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Intensification of heat exchange in gas flues of solid fuel hot water boilers of low power

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Abstract. The introduction of a new flue design ensures a more complete use of thermal energy of fuel and reduces the negative impact on the environment. The main purpose of the study was to optimise the design of the behind-the-screen flue using plate guides for flue gases, which will reduce fuel consumption and increase the efficiency of the hot-water boiler. The results presented in the article were obtained using the following methods: generalisation of the results of previous studies, comparison, comprehensive analysis, elementary theoretical analysis and synthesis, experiment, logical and structural analysis, scientific and analytical analysis, etc. Modern measuring equipment, including a gas analyser, thermal imager, and pyrometers, was used in the experimental studies. The geometry of the behind-the-screen flue duct for Ukrainian-made hot-water boilers was studied and optimised in a wide range of capacities and gas flow rates. The obtained results made it possible to expand the possibilities of using boilers of this type and increasing their energy efficiency. A method of intensification of heat transfer processes and a method of improving the efficiency of the boiler by using a new design of an all-welded tube panel of the convective flue duct with cross-flow pipes with guide plates were proposed. The research extended the scientific knowledge of heat transfer processes in boilers with a shielded flue. The optimisation of the channel geometry and the use of refined theoretical models provide for a reduction in fuel consumption, reduction of harmful emissions and extension of equipment service life. The results of the study, obtained using computational methods and experimental measurements, were confirmed by comparison with the data of other authors and the results of field tests. A distinctive feature of the research is the high degree of agreement between theoretical calculations and experimental data and data given in the technical documentation for boilers. This indicates the reliability of the results obtained and the correctness of the research methods used. The article will be useful for designers, engineers, heat and power engineers and anyone interested in boiler technology

Keywords: energy efficiency; furnace; modernisation; screens; pipe bundles; heat transfer

Introduction

The growing need for energy-efficient heating systems and the need to use alternative energy sources are driving increased interest in solid fuel boilers. Heating water boilers with a manual firebox for burning solid

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fuels are actively used for heating systems in small commercial buildings, private houses, hangars and enterprises. When burning solid fuels, to increase the efficiency of hot water boilers with a manual firebox, it is necessary to increase the intensity of heat transfer by introducing new design changes. This is especially important when using low-quality fuel, which is often used in such boilers. Intensification of heat transfer is a critical task for increasing the overall efficiency of heating water boilers with a manual furnace for burning solid fuels.

In the research of A. Tunggul Ismail *et al*. (2022) developed an indirect combustion system for solid fuels. It was expected that the use of an indirect burner will increase the reliability of solid biomass combustion. In addition, an indirect burner, in which the working fluid reaches a relatively high temperature before entering the boiler, can be used to reduce coal consumption in solid fuel boilers. The article by M. Kharchenko & Yu. Klushyn (2023) described a method for creating a solid fuel boiler efficiency control system consisting of software and hardware that monitors and controls the processes of fuel combustion and water circulation in the boiler. The development environment, its functions and capabilities are considered, and a detailed description of the system's operation for the user is provided. The main goal of this system is to increase the efficiency of space heating and optimise fuel consumption to achieve the desired temperature with minimal error. Thanks to clearly defined protocols of interaction between the system components, its uninterrupted operation and absence of failures are ensured.

The article by P. Samruaisin *et al*. (2019) investigated the intensification of convective heat transfer and the increase in heat exchanger performance by combining a twisted pipe and a twisted strip. Both elements, twisted tubes and twisted tapes, create a vortex flow that improves thermal performance. The effect of a combination of trapezoidal twisted tubes and twisted tapes with different twist pitches (y/w = 2.0, 3.0, 4.0, and 5.0) on heat transfer, hydraulic resistance, and thermal performance was studied experimentally. The working fluid used was water in turbulent conditions (4,500 < *Re* < 16,000). To visualise the features of fluid flow and heat transfer, the velocity, temperature and local Nusselt numbers were also modelled. The results obtained for the combined device were compared with the results for a smooth pipe and a single twisted pipe.

