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Review

Review of Thermal Calculation Methods for Boilers—Perspectives on Thermal Optimization for Improving Ecological Parameters

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Abstract: This article presents an overview of thermal calculation methods used in boilers powered by fossil fuels (solid, liquid or gas). The analysis was carried out mainly in terms of combustion chamber calculation methods. Changing standards and legal regulations regarding the use of fossil fuels in Europe and the world make it necessary to adapt calculation methods and boiler design to current requirements, and many of them are related to outdated boiler models or for fuels that are no longer so heavily used in industrial solutions. Current research and development trends implemented in the EU and in the world related to the issues of the European Green Deal, the Fit for 55 directive and other ecological trends in the energy sector make it necessary to verify and remodel the calculation methods used so far in terms of the thermal efficiency of the device, fuel consumption or the use of fuels not previously used in their wide range in a wider application. Hence, the knowledge and updating of the state of knowledge in the field of the thermal calculation of boilers in terms of their environmental performance is necessary and strongly sought after by researchers. It is undoubted that in the next few years, boilers will continue to be the main source of thermal energy, especially in the power industry or industry. A reasonable energy transition should be based on the direction of the thermal optimization of already functioning structures and adaptation of their operating parameters to the planned new ecological fuels in the sense of the intensification of energy converted from primary form to thermal energy, and in the last step, it should reorganize the energy and industrial sectors, leaving only these groups of devices treated as a stable and necessary source of energy. Therefore, it should be recognized that activities aimed at improving the thermal parameters of boilers should directly improve the thermal efficiency of the device, and this will translate into fuel savings and reduce their negative impact on the environment.

Keywords: boilers; environmental protection; thermal power; heat transfer; thermal calculations; efficiency

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1. Introduction

Thermal calculations of boilers are one of the key elements of thermal engineering, especially in the context of optimizing combustion processes, energy efficiency and minimizing harmful emissions [1–3]. Boilers, used in many industrial sectors and in the energy sector, are devices whose operation must be constantly monitored and optimized to meet growing technical, environmental and economic requirements [4,5]. Increasing demands for efficient energy management and legal and regulatory requirements for exhaust emissions are driving engineers and scientists to adopt increasingly sophisticated calculation methods. Thermal calculations are the foundation of the design, operation and modernization of boilers, because they allow us to precisely determine the operating parameters of devices and predict their impact on the environment [3].

Changes in legal regulations, especially in the European Union, place increasing emphasis on energy efficiency, environmental protection and minimizing the impact of industrial activities on air quality and climate change [6]. EU directives such as the Industrial Emissions Directive (IED) and national environmental laws place a number of requirements on boiler manufacturers and industrial users regarding energy efficiency and emissions of pollutants (e.g. NO_x, SO_x, CO_2) [7,8]. Boilers based on traditional combustion methods must now be designed and modified in accordance with stringent emission standards, which forces designers and operators to carry out detailed thermal and thermodynamic calculations [3,4]. Taking the above into account, it can be concluded that as ecological parameters relating to boilers, these will be indicators assessing their impact on the natural environment, especially in the context of pollutant emissions, energy efficiency and fuel consumption. In the case of boilers, these parameters are important in assessing their compliance with environmental regulations, impact on air quality and strive for sustainable development. The key ecological parameters in the context of boilers include the following:

1. Pollutant emissions: Carbon dioxide (CO_2) as an indicator of greenhouse gas emissions, especially in fossil fuel boilers. Nitrogen oxides (NO_x) formed during high-temperature combustion affect smog and the acidification of the environment. Sulfur oxide (SO_x) emissions are associated with the use of sulfur fuels, e.g., low-quality coal leads to acid rain. Particulate matter (PM10, PM2.5) is particularly important in the case of coal or biomass-fired boilers. Carbon monoxide (CO) indicates the incomplete combustion of fuel [4].
2. Energy efficiency: The efficiency index of a boiler, i.e., the ratio of energy obtained in the form of heat to the energy contained in the fuel. Higher efficiency means lower fuel consumption and lower emissions. Condensing boilers usually have higher energy efficiency than traditional ones [2].
3. Type of fuel: Solid fuel boilers (e.g., coal, wood, biomass) are usually more emission-intensive than natural gas or fuel oil boilers. Biomass boilers can be environmentally friendly if the fuel comes from renewable sources and combustion takes place in a controlled manner [8].
4. Fuel consumption: Less fuel consumption while maintaining the same amount of heat generated is environmentally beneficial as it reduces pollutant emissions [4].
5. Flue gas temperature and heat recovery: A lower flue gas temperature indicates better energy utilization and less heat loss. The use of heat recovery techniques (e.g., in condensing boilers or economizers) reduces emissions and improves efficiency [3].
6. Flue gas filtration: The use of electrostatic precipitators, dust collectors and other technologies reduces the emission of dust and harmful gasses. Legal regulations require reduction in pollutant emissions, e.g., as part of the fight against smog [5].
7. Healthcare: Reducing dust and harmful gas emissions reduces air pollution, improving quality of life [7].
8. Economic efficiency: Higher efficiency and lower fuel consumption translate into savings for the user [4].

Therefore, it can be concluded that thermal calculation methods affect the ecological parameters of boilers by optimizing their design, the selection of operating parameters and energy efficiency. Well-conducted thermal calculations allow for minimizing energy losses and pollutant emissions, which translates into better environmental parameters of the device.

Modern thermal calculations of boilers allow for the accurate prediction of fuel consumption, the amount of heat generated in the combustion process and heat losses in various stages of boiler operation. This allows you to minimize the emission of harmful substances by optimizing the operating parameters of the devices. Legal requirements also affect the need to regularly modernize boilers in order to adapt them to standards, which requires precise thermal analyses both at the design stage and during operation [9–12].

Environmental protection is now one of the priority objectives of industrial policies, both at the national and international level. Industrial boilers, especially those of the older generation, can be a source of significant amounts of pollution if they are not properly designed and operated. One of the main problems is the emission of greenhouse gasses and harmful substances such as sulfur dioxide, nitrogen oxides and particulate matter. Thanks to precise thermal calculations, it is possible to reduce these emissions by increasing the energy efficiency of boilers and using advanced flue gas cleaning technologies [13–16].

Today's technologies, such as flue gas recirculation, condensing heat exchangers and low-emission burners, require thorough thermodynamic and thermal analyses to ensure maximum efficiency with minimum environmental impact. The professional literature, including scientific textbooks and technical articles, emphasizes the role of thermal calculations in assessing and forecasting the environmental impact of thermal installations. For example, through scientific works related to the modeling of combustion processes and the analysis of heat losses and thanks to the optimization of the combustion process, emissions can be reduced without the need to replace the entire device [17–21].

The development of technology, including the digitization of industrial processes, has contributed to a change in the approach to boiler design and operation. New-generation boilers are equipped with automatic control and monitoring systems, which allow for the ongoing adjustment of operating parameters to current needs and the optimization of energy efficiency. Modern methods of thermal calculations include computer modeling and simulations of combustion processes, which allow engineers to accurately predict the efficiency of boilers under various operating conditions. The use of numerical methods, such as finite element analysis (FEM), enables the detailed modeling of thermal and flow processes, which is necessary when designing modern boilers in order to achieve high operating parameters, such as high thermal efficiency and low emissions of harmful substances [22–24].

The scientific literature draws attention to the increase in the popularity of condensing boilers and boilers powered by alternative energy sources, such as biomass. Such devices require specialized thermal calculations that take into account the specifics of the fuel and other unique operating parameters. These boilers are highly energy efficient, but at the same time require precise design and monitoring to maximize their efficiency and minimize emissions [25–30].

The aim of this article is to analyze the existing methods of thermal calculations from the points of view of the following:

1. Available methods and tools used in the design and thermal analysis of boilers.
2. Assessment of their accuracy, merits and limitations in optimizing energy efficiency and emissions.
3. Identification of links between thermal calculations and ecological parameters.

In addition, the relationships between thermal efficiency and fuel consumption and pollutant emissions are discussed. The conclusions indicate proposals for improvements in the process of designing and operating boilers.

