Rapid Start-Up of the Steam Boiler Considering the Allowable Rate of Temperature Changes

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ABSTRACT

In this paper the problem of the dynamics of boiler evaporator was presented. An expression for the heat flow rate from the furnace to the evaporator, as a function of change of the pressure in the boiler drum was derived from the conservation equations of mass and energy. First, the allowable rate of the steam temperature change in the boiler drum was determined with respect to the total stresses on the edge of the drum – down comer intersection using the TRD-301 boiler regulations. Later, after solving the differential equation, the temperature and pressure changes in the boiler drum as functions of time, have been determined. Knowing the pressure changes in the boiler drum, the heat flow rate, which shall be delivered to the boiler evaporator was determined. On the basis of the calculations of the combustion chamber, the changes of the fuel flow, assuring the pressure changes in the boiler evaporator most comparable to the assumed ones, were determined. The fuel consumption was also determined during the start up of the boiler for the case of the maximum allowable change of the temperature of the medium. The results specified in this paper can be used for designing boilers and for the automation of the boiler start up processes.

Keywords: Start up automation, Dynamics of boiler, Thermal stresses.

Nomenclature

c_m – specific heat of the metal, J/(kg·K)
h_w – water enthalpy, J/kg
h' – specific enthalpy of the fluid at the saturation temperature, J/kg
h'' – specific enthalpy of the steam at the saturation temperature, J/kg
m_m – mass of the metal, kg
$\dot{m}_{od}$ – blowdown water mass flow rate, kg/s
$\dot{m}_p$ – saturated steam mass flow rate, kg/s
$\dot{m}_w$ – water mass flow rate, kg/s
p_1 – water pressure at the start of the heating process, Pa
p_2 – steam pressure at the end of the heating process, Pa
p_n – saturated steam pressure, Pa
$\dot{Q}_k$ – heat flow rate from the furnace to the boiler evaporator, W
$\dot{Q}_{ev}$ – heat flow rate, W
t – time, s
T_m – metal temperature, K
T_n – saturation temperature, K

1. INTRODUCTION

The development of the wind turbine engineering, which can be characterised by large variations in the amount of delivered electricity over time, generated new problems regarding the regulation of the power engineering system [1]. At high and low wind speeds, the energy production falls rapidly, what means that the conventional heat or combined gas-steam blocks have to be activated very quickly. Steam boilers in blocks have to be designed in a way, which will allow for a start up of the block within several dozen minutes. The main components limiting the quick start-up of steam boilers are thick walled structural elements, in which thermal stresses can occur during the start up cycle.

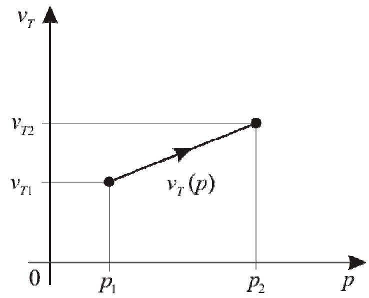


Figure 1. Heating rate of the pressure boiler element as a pressure function, determined in accordance to the TRD-301 regulations

To be able to ensure the appropriate lifetime and safety of the blocks adapted for a rapid start up, an accurate analysis of the flow-heat processes, together with the strength analysis is required. The start up and the shut down processes shall be conducted in a way, which will ensure that the stresses at the locations of stress concentration do not exceed the allowable values

German boiler regulations, TRD – 301 [2] and the European Standard, EN-12952-3 [3] allow to determine 2 allowable rates for heating the pressure element:

- v_{T1} at the pressure p_1 at the beginning of the start up process,
- v_{T2} at the pressure p_2 at the end of the start up process.

Heating rates for intermediate pressures shall be determined using the method of linear interpolation (Fig. 1). To be able to heat the boiler evaporator at the maximum allowable rate, heat flow rate $\dot{Q}_k$ should be delivered to the evaporator in the boiler combustion chamber (Fig. 2). The value of $\dot{Q}_k$ is a function of many parameters, but for the boiler of a specific construction, it depends mainly on the rate of changes of the saturation pressure dp_n/dt and the mass of the saturated steam mass flow rate.