For solid fuel boilers, there has been considerable progress in the study of the boundary layer, but the exact quantitative patterns of fluid flow in this region, especially in the viscous sublayer, remain poorly understood. It was known from the work of W. Wang & E.J. Bisset (2018) that the viscous sublayer with its linear velocity profile is the main obstacle to heat transfer, creating significant thermal resistance. There are two main approaches to intensifying heat transfer in boilers: active, which involves the use of additional devices (intensifiers), and passive, based on optimising the geometry of heat transfer surfaces. Active methods, such as the installation of flow turbulators or secondary emitters, can significantly increase the heat transfer coefficient. However, they can lead to an increase in hydraulic resistance and, as a result, higher energy consumption. Passive methods, such as perforated surfaces or fins, can achieve a significant increase in heat transfer area without significantly increasing the hydraulic resistance.

Despite the significant progress in the study of heat transfer processes in solid fuel boilers, the available works pay insufficient attention to the influence of the variable geometry of tubular elements on the boundary layer structure, especially in the viscous sublayer, where the main thermal resistances are formed. The limited quantitative experimental data on the local temperature and flow rate distribution when using passive intensification methods, such as perforated or profiled surfaces, makes it difficult to optimise the design of heat exchange surfaces. In addition, the literature lacks a comprehensive approach to assessing the effectiveness of such changes, taking into account both thermal and hydrodynamic characteristics. Taking into account these gaps, the aim of this study was to experimentally and numerically substantiate design solutions for intensifying heat transfer in a heating hot-water boiler with a manual furnace by using tubular elements of variable geometry, as well as to analyse their impact on the thermal and hydraulic characteristics of the boiler.

Materials and Methods

The study was based on a comprehensive methodology for researching, analysing and generalising thermophysical processes based on the study of convective unsteady heat flows in heat exchange tubes of solid fuel boilers. The study is devoted to the analysis of the results of the influence of the geometric parameters of the backscreen flue channel on the intensification of heat exchange and hydraulic resistance under different operating modes of a solid fuel boiler. For the study, the methods of heat exchange intensification with convective heating surfaces and the analysis of the current state of low heat output water boilers fired by coal were chosen. The design of solid fuel hot water boilers of low thermal capacity up to 3.15 MW produced by Ukrainian manufacturers was studied. The paper considered a new technology of solid fuel combustion that solves the problem of uneven operation of small coal-fired boilers during the day and in the off-season, which requires mobile control of thermal power. The study of the hydraulic resistance coefficient for the cross-flow channel of the behind-the-screen flue formed by all-welded membrane tube panels with cross tubes was carried out initially under isothermal conditions. The study of heat transfer and the determination of the heat transfer coefficient in the non-isothermal section allowed to determine the drag coefficient under flow cooling conditions.

The full-scale model of the screen duct was subjected to a comparative analysis based on the thermal and hydraulic efficiency indicators calculated using the appropriate formula:

$$P_i = (\frac{j^3}{f})^{0,5}. \quad (1)$$

The value of the response function $P_e = Pi/P_{(eo)}$ is determined using experimental data on heat transfer in the *i-th* channel and the known relationship for the heat transfer coefficient. The heat transfer efficiency, which is determined by the ratio of the Nusselt number for the process under study (Nu_i) to the Nusselt number for the reference process (Nu_o), can be considered as the ratio of the efficiency (Nu_i/Nu_o) to the cost ($\xi_i/\xi_{(o)}$). In this case, an increase in the numerator (useful effect) and a decrease in the denominator (costs) leads to a significant increase in efficiency. This approach which made it possible to assess the potential for increasing heat transfer efficiency even with a slight increase in heat transfer and costs.

The proposed modernisation of the design of small hot-water shell boilers is optimised on the basis of calculations carried out on the basis of generalised, experimentally refined theoretical dependences of aerodynamic, hydrodynamic and thermal characteristics, which are confirmed by field experiments with cross-flow of the screen flue by flue gases. The type of boiler for which the modernisation is proposed is shown in Figure 1. The boilers of this design manufactured by PJSC Khimmash are solid fuel boilers of the KVR-CTC series. Also, boilers of this design were produced by boiler equipment plants in Ukraine, namely industrial hot water boilers "KV".