Thermal calculations of boilers, taking into account new legal regulations, environmental protection and the dynamic development of technology, are a key element of modern thermal engineering. They not only ensure the possibility of precise design and operation of boilers but also contribute to environmental protection and increase energy efficiency [31].

2. Method Review

2.1. Thermal Calculations of Water Tube Boilers

Water tube boilers are widely used in industrial applications due to their efficiency and ability to generate steam at high pressures. Understanding the thermal calculations involved in the operation of these boilers is essential for optimizing performance and ensuring safety. The most common methods for the thermal calculations of water and steam boilers are balance methods based on the unit heat load resulting from the fuel stream supplied to the combustion process and the assumed thermal power on the hot water or steam side. Most of the known and used methods do not take into account the stoichiometry of the fuel combustion process (they assume its complete combustion), and at the same time do not take into account the increased power demand, e.g., for flue gas cleaning. Water tube boilers operate by circulating water inside tubes that are heated by combustion gases. This design allows for a large surface area for heat transfer, which enhances efficiency. The efficiency of a water tube boiler is largely determined by its heat transfer capabilities. The primary modes of heat transfer include conduction, convection and radiation [32,33].

The basic equation in the balance sheet method is the overall heat transfer coefficient:

$$U = \frac{1}{\frac{1}{h_i} + \frac{d}{k} + \frac{1}{h_o}} \quad (1)$$

where h_i—internal heat transfer coefficient (inside the tube) [W/m^2·K]; h_o—external heat transfer coefficient (outside the tube) [W/m^2·K]; d—thickness of the tube wall [m]; and k—thermal conductivity of the tube material [W/m·K].

The thermal efficiency η of a boiler can be expressed as

$$\eta = \frac{Q_{out}}{Q_{in}} \cdot 100\% \quad (2)$$

where Q_{out}—useful heat output [W]; and Q_{in}—total energy input from fuel combustion [W].

Several factors contribute to energy losses in water tube boilers, including the following:

- Flue gas losses: heat carried away by exhaust gasses.
- Radiation losses: heat lost through the boiler casing.
- Blowdown losses: heat lost due to the removal of water to control concentration levels.

Calculating these losses is crucial for improving boiler efficiency and may be important from the point of view of improving the ecological parameters of boilers due to the reduction in harmful substance emissions through the rational management of conventional or alternative fuel resources [34,35].

Ref. [36] presents the method of the thermal conversion of radiated boilers developed by the Central Institute of Boilers and Turbines in Petersburg (CKTI), also known as the method of Gurowicz A. (1950). This method is based on scientific and experimental work carried out by the Institute, which is used in the calculations of low- and high-power boilers. In addition, the WTI method (Timofeyev B., 1934 and 1941 Moscow), the Wohlenberg method (Münzinger F., Berechnung und Verhalten von Wasserrohrkesseln, 1949), which is most widely used for the calculations of grate coal boilers, and the Ledinegg method (1952) are cited.

Ref. [37] presents thermal calculations of flame tube boilers based on the Soviet WTI method (All-Union Technical Institute in Moscow), also known as the method of Timofeyev B. (1939 and 1941), which is a standardized method, and the Wohlenberg method developed by Münzinger F. (1949). Both methods are based on calculating the heat given off by radiation in the combustion chamber bypassing the convection process, which is considered insignificant in the heat transfer of the combustion chamber. Both methods also take into account the temperature of the flue gasses leaving the combustion chamber as one of the balance conditions of the boiler, which should be assumed or calculated. The calculations are based on the classical equation for the heat of radiation resulting from the Stefan–Bolzman equation:

$$Q_{pr} = c \cdot H_{pr} \cdot \left[\left(\frac{T + 273.15}{100} \right)^4 - \left(\frac{T_{sc} + 273.15}{100} \right)^4 \right] \quad (3)$$

where T—temperature of flue gasses leaving the combustion chamber [°C]; T_{sc}—temperature of heated walls [°C]; c—total radiation coefficient (depending on the boiler design, type of fuel, etc.) [W]; and H_{pr}—radiated area [m^2].