2. PRESSURE AND TEMPERATURE CHANGES IN THE EVAPORATOR DURING THE BOILER HEATING PROCESS

In accordance to the TRD 301 regulations (Fig. 1), the changes of the heating rate $v_T = dT_n/dt$ in the pressure function are interpolated using a straight line.

$$\frac{dT_n}{dt} = \frac{p_2 v_{T1} - p_1 v_{T2}}{p_2 - p_1} + \frac{v_{T2} - v_{T1}}{p_2 - p_1} p_n(T_n) \qquad (1)$$

The water saturation pressure $p_n(T_n)$ from Eq. (1) can be expressed in the following way in the temperature function:

$$p_n = \exp(-19.710662 + 4.2367548 T_n) \qquad (2)$$

Where pressure p_n is expressed in bars, and temperature T_n is expressed in °C.

Eq. (1) has been integrated using the Runge-Kutty method of the 4-th order, at the following initial condition:

$$T_n\big|_{t=0} = T_n(p_1) \qquad (3)$$

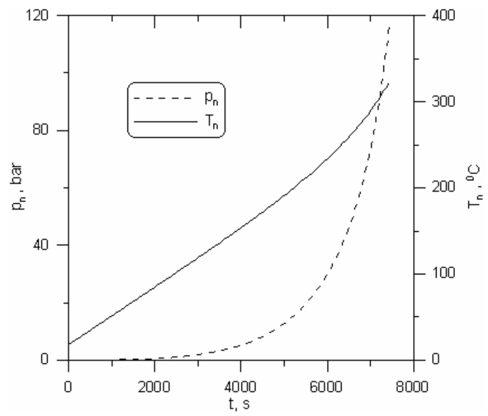


Figure 2. Temperature and saturation pressure changes in the boiler evaporator during the heating process

After determining, by solving the initial condition (1-3), the flow of the saturation temperature in a function of time, that is $T_n(t)$, the pressure changes $p_n(t)$ can be determined, e.g. from function (2). The pressure changes rate dp_n/dt and the saturation temperature changes rate dT_n/dt in a function of time are determined on the basis of the assumed run $v_T(p_n)$ (Fig. 1).

In this paper, the dynamics of the boiler evaporator of the OP-210M boiler will be analysed. OP-210M is a pulverized coal fired boiler with natural circulation. The $T_n(t)$ and $p_n(t)$ changes, determined for p_1 = 0 bar, v_{T1} = 2 K/min and p_2 = 108.7 bar, v_{T2} = 5 K/min are presented in Fig. 2.

After determining the $T_n(t)$ and dT_n/dt time changes, it is possible to determine the rate of pressure changes dp_n/dt using the following formula:

$$\frac{dp_n}{dt} = \frac{dp_n}{dT_n}\frac{dT_n}{dt} \qquad (4)$$

where the derivative dp_n/dT_n for the saturated steam can be determined by the differentiation of formula (2).

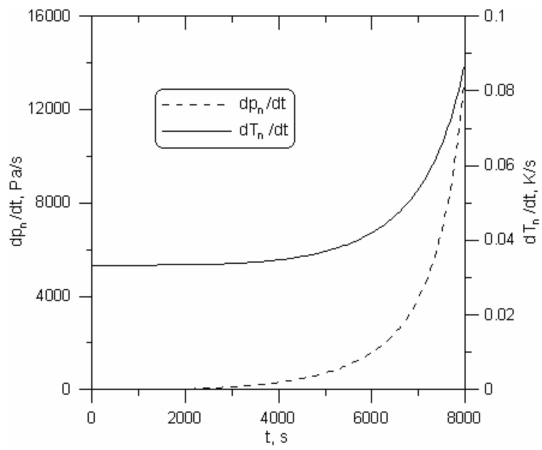


Figure 3. Rates of the pressure dp_n/dt and temperature dT_n/dt changes, during the evaporator heating process

The pressure dp_n/dT_n changes rate can also be calculated using an approximate formula:

$$\frac{dp_n}{dt} = \frac{p_n(t+\Delta t) - p_n(t-\Delta t)}{2\Delta t} \qquad (5)$$

where: Δt is the time step.

