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DYNAMIC BEHAVIOR OF HOT WATER BOILERS DURING START UP

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Abstract. *The most commonly used central units in the district heating system are most certainly hot water boilers. Experience in exploitation as well as their former development have given rise to new demands and possibilities of using hot water boilers for achieving a more efficient utilization of fuel. Yet, the current trend is not only for an efficient operation in terms of energy efficiency of primary fuel, but it also comprises many strict requirements when it comes to a cost-effective, reliable and safe operation. A mathematical - empirical model of the hot water boiler during the start-up process is presented in this paper. The dynamic behavior of the object will be discussed in the start-up regime because it represents one of the most critical transient regimes during the operation.*

Key Words: *Dynamic Behavior, Hot Water Boiler, Start-up, Transitional Operating Modes*

1. INTRODUCTION

During the hot water boilers' operation, their work is subjected to high temperature and pressure conditions. In addition to their energy efficiency, it is also necessary to take into consideration the system safety and reliability in order to avoid major operation disturbances and downtimes [1]. The basic elements of the hot water boilers are exposed to the effects of high pressure and temperature of the working fluid during the boilers' operation. In transient processes, such as start-up, stopping and load changing, sometimes thermal stresses occur. Usually they are caused by thermal expansion of individual elements or assemblies [2, 3].

One of the most important parameters in defining reliability, availability and efficiency of the hot water boiler plant certainly refers to the failures that occur in the boiler piping system [4, 5]. This is confirmed by the results of a research project conducted by the North American Electric Reliability Council, which have shown that with the boiler piping system failures, an average decrease of the plant availability is over 6% [6]. The boiler piping system failures represent the primary cause of delays of thermal

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plants. More than 80% of such failures result in an unplanned downtime, where the average downtime lasts for approximately three days thus leading to high costs [6].

Shutting down the hot water boilers and their re-starting and re-integrating into work represent integral parts of every conventional hot water boiler plant as well as thermal one. Periodic changes in energy demand also require shutting down of the boilers for inspection and their starting up again. During the process of the boiler load change, as well as in the situations described above, there are significant thermal loads in the boiler elements especially in those with thick walls, which define the permissible intensity of thermal stresses [7]. High thermal stresses, which occur in the thick-walled pressure elements of the boiler during the transient operations, limit both the heating and the cooling rates of temperature changes in the boiler elements [8].

It is considered that one of the most critical modes, where the greatest thermal stress in the boiler's elements occurs, is certainly the process of the boiler plant's start-up. Thermal stresses are the results of temperature caused by the differences in the boiler structure. This is due to high time gradients of temperature of combustion products during the process of the boiler start-up. Thermal stresses are particularly high in certain parts of the boiler's thick walls, where the greatest temperature difference appears. As far as the hot water boilers are concerned, these thermal stresses are located in the pipe carrying wall of the first deflecting chamber. There is evidence that numerous accidents have occurred on this carrying wall [9].

The precise modeling of the boiler elements' dynamic behavior is also essential for improving the quality of boiler operation monitoring and control. Designing a mathematical - empirical model describing boiler dynamics is also very important regarding a reliable and safe boiler operation in transient regimes [10]. This paper presents the methods for determining basic operating parameters of the process of boiler start-up, which can be used to analyze the process of starting up not only steam boilers but hot water boilers as well.

2. THE PROCESS OF STARTING UP THE BOILER

When the steam boiler is started, the combustion chamber is partially filled with flame. Flame of some burners depends, in size and shape, on the structure and strength of the burner. The burner ignition and fuel used in these cases (oil, gas) should ensure a normal operation of each burner independently of the total load of the combustion chamber. Insufficient flame fulfillment of the combustion zone disables all fuel particles that are under the suitable condition for ignition and complete combustion. Due to low temperatures in the combustion chamber during the start-up process, insufficient fuel mixing with air forms a large amount of soot; the most massive drops of fuel oil, which do not come into the combustion zone, are cooled in a stream of cold air and flue gases which go out from the combustion chamber unburned. This leads to a decreased efficiency of the combustion chamber and unfavorable working conditions. The terms of ignition and combustion of fuel are also getting worse because of the wall temperature of the combustion chamber [9, 11].