In addition, the book presents the heat transfer coefficient (α) with the flow of flue gasses across pipes arranged in parallel and crosswise (staggered system). Both equations come from the scientific works of Antywiewa and Kozaczeński, taking into account the research of Kuznetsov and Lokrin. The equations also take into account correction factors based on Babcock–Wilcox research.

Ref. [38] present identical methods of calculating water tube boilers (flame tube boilers) as those included in [1]; however, as the most accurate measurable calculation results, they consider the CKTI method (Gurowicz A. method), taking into account the favorably calculated heat flux in individual zones of the boiler resulting directly from the WTI method (Timofeyev B., method). This method is today referred to by scientists as the zonal method. In addition, over the years, the beneficial aspects of the CKTI and WTI methods have been combined into one and established as the Soviet Steam Boiler Calculation Method.

Ref. [39] presents two Soviet methods (CKTI and WTI) as the most advantageous current methods of calculating low-, medium- and high-power boilers. In the book, both methods are considered together under the concept mentioned above. The author also presents the Wohlenberg method as a method also used in the United States (not only the German method), which has the advantage of quick and consistent calculations of the thermal parts of the boiler.

Ref. [40] presents examples of standards that allow us to define and calculate the efficiency of a boiler (German standard DIN 1942, American standard ASME PTC 4.1 and Polish standard PN–72/M–34128). In the case of the presented method of calculating thermal processes occurring in a boiler, the CKTI method is given, the description of which includes both calculations in accordance with this method, but also elements derived from the WTI method, which allows us to believe that in the scientific nomenclature, elements of the CKTI and WTI methods have been combined into one method, commonly referred to as the Soviet Method of Calculating Steam Boilers.

Ref. [41] presents, like the previous authors, a balance method of thermal calculations for boilers based on the CKTI method model.

2.2. Thermal Calculations of Fire Tube Boilers

Ref. [42] presents the methods of calculating thermal processes (mainly heat transfer) occurring in fire and tube boilers. The method described in this book is based mainly on the results of operational tests of operating fire and tube boilers and current scientific works on heat transfer. The described methods are based on the recommendations for determining the heat transfer coefficient (α) along the length of the fire tube and determining the temperature of the flue gas at its end, which is taken as the starting temperature for thermal calculations of the entire boiler fire tube system. Łachanin W. took this method from Dolgolenko W., who described it in the book entitled Steam Ship Devices in 1940. Another simplified method described by Łachanin W., is the determination of the velocity of flue gasses flowing in the fire tube as a determinant of the calculation of the number of tubes of the convection part of the boiler. He took this method from Barasz P., described by him in 1939 in his book entitled Fundamentals of Theory and Thermal Calculations of Steam Ship Boilers.

Ref. [43] presents methods for calculating low-temperature water heating boilers burning natural gas. It provides methods for calculating the heat given off by convection, with particular emphasis on fire tube boilers, but also flame tube boilers. The author suggests that the share of convection in the heat exchange process taking place in the combustion chamber, especially in a low-power heating boiler, is on average about 20%, although he also notes that due to the high temperature of the flue gas in the combustion chamber, the heat exchange mechanism mainly occurs by radiation, which can be considered about 80% of all energy given off by heat exchange in the combustion chamber. The author also states that in this type of construction, the heat transfer coefficient (α) can be calculated from the Sieder–Tate relation for which the Nusselt number takes the following form:

$$Nu = 1.86 \cdot \left(Re_{\mathrm{f}} \cdot Pr_{\mathrm{f}} \cdot \frac{d_{\mathrm{e}}}{L} \right)^{1/3} \cdot \left(\frac{\nu_{\mathrm{f}}}{\nu_{\mathrm{s}}} \right) \quad (4)$$

where Re_{f}—Reynolds number of the fluid [–]; Pr_{f}—Prandtl number of the fluid [–]; d_{e}—diameter of the flue gas (internal) [m]; L—length of the flue gas [m]; ν_{f}—coefficient of kinematic viscosity for the mean temperature of the flue gas [m^2/s]; and ν_s—coefficient of kinematic viscosity for the flue gas for the wall temperature [m^2/s].