For the calculations, it can be assumed for example, that Δt = 1 s. Temperature dT_n/dt and pressure dp_n/dt changing rates are presented in Fig. 3.

3. MASS AND ENERGY BALANCE FOR THE BOILER EVAPORATOR

Modelling of the transient state effects, occurring in the boiler evaporator is usually done while assuming that it is an object having a concentrated mass and heat capacity [4-9]. The start point for the determination of the heat flow rate $\dot{Q}_k$, which assures that the evaporator is heated at the desired rate $v_T(t)$, are the mass and energy balance equations for the evaporator (Fig. 4):

$$\frac{d\left(V'\rho' + V''\rho''\right)}{d\tau} = \dot{m}_w - \dot{m}_p - \dot{m}_{od} \qquad (6)$$

$$\frac{d\left(V'\rho'u' + V''\rho''u'' + m_m c_m T_m\right)}{d\tau} = \dot{m}_w h_w - \dot{m}_p h'' - \dot{m}_{od} h_{od} + \dot{Q}_k \qquad (7)$$

After transforming Eqs. (6) and (7) we obtain:

$$\dot{Q}_k = \dot{m}_{od}\frac{\rho''}{\rho'-\rho''}\left(h''-h'\right) - \dot{m}_w\left(h_w - \frac{\rho' h' - \rho'' h''}{\rho'-\rho''}\right) + \dot{m}_p\frac{\rho'\left(h''-h'\right)}{\rho'-\rho''} + \left[V'\left(\rho'\frac{dh'}{dp}+\frac{\rho'\left(h''-h'\right)}{\rho'-\rho''}\frac{d\rho'}{dp}-1\right) + V''\left(\rho''\frac{dh''}{dp}+\frac{\rho'\left(h''-h'\right)}{\rho'-\rho''}\frac{d\rho''}{dp}-1\right)+m_m c_m\frac{dT_n}{dp_n}\right]\frac{dp_n}{dt} \quad (8)$$

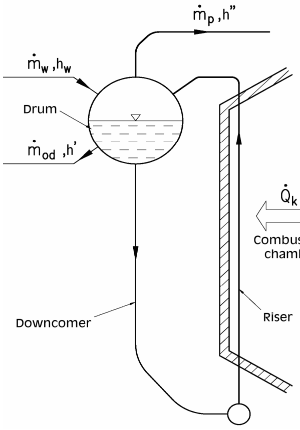


Figure 4. Diagram of the boiler evaporator

Formula (8) allows to determine the heat flow rate $\dot{Q}_k$, which should be delivered to the evaporator from the combustion chamber in order to ensure the assumed rate of the pressure change dp_n/dt. Changes of the $d\rho'/dp$ and $d\rho''/dp$ functions and the dh'/dp and dh''/dp functions, appearing in formula (8) are presented in Fig. 5 and Fig. 6.

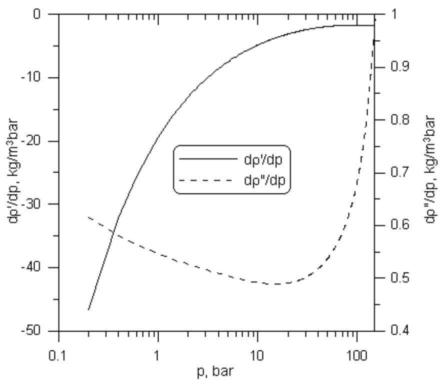


Figure 5. Changes of the $d\rho'/dp$ and $d\rho''/dp$ derivatives, as a function of pressure

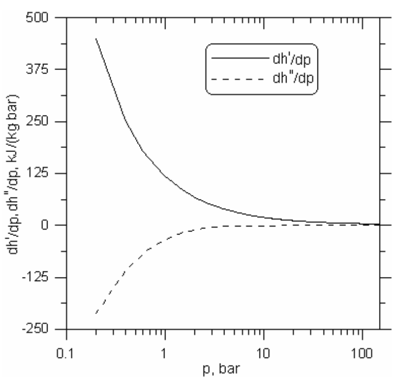


Figure 6. Changes of the dh'/dp and dh''/dp derivatives, as a function of pressure

The accuracy of in determining those functions is very important. The best way is to determine those functions through analytical differentiation of the $\rho'(p)$ and $\rho''(p)$ functions, obtained earlier using the least square methods on the basis of the property tables.