In the start-up process of the hot water boiler, the problem is much simpler. There is a great similarity with the problem that is presented by Cwynar, but the hot water boilers have only one burner and regarding the combustion chamber, its role has the flame pipe. Problems that may occur in this case are caused by the possibility of tearing the flame and damaging the boiler structure at the end of the flame tube.

On the basis of the above mentioned facts it can be concluded that the conditions for the boilers' start-up process taken here into consideration depend on many parameters, which are determined by the burners' structures, the combustion chamber and its technical condition, as well as on the organizational chart of the start-up procedure and of the boiler's thermal state. In the process of the boiler's start-up, it is necessary to determine the changes of the values of parameters related to the operation of the combustion chamber: the amount of heat that is released with combustion and the temperature and the flow rate of those combustion products that are leaving the combustion chamber. For their determination the variables such as combustion chamber efficiency η^r_C, excess air ratio λ^r and temperature of combustion products ϑ^r should be known.

3. Combustion Chamber Efficiency during the Boiler's Start-Up

The combustion chamber efficiency during the process of the boiler's start-up is changed as the load changes, depending on the coefficient of excess air and changed conditions of fuel ignition and combustion. Load change of the combustion chamber in the process of the boiler's start-up is determined by variable u_Q. Value u_Q represents the ratio of the current boiler load and the nominal load.

$$u_Q = \frac{Q^r}{Q^z} \tag{1}$$

where superscripts r and z refer to the regime in the boiler's start-up and to the nominal one, respectively.

Therefore, the combustion chamber efficiency during the process of start up (η^r_C) in a wide range of the load change, can be described by [11]:

$$\eta^r_C = 1 - S^Z / u_Q \tag{2}$$

where $S^z = 1 - \eta^z_C$ represents the losses in the combustion chamber during the nominal load. Graphical representation of the combustion chamber efficiency change, Eq. (2), for some values of S^z can be seen in Fig. 1.

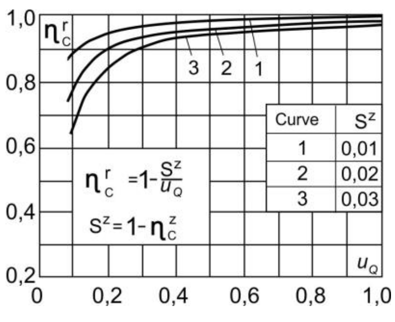

Fig. 1 Combustion chamber efficiency depending on a wide range of boiler load [11]

4. Coefficient of Excess Air Ratio during the Boiler's Start Up

Coefficient of excess air during the boiler's start-up λ^r is defined by the following assumptions [11]:

- starting up the boiler is carried out at constant sub-pressure in the combustion chamber, which is equal to the vacuum, which is maintained in the stationary mode, and,
- suction of the "waste" air from the atmosphere, which depends on non-hermetic boiler's properties, is considered as a constant value that is determined by the constructive scheme of the fuel supply and technical condition of the boiler.

According to these assumptions, mass flow of intake air L_f, entering in the combustion chamber from environment during the boiler's start-up is approximately equal to air suction in the combustion chamber at nominal load, $L_f^z = L_f^r = L_f$. For nominal load it stands:

$$\lambda^z = \lambda_1^z + \lambda_f^z \tag{3}$$

where λ_1^z is the coefficient of excess air in nominal mode and $\lambda_f^z = n_1\lambda_1^z$, where n_1 is the coefficient that characterizes non-hermetic properties of the combustion chamber's lower level (known from the calculations or measurements).

The mass balance in the burner zone during the process of the boiler's start-up is given as:

$$\lambda_1^r L_t^r b^r + n_1\lambda_1^z L_t^z b^z = \lambda_p^r L_t^r b^r \tag{4}$$

where L_t represents a theoretical amount of the air required for complete combustion.