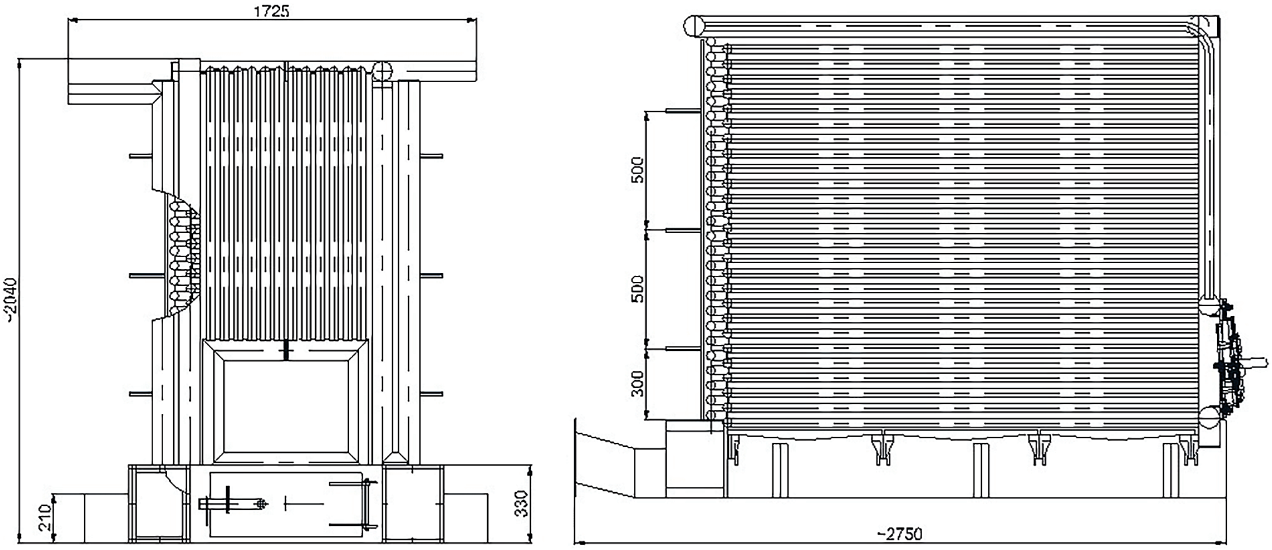

Figure 1. Frontal view of a hot water boiler with a manual furnace for solid fuel combustion (left) and longitudinal section of the boiler (right)
Source: developed by the authors

Results

The scientific and technical literature discusses various approaches to increasing the intensification of heat transfer, including the geometry of gas flues, the introduction of special turbulators and the introduction of new materials for surfaces. A systematic analysis of experimental data and theoretical models presented in V. Ganapathy (2003) and V. Kondratiuk *et al.* (2015), allowed to establish that the cross-flow of tube elements is the most efficient way to organise heat transfer in low-power boiler plants. This design is typical for superheaters, water heaters and air heaters. The staggered arrangement of the tubes provides optimum conditions for heat transfer, resulting in high heat transfer coefficients. The hydrodynamics of the cylinder cross-flow is characterised by the complexity and variability of flow regimes on its surface. A laminar boundary layer is observed in the frontal part of the cylinder, which can transition to a turbulent regime depending on external conditions. Heat transfer in this zone is determined by both approximate and exact analytical methods.

The results obtained indicate an increased intensity of heat transfer at steady-state flow. At low flow velocities and low Reynolds numbers, the separation of the boundary layer from the cylinder surface occurs later, at an angle relative to the flow direction equal to $\alpha = 125° \div 150°$. With increasing velocity and Reynolds number, the breakaway point shifts upstream, and at high *Re* values, the breakaway occurs at an angle of 82° to 90°. This flow pattern is observed up to the critical Reynolds number, $Re = 2 \times 10^4$. The presence of even minor turbulence leads to a significant increase in heat transfer, especially in the frontal part of the cylinder, where the heat transfer coefficient can increase by 30-50%. With a further increase in the Reynolds number to $Re = 5\times10^{(5)}$, the heat transfer in the aft part of the cylinder significantly exceeds the heat transfer in the frontal part. The installation of pipes in the confined space of the channels leads to a complication of the flow pattern, the degree of which depends on the ratio of the pipe diameter to the channel height.