If the diameter of the flue gas duct (flame tube) is significantly smaller than its length and the L/d_e coefficient > 4 or more, then the equation takes the following form:

$$Nu = 6.43 \cdot \left(Re_f \cdot Pr_f \cdot \frac{d_e}{L} \right)^{1/3} \cdot \left(\frac{\nu_f}{\nu_s} \right) \tag{5}$$

The author notes that in the case of flame tubes, the condition of forced convection occurs in the laminar flow velocity range, which causes the appearance of the Grashof number in the empirical formula for the mean Nusselt number borrowed from Mikhaev (1953).

$$Nu = 0.15 \cdot {Re_f}^{0.33} \cdot {Gr_f}^{0.1} \cdot {Pr_f}^{0.43} \left(\frac{Pr_f}{Pr_s} \right)^{0.25} \varepsilon_l \tag{6}$$

where Pr_w—Prandtl number of the wall [–]; and ε_l—emissivity of the heated surface [–].

The characteristic linear dimension in this case is the inner diameter of the pipe (d_e—equivalent diameter), and the value of the physical parameters of the fluid is determined for the arithmetic mean temperature at the inlet and outlet of the tube. The author also gives the average value of the heat transfer coefficient at the flow of a single cylinder based on the work of Hilpert and Żukauskas. The equivalent thickness of the gas layer for the flow in the duct developed by Hottel is also mentioned.

Ref. [31] presents an exemplary design of thermal calculations of a fire and tube boiler based on the entapliative method, taking into account the parameters of dissociation of gasses (mainly triatomic) with the assumption of the ratio of the length of the combustion chamber to its diameter in the range of the L/d_e coefficient parameter in the range of 2–5 [–], within which the calculation of the Nusselt number value for the combustion chamber is proposed, taking into account the additional viscosity coefficient kinematic flue gas with regard to the density of flue gasses at a given point of the analyzed temperature distribution in the combustion chamber:

$$Nu = 6.43 \cdot \left(Re_f \cdot Pr_f \cdot \frac{d_e}{L} \right)^{1/3} \cdot \left(\frac{\nu_f \cdot \rho_f}{\nu_s \cdot \rho_s} \right)^{0.14} \tag{7}$$

where ρ_f—density of the fluid in the center of the stream [kg/m^3]; and ρ_s—density of the fluid on the heating surface [kg/m^3].

Within the framework of the presented method, the author divides the heat transfer processes for the combustion chamber as follows:

- Heat given by convection: about 4.5–5%;
- Heat given by flame radiation: about 75–80%;
- Heat given by flue gas radiation: about 15–20%.

2.3. Other Methods for Calculating Boiler Combustion Chambers

The method of Lobo and Evans is based on the use of the total heat transfer coefficient and radiation calculations based on the Stefan–Boltzmann equation. It has been used for systems operating in refinery–furnace design work and it is also recommended for oil- and gas-fired boilers (and also for heating natural gas-fired boilers to the max. heat power of 300–1500 kW with pipeline heat exchanger). The average deviation between the predicted and observed heat absorption for 85 tests on 19 different refinery furnaces varying widely in physical and operating characteristics was 5.3%. The max. deviation was 16%. In addition, this method is widely used in industry, especially for large furnaces [44]. According to this method, it is determined that the boiler efficiency (net) is the ratio of the amount of heat released to the heating medium circuit in a specific unit of time to the amount of heat energy generated at that time. The heat flow from the flue gas to the exchanger in the form of tubes with the circulation of the working medium takes place mainly by means of radiation and forced convection. The water or steam in the pipes receives heat energy first in the convection zone and then in the radiation zone, which increases the efficiency of heat transfer. Lobo and Evans assumed the complete mixing of the flue gasses in the radiation section, i.e., the conditions are constant throughout this zone and there are no longitudinal or transverse temperature gradients. The average radiation temperature is equal to the temperature of the gas leaving the radiation zone. Radiation to the convection zone is omitted. This method involves the use of the general heat transfer coefficient and the aforementioned Stefan–Boltzmann equation. The equation for the radiant heat flux was proposed by De Baufre [44]. It is presented below:

$$Q_R = A_{cp} \cdot E \left[\left(\frac{T_g}{100} \right)^4 - \left(\frac{T_s}{100} \right)^4 \right] \quad (8)$$

where A_{cp}—a plane with an area equivalent to the exchanger area [m^2]; E—heat exchange efficiency coefficient per unit boiler volume (at the end of the sequence [$W \cdot m^2/K^4$]; T_g—average temperature of the gas leaving the radiation zone [K]; and T_s—temperature of the exchanger surface (tubes) [K].

Unfortunately, this method is characterized by poor data correlation, while Lobo and Evans aimed to achieve the highest possible accuracy. The equation they determined by means of research is presented below:

$$Q_R = 0.173 \cdot F \left[\left(\frac{T_g}{100} \right)^4 - \left(\frac{T_s}{100} \right)^4 \right] \alpha \cdot A_{cp} \quad (9)$$

where F—coefficient of efficiency or total heat transfer [–]; and α—coefficient decreasing A_{cp} in such a way as to obtain the effective surface of the exchanger and absorption efficiency coefficient [–].

The equation with the heat balance on the gas side is as follows:

$$Q_R = H_{in} - M \cdot c_p \cdot T_g \quad (10)$$

where H_{in}—inlet enthalpy of flue gas [W]; M—gas flow rate [kg·s]; and c_p—averaged specific heat of gas (e.g., by interpolation method) [J/kg K].

The above equation with the added convective term also takes into account the heat transfer by convection. It is presented below:

$$Q_R = 0.173 \cdot F \left[\left(\frac{T_g}{100} \right)^4 - \left(\frac{T_s}{100} \right)^4 \right] \alpha \cdot A_{cp} + h_c A \left(T_g - T_s \right) \quad (11)$$

where h_c—convective transmittance coefficient [$W/m^2 \cdot K$]; and A—total area of the exchanger (pipes) [m^2].

The F-factor is based on Christiansen's formula and is determined as follows:

$$F = \frac{1}{\frac{1}{F_s} + \frac{1}{P_c} - 1} \quad (12)$$

where P_C—cold surface emissivity [–].

The equation of F_S, on the other hand, is determined from the following formula:

$$F_S = p_f \left[1 + \left(\frac{A_R}{\alpha A_{cp}} \right) \frac{1}{1 + \left(\frac{p_f}{1 - p_f} \right) \frac{1}{F_{RC}}} \right] \quad (13)$$

where p_f—flame emissivity [–]; A_R—resistive surface [m^2]; and F_{RC}—coefficient determined empirically by Lobo and Evans [–].

The heat absorbed in the radiation zone Q_R can be determined as follows:

$$\frac{Q_R}{\alpha A_{cp} F} = 0.173\left[\left(\frac{T_g}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right] + 7(T_g - T_s) \quad (14)$$

The Lobo and Evans method assumes constant conditions throughout the chamber and treats it as one large zone, while in reality there are temperature gradients, the degree of mixing of gasses is not complete, and the properties of the exhaust gas and the working medium are different at different points. This can result in large inaccuracies, as the model can only provide an approximate result. Nevertheless, the Lobo and Evans method works quite well for large boilers. The assumption of complete mixing of gasses is generally acceptable except in high-temperature boilers with tall, narrow furnaces, where transverse and longitudinal temperature gradients cannot be ignored. In this case, a more accurate method of estimating the temperature of the gas should be considered. To increase accuracy, the radiation zone can be divided into several sections [44].