4. HEAT FLOW RATE ABSORBED IN COMBUSTION CHAMBER

From the conducted calculations, we can see that the heat flow rate $\dot{Q}_k$ delivered to the evaporator can be lowered significantly by reducing steam mass flow rate $\dot{m}_p$ delivered from the boiler drum. The minimum steam mass flow rate $\dot{m}_p$, which shall be produced in the boiler during the start up process can be determined from the condition, stating that the maximum allowable temperatures for the particular stages of the heater shall not be exceeded. The furnace oil mass flow rate $\dot{m}_{pal}$, delivered to the burners during the boiler start up process, which is necessary to assure the heat flow rate $\dot{Q}_k$, shall be determined on the basis of the calculations of the boiler combustion chamber.

The heat flow rate $\dot{Q}_{k,kom}$ absorbed by the walls of the boiler combustion chamber, expressed in W, can be calculated from the following formula:

$$\dot{Q}_{k,kom} = \dot{m}_{pal}W_d + \dot{m}_{pow}\, c_{p,pow}\Big|_0^{T_{pow}} T_{pow} - \dot{m}_{sp}\, c_{p,sp}\Big|_0^{T''_{sp}} T''_{sp} \quad (9)$$

where:

- $\dot{m}_{pal}$ – fuel mass flow rate, kg/s,
- W_d – fuel calorific value, J/kg,
- $\dot{m}_{pow}$ – air mass flow rate, kg/s,
- $c_{p,pow}\Big|_0^{T_{pow}}$ – average specific heat of air, at constant pressure and at temperature from 0 to T_{pow} [°C], J/(kg·K),
- T_{pow} – temperature of air delivered to the combustion chamber, °C,
- $\dot{m}_{sp}$ – flue gas mass flow rate, kg/s,
- $c_{p,sp}\Big|_0^{T''_{sp}}$ – average specific heat of flue gas, at constant pressure and at temperature from 0 to T''_{sp} [°C], J/(kg·K),
- T''_{sp} – flue gas temperature at the exit of the combustion chamber, °C.

The temperature of flue gases at the exit of the combustion chamber, T''_{sp} is calculated from the equation:

$$T''_{sp} = \frac{T_{ad}+273.15}{M\left(\dfrac{a_p}{Bo}\right)^{0.6}+1} - 273.15 \quad (10)$$

where: Bo is the *Boltzmann number,* determined by the formula:

$$Bo = \frac{\dot{m}_{sp}\bar{c}_{p,sp}}{\sigma\psi A_k T_{ad}^3} \quad (11)$$

and $\bar{c}_{p,sp}$ is the average specific heat of flue gases in J/(kg·K), at temperature ranging from T''_{sp} to T_{ad}

$$\overline{c}_{p,sp} = c_{p,sp}\Big|_{T''_{sp}-273.15}^{T_{ad}-273.15} . \tag{12}$$

Other symbols in Eqs. (10) and (11) mean:

a_p – emissivity of the combustion chamber,

M – parameter characterising the elevation at which the flame temperature in the combustion chamber is maximum,

A_k – area of the waterwalls of the boiler combustion chamber, m^2,

T_{ad} – theoretical (adiabatic) combustion temperature, $^{\circ}$C,

σ – Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ W/(m^2 K^4),

ψ – waterwall thermal effectiveness defined as the ratio of the heat flux absorbed by the combustion chamber wall to the incident heat flux.

The calculation of the heat flow rate $\dot{Q}_{k,kom}$ absorbed by the walls of the combustion chamber of the OP-210M boiler, have been calculated, using Eq. (9). In the function of the fuel mass flow rate $\dot{m}_{pal}$ and the excess air number λ; the calorific value of the oil was assumed to be W_d = 41060 kJ/kg. The results of the calculations are presented in Fig. 7.

