compared to the cipher obtained when this boiler is used for a temperature mode of 80…60 °C (traditional radiator heating), at which the combustion products condensation will not occur and, accordingly, the efficiency decreases;

– the operation of the boiler in non-condensing mode will be 33% of the entire heating period;

– the area of heating devices without condensation mode will increase by 2 times.

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