The Wilson, Lobo and Hottel method is an empirical method that has been used in box-type furnaces powered by oils and gasses for an estimated heat load from 15,000 to 95,000 W/m^2 for the perimeter pipe area. Another limitation in the application of this method is the temperature range for the unit temperature of the pipe surface, which should not be higher than about 200 °C for the radiation parts of the boiler, taking into account the flue gas temperature. It is believed that the average length of the radiated surface should not exceed about 4.5 meters for such boilers. This method is widely used in industry and recommended for the above limitations when the accuracy of the Lobo–Evans equation is not required; therefore, it is used when the accuracy of the calculation is not strongly required (indicative method), and hence, it is considered a preliminary estimation method. The equation used to estimate the rate of heat absorption by the heat transfer surface considered in this method is given by the following equation:

$$\mu = \frac{Q}{Q_F} = \frac{1}{1 + \frac{G\sqrt{\frac{Q_F}{\alpha A_{cp}}}}{4200}} \quad (15)$$

where μ—ratio of heat absorbed to heat released in the boiler [–]; Q—net calorific value of the fuel [kJ/kg]; Q_F—heat supplied by the fuel (average calorific value or calorific value of the fuel in the operating condition) [kJ/kg]; G—ratio of air to fuel [–]; and A_{cp}—heat exchange area [m^2].

From a practical point of view, with the Wilson, Lobo and Hottel method, the heat transfer area should be properly estimated using the above equation, especially in the case of a boiler with a single and double row of fire tubes, without taking into account the surfaces washed by the flame (for the combustion chamber). This equation does not work for calculations for very low and high calorific values, because the effect of excess air on the efficiency of heat transfer by radiation is difficult to define by the ratio of excess air to fuel. This equation is used in the energy balance to calculate the amount of total radiant heat [44].

The Orrok–Hudson method, as an early empieric equation for calculating the absorbed heat in the radiating part of a water tube boiler, is used to estimate the combustion chambers on the basis of changes in and parameters of the combustion rate of the burned bed and the related air–fuel ratio (excess air coefficient). It is quite measurably used in the design of heating boilers or low-power steam boilers. It has been replaced with more precise expressions and has limited value for design work. It can be used to estimate the effects of changes in the combustion rate or air–fuel ratio for an existing coal or oil-fired boiler if the impact and degree of slag deposition on the furnace tubes is known. In such applications, it may be necessary to adjust the constant in the equation to the known operating conditions of the boiler being analyzed. The equation used in this method has the following form:

$$t_e = 20 + \frac{1000}{\frac{7.495}{\sqrt{q_i}} + \frac{1164}{h_g}} \tag{16}$$

where t_e—temperature of the exhaust gasses [°F]; q_i—one-set heat load of the combustion chamber [W/m^2 ·K]; and h_g—the amount of heat supplied per kilogram of flue gas [W].

The equation showing the dependence of the temperature of exhaust gasses to the unit heat load and the amount of heat supplied per kilogram of flue gasses, derived on the basis of the Orrok–Hudson equation at the ambient temperature of 20 °C for the boiler operating temperature range of 600–1200 °C, is characterized by a calculation error of ±20 °C (about 2–3%) [44].

The methods shown are designed to increase the precision of calculations related to heat transfer and combustion efficiency, which are critical for optimizing the efficiency of boiler combustion chambers. In conclusion, alternative methods for calculating boiler combustors are critical to meeting evolving energy efficiency and environmental compliance requirements. Their use not only improves design accuracy but also facilitates innovation in boiler technology. It is important to emphasize that it is important to choose the right method based on the type of boiler, operating requirements and available computing resources.

3. Discussion on Improving Ecological Parameters

As part of the discussion of the review of methods of thermal calculations of boilers, considering the known and used methods of thermal calculations of boilers, it can be observed that most of them derive from or refer to old methods. Most of them were developed at the beginning of the twentieth century, and therefore, due to the early principles and approaches to ecology, they do not take into account assumptions related to the optimization of the ecological parameters of boilers. The following parameters should be considered as environmental parameters of a boiler: parameters related to the emission of harmful substances into the atmosphere and greenhouse gas emissions (e.g., CO_2) [45–49]. Another environmental indicator would be the heat lost to the environment and the thermal efficiency of the boiler (on the water or steam side), which will directly affect the amount of fuel burned in the boiler, and this will affect the change in environmental parameters [50–54].