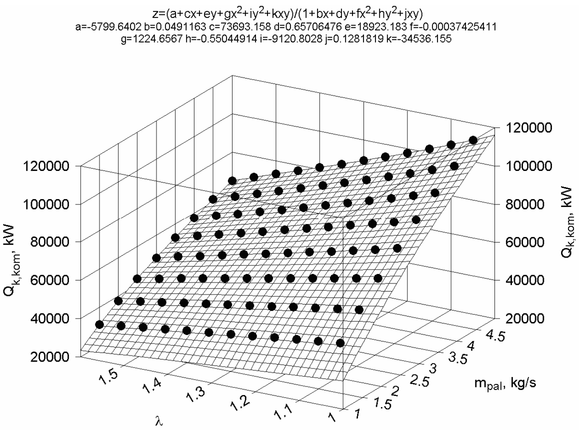


Figure 7. Heat flow rate $\dot{Q}_{k,kom}$, in kW, delivered to the evaporator of the OP-210M boiler, as a function of the fuel mass flow rate $\dot{m}_{pal}$ in kg/s and the excess air number λ

It was proven, that the increase of the excess air number λ at the assumed fuel mass flow rate $\dot{m}_{pal}$ leads to the reduction of the heat flux, delivered from flue gases in the combustion chamber to the evaporator. This is due to the fact, that the temperature of the flue gases in the combustion chamber T_{pl} was decreased significantly, what in turn, led to a significant decrease of the heat flow rate $\dot{Q}_{k,kom}$, as the heat flux is proportional to temperature difference between the flame temperature and the temperature of the chamber walls raised to the fourth power, that is $\left(T_{pl}^4 - T_{sc}^4\right)$.

When λ increases, $\dot{Q}_{k,kom}$ is reduced, and the heat flux absorbed by the steam superheaters increases. Increasing the fuel mass flow rate $\dot{m}_{pal}$ at the assumed excess air number λ, leads to the increase of the heat flow rate $\dot{Q}_{k,kom}$ absorbed by the walls of the combustion chamber.

Next, the fuel mass flow rate $\dot{m}_{pal}$ delivered to the boiler during the start-up (heating) process was determined. After determining from Eq. (8) the heat flow rate $\dot{Q}_k(t)$, the non-linear algebraic equation

$$\dot{Q}_k(t) = \dot{Q}_{k,kom}\left(\dot{m}_{pal}, \lambda\right) \tag{13}$$

is solved.

The fuel mass flow rate, at the assumed value of the excess air number λ, is determined from Eq. (13). The mass of the oil fuel used for the boiler start up process from time t = 0 to $t = t_k$ can be calculated using the formula:

$$m_{pal} = \int_0^{t_k} \dot{m}_{pal} dt . \tag{14}$$

The integral (14) was calculated numerically, using the trapezoidal rule for integration.

5. CALCULATION RESULTS

The calculations have been conducted for the evaporator of the OP-210M boiler, for the pressure change rate dp_n/dt presented in Fig. 3. The temperature of the feed water T_w during the evaporator heating process is at a given moment, lower by 10 K than the saturation temperature T_n. The temperature of the feed water T_w, the saturation temperature T_n and the pressure in the evaporator p_n are presented in Fig. 8.

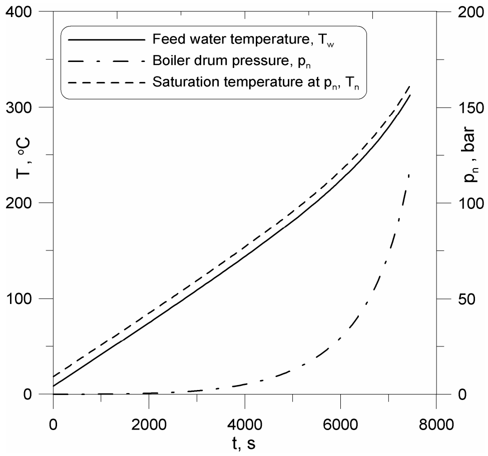


Figure 8. Temperature of the feed water T_w, saturation temperature T_n and pressure in the evaporator p_n, during the boiler start up

The calculations have been performed for the following data: $\dot{m}_{ods}$ = 0.51 kg/s, $\dot{m}_w$ = 17.1 kg/s, $\dot{m}_p$ = 16.57 kg/s, m_m = 171900 kg, c_m = 511 J/(kg·K), V' = 43.6 m^3 and V'' = 15.9 m^3. The results of the $\dot{Q}_k$ calculations for various saturated steam mass flow rates are presented in Fig. 9a and Fig. 9b.