From Eq. (4) it can be obtained:

$$\lambda_p^r = \lambda_1^r + n_1\lambda_1^z (L_t^z b^z / L_t^r b^r) \tag{5}$$

where b refers to fuel consumption during the process. Taking into account the above defined conditions it may be accepted:

$$L_t^z / L_t^r = Q_w^z / Q_w^r \tag{6}$$

$$u_Q = b^r Q_w^r / b^z Q_w^z \tag{7}$$

Quantity Q_w represents the amount of heat that is released by fuel combustion. Rearranging Eq. (5) with the values from Eqs. (6) and (7), the following equation for the coefficient of excess air in the burner zone during the boiler's start-up (λ_p^r) can be obtained:

$$\lambda_p^r = \lambda_1^r + \lambda_1^z (n_1 / u_Q) \tag{8}$$

or, when $\lambda_1^z = \lambda_1^r = \lambda_1$:

$$\lambda_p^r = \lambda_1^r (1 + n_1 / u_Q) \tag{9}$$

Graphic dependence of the coefficient of excess air during the process the boiler's start-up λ_p^r as a function of u_Q for different values $\lambda_1^z = \lambda_1$ and n_1 is presented in Fig. 2.

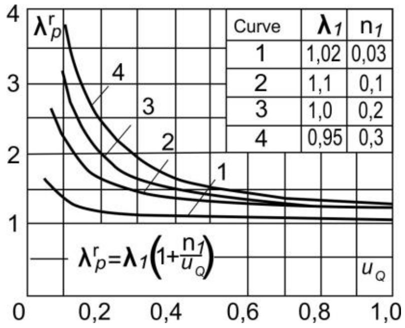

Fig. 2 Characteristics of excess air ratio depending on a wide range of boiler load [11]

5. Heat Received by the Combustion Chamber Walls during the Boiler's Start-Up

While changing boiler load, the heat amount that is received by the screens of the combustion chamber is changed also. It can be seen in Fig. 3a, where the amount of heat received by the screens of combustion chamber at the stationary mode is Q_0^u, compared to the total amount of heat delivered by combustion Q_c^u at the nominal mode, is represented in terms of u_Q:

$$\xi(u_Q) = Q_0^u / Q_c^u \tag{10}$$

With reduction of heat load u_Q, one part of the heat, which is received by the screens of the combustion chamber, increases. The character of these curves for different boilers is the same. Along with reduction u_Q what is also increased is the heat received by the surface area in the following elements of the boiler, economizers of steam boilers or gas pipes II and III pass of hot water boilers (Fig. 3b) [11].

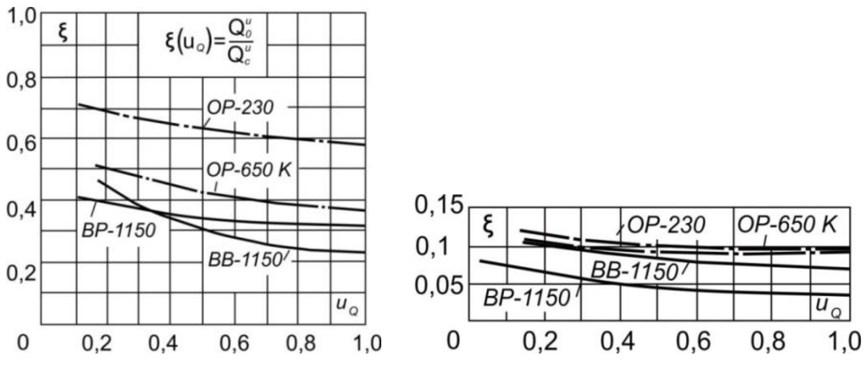

Fig. 3 Dependence of the relative heating of the combustion chamber walls (a) and flue pipes, or economizer (b) of the boiler load with coal powder combustion OP-230, OP-650k, BP-1150 and BB-1150 [11]