In the case of modern boiler technical solutions, flue gas treatment systems (filtration systems, catalytic converters, selective non-catalytic systems and others) are often used in their construction, and systems related to the improvement of emission parameters and efficiency, such as flue gas recirculation systems or flue gas moisture condensation systems, are used. In most cases, these systems require additional energy for their proper operation, and this energy is often associated with high flue gas temperature (e.g., selective or non-selective catalytic reactors, urea or ammonia water dosing systems or electroylters). This demand is often covered by the boiler's own energy or is supplied artificially from an additional energy source (e.g., additional burners or regenerative reactors based on other fuels or electricity). All these solutions at the stage of designing the boiler structure should be ignited and provided for as part of the boiler's energy surplus, so that the energy needed for the operation of appropriate flue gas treatment systems can be covered from the net energy produced by the boiler. In the case of boilers already in operation, another option available is the use of additional heat recovery systems; for example, with economizers, if a high chimney loss is observed on the side of high flue gas temperature and if the fuel used allows (marginal sulfur content), a possible course of action is to transform the boiler structure into a condensing system [55–67].

However, in the case of a large group of devices with an outdated design, it is necessary to modernize them or replace them with a system of modern design with the use of systems that improve the ecological parameters of the boiler. The presented analysis also shows the need to verify the currently used calculation methods and develop them in terms of taking into account the improvement of the thermal and emission parameters, especially due to the continuously strong popularity of these technical solutions and their continued use as peak or transient sources in the near future [68–72].

4. Conclusions

The most important conclusions from this review of the state of knowledge include the following:

1. Various methods of thermal calculation for boiler heating surfaces are known. Empirical methods, theoretical methods with the empirical refinement of indicators and purely theoretical formulas are used.
2. As part of the thermal calculations, both equations based only on the thermal parameters and heat transfer of the boiler are used, and there are known equations in which the parameters of the combustion process are additionally used (most often referred to as combustion stoichiometry).
3. Further activities on the thermal optimization of boilers are still carried out; attention is mainly paid to the parameters of the thermal power of the boiler and its efficiency, while issues related to the reduction in the emissions of harmful substances, including the improvement of the ecological parameters of boilers, are mainly addressed as separate issues from the construction and operation of boilers.
4. The increase in the share of biomass and alternative fuels in the construction and exploration of boilers requires the research and development of empirical coefficients for this new group within the equations for the thermal calculations of boilers in order to adapt the currently known calculation methodology to take into account these fuels (especially due to lower combustion temperatures and different stoichiometry of the combustion process compared to for conventional fuels).
5. It should be recognized that the environmental protection and ecological parameters of boilers, as a currently necessary aspect of their use, should be significantly taken into account in the process of designing new equipment or modernizing old solutions. In the case of improving the ecological parameters of boilers, the changes taking place in the scope of their operation (developed control systems) [73–76] or monitoring (carbon footprint, flue gas emission monitoring systems, drones) [77–79] should also be taken into account at the stages of design and the adaptation of the structure, so that continuous measurements of thermal and emission parameters can be carried out in a reliable manner.

The main direction of the latest research and development of boiler calculation methods is the introduction of numerical methods into boiler designs (new and those based on the formulas presented in the article). Empirical studies related to heat transfer, especially on the side of combustion chambers, take into account the processes of radiation and convection. Another important aspect is the deepening of empirical research in the field of heat transfer processes for biomass or formed, torrefied fuels or clean energy fuels, i.e., related to zero or low emissions of harmful substances, which are relatively new and still require the creation of good databases of indicators, variables or coefficients to correlate the thermal parameters of a newly built boiler or modernized in relation to the fuel intended for combustion. Hence, the direction of the development of empirical research for thermal processes and further development of numerical methods or machine learning is important from the point of view of improving the ecological parameters of boilers. However, they will still be based on well-known and refined mathematical formulas developed in the past, while of course taking into account these new aspects.

Thermal calculations for boilers involve complex interactions between heat transfer, steam generation and efficiency metrics [80–82]. By optimizing these calculations, operators can enhance performance and reduce operational costs. Understanding these principles is vital for engineers working with boiler systems in industrial settings [83–92].

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