After analysing the results shown in Fig. 9a we can see, that if the steam mass flow rate from the evaporator $\dot{m}_p$ is zero, then the heat flow rate $\dot{Q}_k$ transferred to the evaporator increases. In this case, all heat absorbed from the combustion chamber is mainly used for heating water contained in the boiler evaporator. This is due to the increase of the specific heat of water c_w, which increases with the pressure raise, for example at the pressure p_n = 1 MPa water specific heat is c_w = 4405 J/(kg·K) while at the pressure p_n = 10 MPa specific heat is c_w = 6127 J/(kg·K). Moreover, at the end of the start up process a large increase of the rate of temperature changes in the evaporator occurs (Fig. 3), what requires increased heat flow rate $\dot{Q}_k$ to be transferred to the evaporator.

For larger steam flow rates $\dot{m}_p$ the heat flow rate $\dot{Q}_k$, which should be delivered from the combustion chamber to the evaporator, increases significantly, because there is a large power consumption for water evaporation (Fig. 9). However, for the evaporator capacities greater than $90{\cdot}10^3$ kg/h (Fig. 9b) the reduction of the heat flow rate $\dot{Q}_k$ occurs during the end phase of the heating process, despite the increase of the rate of evaporator heating (Fig. 3).

a)

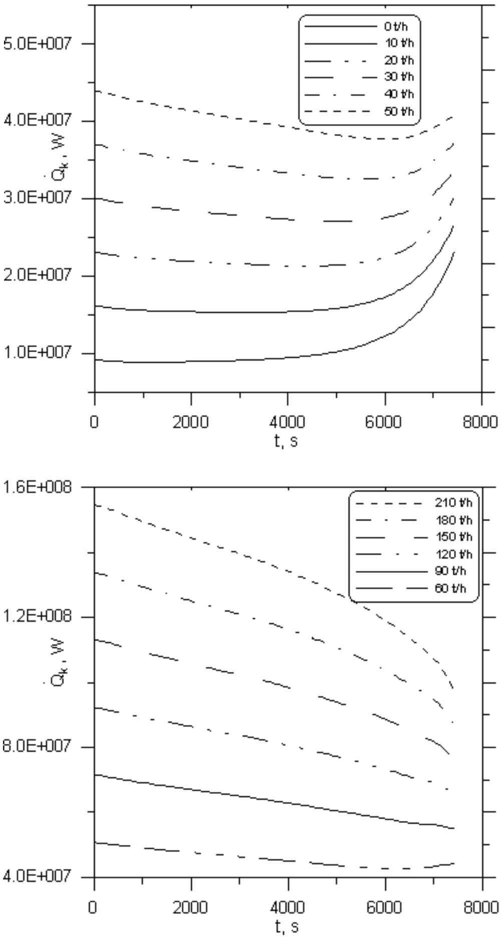


Figure 9. Heat flow rate $\dot{Q}_k$ transferred to the evaporator of the boiler in the combustion chamber for various steam mass flow rates $\dot{m}_p$ in t/h (in 10^3 kg/h)

Fuel mass flow rate $\dot{m}_{pal}$ during the start up of the OP-210M boiler obtained from Eq. (13) for the excess air number $\lambda = 1.1$ are shown in Figs. 10a and 10b.

The calculations are carried out for various steam flow rates $\dot{m}_p$ generated in the evaporator.