6. CWYNAR'S METHOD FOR DETERMINING THE HEAT DURING COMBUSTION PROCESS AND TEMPERATURES OF COMBUSTION PRODUCTS IN THE COMBUSTION CHAMBER DURING THE PROCESS OF STARTING UP THE BOILER

The method is based on the assumption that, on the basis of measurements or calculation, the results are known for the basic parameters, which describe the process of heat transfer in the combustion chamber, for all stationary states of the boiler operation [11, 12]. Knowing the function describing the change of specific parameters for different boiler load (i.e., from 60% and more, Fig. 4) can be analytically extrapolated to the low-load area. The failure occurring during this procedure depends on the range and accuracy of the known values of the parameters for medium and nominal load.

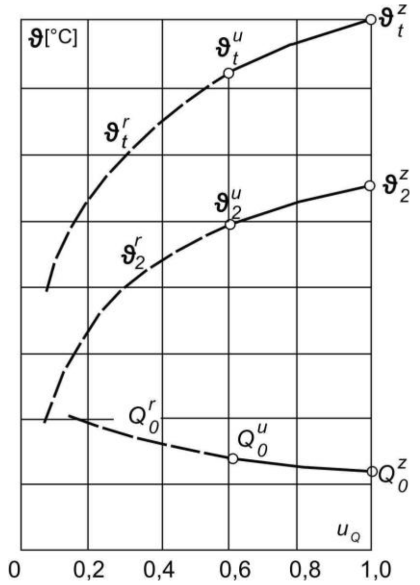

Fig. 4 Dependence of theoretical combustion temperature (ϑ_t); temperature of combustion products that leave the combustion chamber (ϑ_2); and heat that is received by the screens of the combustion chamber (Q_0) of boiler load with coal powder combustion OP-230, OP-650k, BP-1150 and BB-1150 [11].

The function describing the change of heat, which is received by screens of combustion chamber during the process of the boiler's start-up can be determined from the equation:

$$Q_0^r = N_0 \varphi^r a_F^r [(T_G^r/100)^4 - (T_n^r/100)^4] \quad (11)$$

$$T_G = \sqrt{T_t^r T_2^r};\ \ T_t^r = \vartheta_t^r + 273;\ \ T_2^r = \vartheta_2^r + 273;\ \ T_n^r = t_n = 273 \quad (12)$$

where φ is the parameter, which characterizes the position of burners compared to basic position and a_F the coefficient of flame emission. In accordance with the assumptions the following parameters are known:

$$Q_0^z, \vartheta_t^z, \vartheta_2^z, a_F^z, \varphi^z \tag{13}$$

or dependence $Q_0^u, \vartheta_t^u, \vartheta_2^u, a_F^u$ of changing these parameters in certain range of loads.

Coefficient N_0, which characterizes the heat transfer in the combustion chamber can be determined by replacing in Eq. (11) the values from Eq. (13) or the known dependencies $Q_0^u, \vartheta_t^u, \vartheta_2^u, a_F^u$:

$$N_0^z = (Q_0^z / a_F^z)\{[(\vartheta_t^z + 273)/100]^2[(\vartheta_2^z + 273)/100]^2 - [(t_n^z + 273)/100]^4\} \tag{14}$$

or

$$N_0^u = (Q_0^u / a_F^u)\{[(\vartheta_t^u + 273)/100]^2[(\vartheta_2^u + 273)/100]^2 - [(t_n^u + 273)/100]^4\} \tag{15}$$

Knowing dependence $N_0(u_Q)$, Eq.(11) for the heat flow that is received by irradiated surfaces of the combustion chamber can be written in the following form [11]:

$$Q_0^r = N_0 \varphi^r a_F^r \{[(\vartheta_t^r + 273)/100]^2[(\vartheta_2^r + 273)/100]^2 - [(t_n + 273)/100]^4\} \tag{16}$$

where $N_0 = \overset{u}{N_0}(u_Q)$.