The boiler's draft system was designed to ensure natural combustion of fuel. The boiler is designed to operate with natural water circulation in the heating system, and therefore, when designing and installing the system, it is necessary to ensure laminar flow of the coolant along its entire length. The modernisation of the hot-water boiler was aimed at ensuring reliable operation at water pressures corresponding to the operation of hot-water boilers with a closed heat supply scheme, when the water pressure in the system was kept constant and hot water was supplied by connecting heat exchangers according to a separate scheme. The boiler can operate with forced water circulation at an overpressure of up to 0.06 MPa (0.6 kgf/cm^2) and a heating temperature of up to 95°C. Fuel is supplied through the feed door to the grate. The generated combustion products move along all convective heating surfaces and, due to the presence of a vacuum behind the boiler, move to the rear of the boiler and leave it through the flue gas duct.

Technical measuring instruments were installed on the model of the behind-the-screen flue duct with transverse gas flow through the all-welded tube panel. The heat transfer coefficient from the heated gas behind a hot-water solid fuel boiler with a heat emitter to the walls of the transverse pipes and the membrane panel was determined by formula (2):

$$\alpha = \frac{1}{\frac{1}{k}+\frac{F\delta}{F\lambda}+\frac{F}{\alpha_2 F_v}}, \tag{2}$$

where k is the heat transfer coefficient, W/(mK); a_2 is the heat transfer coefficient from the wall to the water, determined by V. Kondratiuk *et al.* (2015), W/(m$^{(2)}$ K); *F, Fδ, Fv* – channel surface at the screen flue on the gas side, pipe walls, water-gas interface and inner surface of pipes, m^2; *d* – pipe wall thickness, m; *l* – thermal conductivity of steel, W/(mK).

The heat output is transferred by the heated gas after the hot water boiler in the modernised area:

$$N = V(C_p T' - C_p'' T'), \tag{3}$$

where V is the volumetric flow rate of gases through the boiler, m^3/s; C_p is the specific volumetric heat capacity of combustion products, taking into account humidity, J/(m^{3}K).

Heat output in the form of heat losses to the environment through thermal insulation:

$$N_s = \alpha_{pr}[(T_w - T_{nw}) \cdot F_s + (T_p - T_{nw}) \cdot F_p], \tag{4}$$

where $a_{(pr)}$ is the heat transfer coefficient for natural convection, W/(m^2×K); T_w, $T_{(nw)}$, T_p are the temperatures of water, environment and fin in the pipe panel, K; F_s is the outer surface of the pipes of the experimental section and all external fins, m^2

The average temperature of the side ribs welded to the bottom all-welded pipe panel of the upgraded section:

$$T_p = \bar{T} - E(\overline{T_w} - T_w), \tag{5}$$

where E is the efficiency of the side ribs and membranes between the tubes of the all-welded tube panel, which are washed by combustion products on one side.

$$E = \frac{th(mh)}{mh}, \tag{6}$$

where m is the parameter of the side edge.

For the membranes in the bottom panel and the side fins that are washed by flue gases on one side, the parameter m was calculated using the formula:

$$m = \sqrt{\frac{2\alpha}{\delta\lambda_s}}, \tag{7}$$

Hydraulic resistance is a crucial characteristic in heat exchanger calculations. The hydraulic resistance in cross-flow ducts is determined by the static pressure drop over the measured area and depends on the qualitative picture of the gas flow behind the cross-flow pipe and the elements that make up the walls of the duct. The periodic acceleration and deceleration of the flow, characteristic of the staggered cross-pipe flow, forms vortex traces and zones, which leads to a loss of kinetic energy of the moving flow. For channels with a small number of cross-flow pipes, the total hydraulic resistance is affected by additional kinetic energy loss in the first row and head loss at the outlet of the section. An integrated approach to determining the optimal aerodynamic and heat transfer characteristics can improve the design parameters of a solid fuel hot water boiler. It should be noted that in the modernised channel of the behind-the-screen flue with cross-flow pipes, one wall with transverse plates interacts with the vortex flow only in terms of hydrodynamics without heat exchange. Active heat exchange in such a duct occurs only with the surface of the cross tubes and the tubes in the all-welded tube panel. This factor explains the more careful selection and selection of not only the geometry of the behind-the-screen duct, but also the aerodynamic and heat exchange characteristics and flow modes. Figure 2 illustrates the change in static pressure along the length of the upgraded section every 150 mm for different Reynolds numbers.

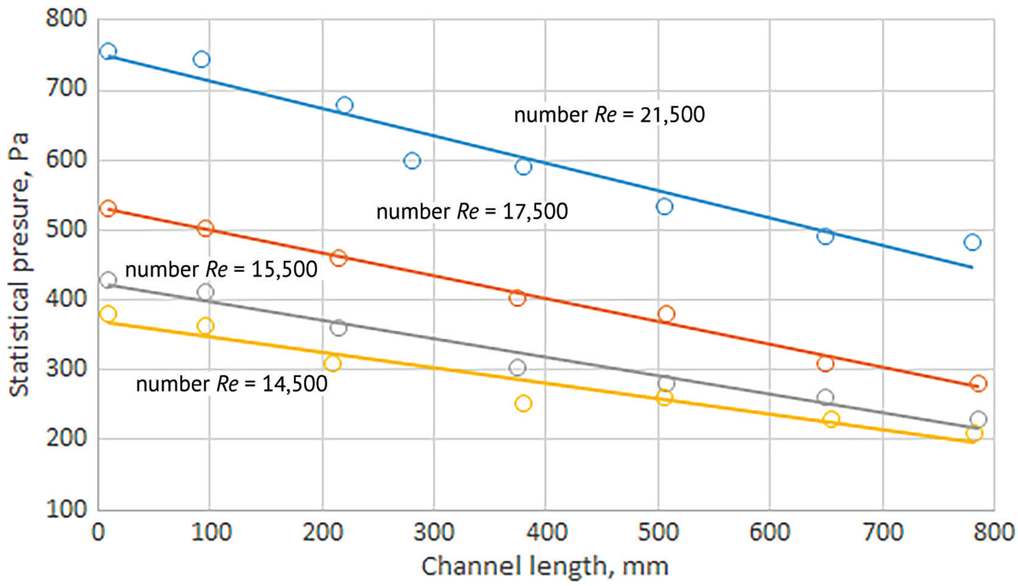

Figure 2. Distribution of static pressure along the length of a staggered pipe bundle
Source: developed by the authors

At the inlet of the experimental section for the four values of *Re,* the static pressure is significantly higher than at the outlet of the experimental section. This is due to the fact that the area of the complex cross-section of the experimental section with transverse pipes after leaving it increases, since the cross-section is considered along the outer contour without pipes and therefore the flow rate decreases. At the same time, Figure 2 illustrates from the solid lines that with an increase in the flow rate (*Re*), the steepness of the lines and the total static pressure drop at the initial and final experimental sections increases.

According to the above dependences, a stabilised section with a linear change in static pressure was selected, and the hydraulic resistance coefficient was calculated from the difference in the experimental section with a uniform static pressure drop. The studied range of low flow rates with small values of *Re* corresponded to the most commonly used in the practice of operating thin bed coal combustion in low-power hot water boilers. Therefore, when the boilers operate at low and medium loads, the gas velocity values are low in the behind-the-screen flue. Additionally, Figure 2 shows that with an increase in the flow velocity and *Re* number in the considered model of the stack channel, there is a clear alternation of static pressure values, which characterises the variable movement of this flow, either with an increase in velocity or with a decrease in velocity behind each transverse insert in the channel.