Function $\overset{r}{Q_0}(u_Q)$ (Fig. 4) is determined more precisely in a higher range of loads, for which are known function $\overset{u}{Q_0}(u_Q)$, $\overset{r}{\vartheta_0}(u_Q)$ and so on, which allows determination of $\overset{r}{N_0}(u_Q)$. The minimum accuracy will be in the case when only data for nominal load are available, i.e. N_0^z can only be determined.

Theoretical combustion temperature in the process of starting up the boiler, ϑ_t^r, can be determined from the known dependence [11]:

$$\vartheta_t^r = (Q_w^r \eta_C^r + \lambda_p^r L_t^r \bar{c}_L \bar{t}_L^r) / V_{Gp}^r \bar{c}_{Gp} \tag{17}$$

where $\bar{c}_L$ is the average specific heat capacity of air [kJ/m^{3}K], $\bar{c}_{Gp}$ the average specific heat capacity of combustion products during process of starting up the boiler [kJ/m^{3}K] and V_{Gp} the combustion products volume flow rate during the boiler's start-up [m^3/s].

Temperature of the combustion products that leaves combustion chamber in the process of starting up the boiler, ϑ_2^r, can be determined from the heat balance equation:

$$Q_C^r - Q_0^r - Q_G^r = 0 \tag{18}$$

whereby $Q_c^r = u_Q Q^z = u_Q b^z (Q_w^z + \lambda_1 L_t^2 i_L^z)$ is the heat generated in combustion chamber, Q_0^r the amount of heat determined with Eq. (16) and $Q_G^r = V_G^r c_G^r (T_2^r - 273) b^r$ the heat quantity of flue gases that leave the combustion chamber.

By substituting the precious values in eq. (18), it can be obtained:

$$\alpha (T_2^r)^2 + \beta T_2^r - \gamma = 0 \tag{19}$$

where α, β, γ are coefficients whose values are:

$$\alpha = 10^{-4} N_0 \varphi^r a_F^r [(\vartheta_t^r + 273)/100]^2$$

$$\beta = V_G^r c_G^r b^r \tag{20}$$

$$\gamma = u_Q Q^z + N_0 \varphi^r a_F^r [(t_n + 273)/100]^4 + 273 V_G^r c_G^r b^r$$

Substituting expression $T_2^r = \vartheta_2^r + 273$ into Eq. (20), the temperature of combustion products, which leave the combustion chamber, can be determined:

$$\vartheta_2^r = (-\beta + \sqrt{\beta^2 + 4\alpha\gamma})/2\alpha - 273 \tag{21}$$

7. Gurvich's Method for Determining the Heat during Combustion Process and Temperatures of Combustion Products in the Combustion Chamber during the Process of Starting Up the Boiler

According to the carefully thought-out empirical method of A. M. Gurvich for determining heat exchange in the combustion chamber, the temperature of the combustion products that leave the combustion chamber is given with the following equation [13]:

$$\vartheta_2^r + 273 = (\vartheta_t^r + 273)(Bo^r)^{0,6} / [M(a_F^r)^{0,6} + (Bo^r)^{0,6}] \tag{22}$$

where Bo represents Boltzmann constant:

$$Bo^r = (10^8 / 4.9)\{b^r V_G^r c_G^r / [\zeta H_{opr} (\vartheta_t^r + 273)^3]\} \tag{23}$$

where ζ represents the coefficient of cleanliness of heating surfaces.

$$M = A - BX \tag{24}$$

In the last equation, it is A = 0.59; B = 0.5 for coal combustion and A = 0.52; B = 0.3 for fuel oil or gas combustion; $X = X_0 + \Delta X$, where $X_0 = h_1/h_2$, h_1 is the height of the combustion chamber from the floor up to level of the maximum flame temperature (when the boiler starts to the level of burners position), h_2 is the full height of the combustion chamber; ΔX the correctional member, which takes into account the distribution of burners position, their tilting angles, the quality of minced coal, etc. (detailed data for ΔX and the coefficient of flame emission a_F can be found in [14]).