From Figure 2, it can be concluded that the alternating static pressure drop for *Re* numbers from 6,000 to 17,000 for the studied channel of the backscreen flue with inserts located at an angle of 45° to the wall exceeded the calculated error in static pressure, and therefore the obtained variable static pressure spread is quite real and understandable. The stability of the $Nu_{(w)}/Nu_w$ ratio in the *lgRe* range from 3.8 to 4.1 for the behind-the-screen flue duct is explained by the periodic change in flow direction caused by the tilt of the plates. At low flow rates, each successive plate deflects half of the flow at a 45-degree angle to the side wall of the adjacent pipe. This mechanism ensures relatively stable heat transfer in this range of Reynolds numbers.

In the experiments with air velocity from 8 to 24 m/s (*Re* = 21,000 to 55,000) in the setup without transverse rods, effective self-cleaning of the convective surface of the model boiler was achieved, which enabled the use of similar conditions in industrial high-capacity boilers. The analysis of the experimental data indicates the establishment of an automodel regime of isothermal air flow at Reynolds numbers exceeding 60,000. In this mode, the drag coefficient is practically stable $\lg 100\xi = 0.68 \div 0.69$. For the ducts of the behind-the-screen flue with longitudinal pipe panels, the drag coefficient is higher compared to a straight pipe and increases with an increase in the Reynolds number. Thus, at *Re* = 20,000, $\xi_{t.p.}/\xi_o = 1.78$, and at *Re* = 60,000 – by a factor of 2.1. The obtained dependence of the drag coefficient for the behind-the-screen flue duct with longitudinal pipe panels in the range of Reynolds numbers from *lgRe* 4.28 to 4.52 allows for a more accurate calculation of hydraulic losses in such ducts. This data is important for the design and optimisation of heat exchangers.

Discussion

The intensity of heat transfer in heat exchange equipment is a rather multifaceted process that is of interest to many researchers and is relevant to various areas of heat and power engineering. Drawing an analogy of the above study with the results of works in tangential directions, it was emphasised that W. Wang & E.J. Bisset (2018) showed that for a given Reynolds number (*Re*), the Nusselt number (*Nu*), friction coefficient (*f)* and thermal characteristics of a twisted pipe with a twisted tape installed in it are significantly higher than for a separate twisted pipe and a smooth pipe. In addition, heat transfer, frictional losses and thermal efficiency increase with decreasing twist pitch (*y/w*), as a lower *y/w* tape generates a more intense and stable vortex flow.

The Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine is actively conducting research in this area, which has the following projects in the context of the above study: improvement of combustion chambers of fire-tube boilers to intensify heat generation, as well as analysis of the impact of numerous sensitive and design parameters on heat transfer in combustion chambers; it was found that radiation selectivity significantly affects combustion characteristics, local and total heat transfer in combustion chambers; the studies were conducted for boilers BC-21, VK-22 One of the most promising ways to increase the efficiency of fuel use in boilers is to intensify heat exchange in combustion chambers. The technology developed by the Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine to intensify heat exchange by installing secondary emitters helps to increase fuel combustion efficiency and reduce harmful emissions into the atmosphere. The implementation of this technology resulted in natural gas savings and a significant reduction in nitrogen oxides (by half) and carbon monoxide emissions (by five times) (Khalatov *et al.*, 2024).

S. Sydorenko & M. Sydorenko (2023) concluded that the heat transfer coefficient is a key parameter that determines the intensity of heat transfer in heat exchange equipment. Its value is determined by the set of thermal resistances arising in the system, and also depends on the geometric parameters and thermal properties of heat exchange tubes. The analysis of the calculated data shows that modification of the state of the outer surface of heat exchange tubes contributes to an almost threefold increase in the heat transfer coefficient during water vapour condensation. This, in turn, provides an increase in heat transfer efficiency by more than 10% and makes it possible to reduce the working area of the heat exchanger, which is especially relevant in the operation of power equipment when there is a need for its emergency modernisation.

The article by V. Tuz *et al*. (2021) considered the specifics of the heat transfer process in heat exchangers with spiral tube geometry under external airflow in an annular channel. The authors carried out a detailed analysis of the influence of the geometric parameters of the twisted tubes, in particular the spiral pitch and diameter, on the heat transfer intensity, paying special attention to the formation of the thermal initial section. It has been established that twisted pipe structures contribute to more efficient mixing of the flow, which, in turn, provides an increase in heat transfer coefficients compared to traditional smooth pipes. The empirical dependencies proposed by the authors enabled estimation of the length the of the thermal initial section, which is an important step in the design of highly efficient heat exchange equipment. This study deepens the understanding of heat transfer in non-standard channel geometries and opens up prospects for further optimisation of power plant designs. Intensification of heat exchange in the flues of low-power solid fuel hot water boilers is an important step towards energy efficiency of thermal power facilities.