The limited condition for applying the Gurvich equation are $Bo < 10a_F$ and $(\vartheta_2^r + 273)/(\vartheta_t^r + 273) < 0,9$, and it emphasizes the lower boiler load during the process of start-up.

Knowing the temperature of leaving flue gases ϑ_2^r from Eq. (22), their flow and heat quantity brought into the combustion chamber $Q_c^r = u_Q Q_c^z$, the heat quantity Q_0^r, received by the screens of the combustion chamber (according to Eq. (18)) can be determined.

If values $Bo^u, b^u, V_G^u, \vartheta_t^u, c_G^u$ are known (Fig. 4) for variable boiler loads, the Boltzmann constant in the condition for the boiler's start-up can be determined:

$$Bo^r = Bo^u \frac{b^r V_G^r c_G^r}{b^u V_G^u c_G^u} \left(\frac{\vartheta_t^u + 273}{\vartheta_t^r + 273} \right)^3 \tag{25}$$

8. Conclusion

The most sensitive elements of the hot water boilers are certainly their pipe systems. They mainly affect the reduction in availability, reliability and time utilization, and even in energy efficiency. Stresses in the hot water boiler elements, subjected to a high pressure of the working fluid, are substantially different from those occurring in other machines and objects. The difference is primarily that the stresses in the boiler elements are not only the result of the external forces but internal as well, which depend on the number of structural details, as well as technological and exploitation factors. In addition, many elements of the boiler are exposed to very high temperatures and variable loads, which can cause, especially in the transitional operating mode, extremely high stresses. Damages of pipes of heating surfaces of both hot water and steam boilers, especially those with greater capacity, are rare. They usually occur suddenly and can have devastating consequences. They can be prevented only by careful handling and maintenance of the plant and expert monitoring of the processes of the built-in screen pipes exploitation [15, 16].

In the previous studies of the boilers' availability and its models the main focus should be on the ignition and combustion conditions in the combustion chamber, as well as on the operation of the burners and flame pipe in the regimes other than nominal. However, the above described conditions, as well as the heat transfer at low loads (less than 40%) have not been sufficiently explored so far. This paper presents the methods of determining the basic parameters that characterize fuel combustion and heat transfer in the combustion chamber. In the previous studies there are also analyses of the start-up process of the boilers manufactured by "Minel - kotlogradnja", according to the presented procedure. This analysis has given satisfactory results, which are presented in [9]. For further analysis, it is necessary to measure some of these parameters during the start-up procedure. In this way, more current analyses will show and confirm the above presented procedure for determining significant parameters for the process of the boiler plant's start-up.

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DINAMIČKO PONAŠANJE VRELOVODNIH KOTLOVA ZA VREME PUŠTANJA KOTLA U RAD

Najzastupljeniji centralni uređaji u sistemima daljinskog grejanja su svakako vrelovodni kotlovi. Iskustveni podaci kao i dosadašnji razvoj vrelovodnih kotlova su ukazali na nove zahteve i mogućnosti korišćenja vrelovodnih kotlova kako bi imali efikasno iskorišćenje toplotne moći goriva. Ali u današnje vreme se ne zahteva samo efikasan rad u smislu energetske efikasnosti iskorišćenja primarnog goriva, već se nameće niz strogih zahteva u pogledu rentabilnog, pouzdanog i sigurnog rada. Matematičko - empirijski model vrelovodnog kotla pri puštanju kotla u rad je prezentovan u ovom radu. Dinamičko ponašanje objekta je razmatrano u režimu puštanja u rad vrelovodnog kotla, zato što predstavlja jedan od najkritičnijih prelaznih režima rada.

Ključne reči: *dinamičko ponašanje, vrelovodni kotlovi, puštanje u rad, prelazni režimi rada*