Conclusions

In finding the optimal characteristics of the behind-the-screen duct, the hydraulic drag coefficient at a velocity of 7 m/s was investigated and conclusions were drawn, and the thermal efficiency of the duct and heat transfer in it were estimated. The increase in heat transfer in the channel with flat plates at an angle of 45° to the flow in the low velocity zone, relative to the equivalent staggered bundle, is explained by the additional direction of half of the flow in the channel of the screen flue to each subsequent transverse pipe and the radiant component from the lateral heat-emitting surface. Therefore, in the convective duct of the screen flue with inclined plates, with cross-flow of pipes with low velocities and flow temperatures up to 800°C, an increase in heat transfer close to the classical staggered pipe package is expected, with lower promotion costs. The increase in heat transfer efficiency in the channel with inclined plates compared to the staggered bundle at low flow rates is explained by several factors. Firstly, the inclination of the plates leads to an additional direction of a part of the flow to the side surfaces of the pipes, which increases the area of contact between the coolant and the walls. Secondly, the high blackness of the heated plates (about 0.9) contributes to intensive heat transfer through thermal radiation. Thus, the combination of convective and radiation heat transfer provides a significant increase in the overall heat transfer in the channel. Prospects for further research include an extended analysis of the effect of the angle of inclination of the plates, the distance between them, materials with different emissivity, as well as the study of flow behaviour at variable temperatures and in a wider range of velocities.

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Conflict of Interest

None.

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Інтенсифікація теплообміну в газоходах твердопаливних водогрійних котлів малої потужності

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Анотація. Впровадження нової конструкції газоходу забезпечує більш повне використання теплової енергії палива та знижує негативний вплив на довкілля. Основна мета дослідження полягала у оптимізації конструкції заекранного газоходу з використанням пластинчастих напрямних для димових газів, що дозволить знизити витрати палива та підвищити ефективності роботи водогрійного котла. Результати, наведені у статті, отримані з використанням методів: узагальнення результатів попередніх досліджень, порівняння, комплексний аналіз, елементарно-теоретичний аналіз і синтез, експеримент, логіко-структурний аналіз, науково-аналітичний аналіз тощо. В експериментальних дослідженнях використовувалися сучасне вимірювальне обладнання, в тому числі газоаналізатор, тепловізор, пірометри. Проведено дослідження та оптимізацію геометрії каналу заекранного газоходу для водогрійних котлів українського виробництва у широкому діапазоні потужностей та швидкостей газового потоку. Отримані результати дозволяють розширити можливості застосування котлів цього типу та підвищити їх енергоефективність. Запропоновано метод інтенсифікації процесів теплопередачі та метод покращення ефективності роботи котла за рахунок використання нової конструкції цільнозвареної трубної панелі конвективного каналу газоходу з поперечним обтіканням труб з напрямними пластинами. Проведені дослідження розширюють наукові знання про процеси теплообміну в котлах з заекранним газоходом. Оптимізація геометрії каналу та використання уточнених теоретичних моделей забезпечують зниження витрат палива, зменшення шкідливих викидів та продовження терміну служби обладнання. Результати дослідження, отримані за допомогою розрахункових методів та експериментальних вимірювань, були підтверджені порівнянням з даними інших авторів та результатами натурних випробувань. Відмінною рисою проведених досліджень є висока ступінь узгодження теоретичних розрахунків з експериментальними даними та даними, наведеними в технічній документації на котли. Це свідчить про достовірність отриманих результатів та коректність використаних методів дослідження. Стаття буде корисною проектувальникам, інженерам, теплоенергетикам та всім, хто цікавиться котельною технікою

Ключові слова: енергоефективність; топка; модернізація; екрани; пучки труб; передача тепла