The results of the calculations of the fuel consumption m_{pal} corresponding to the fuel mass flow rates $\dot{m}_{pal}$ shown in Fig. 10, are presented in Fig. 11.

a)

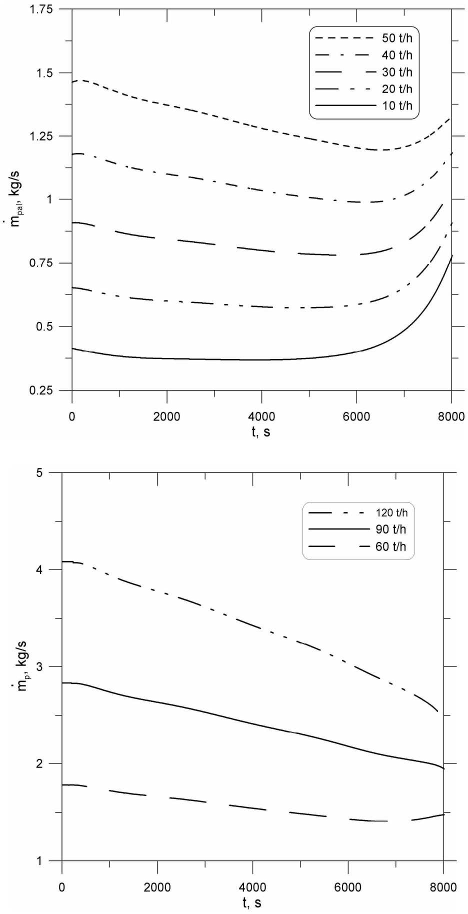
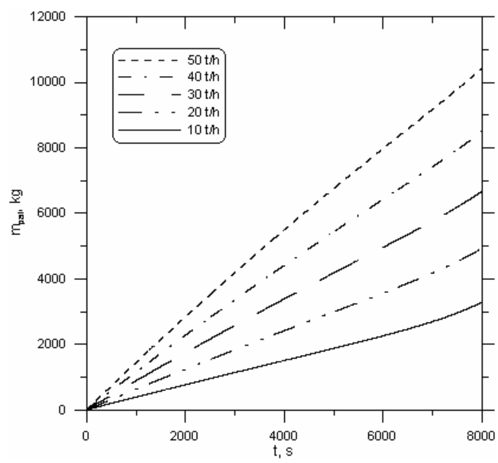


Figure 10. Fuel mass flow rate $\dot{m}_{pal}$ in kg/s, during the start up of the OP-210M boiler for various mass flow rates of steam $\dot{m}_p$ in t/h (in 10^3 kg/h) generated in the boiler evaporator

This is due to decreasing the water evaporation heat, $r = h'' - h'$ when the pressure in the evaporator increases. For example at the pressure p_n = 1 MPa, water evaporation heat is r = 2014.4 J/(kg·K) while at the pressure p_n = 10 MPa, the evaporation heat is reduced to r = 1317.7 J/(kg·K).

a)



b)

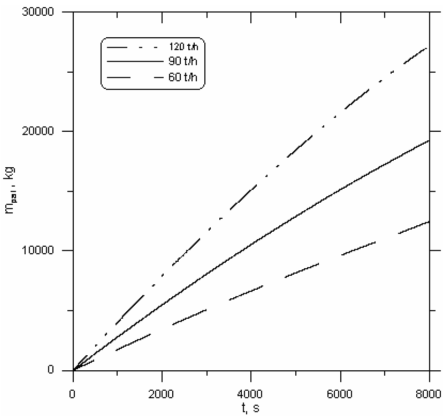


Figure 11. Fuel consumption m_{pal}, in kg, during the start up of the OP-210M boiler, for various steam mass flow rates $\dot{m}_p$ in t/h (in 10^3 kg/h) produced in the boiler evaporator

From the analysis of the results presented in Fig. 11, we can see, that the fuel consumption depends mainly on the steam mass flow rate $\dot{m}_p$ generated in the boiler evaporator. During the start up process, lasting 8000 s, the fuel consumption varies from m_{pal} = 3308 kg, at the steam mass flow rate $\dot{m}_{pal} = 10 \cdot 10^3$ kg/h, to m_{pal} = 27207 kg, at the steam mass flow $\dot{m}_{pal} = 120 \cdot 10^3$ kg/h. Due to the high price of the oil fuel, the boiler start up process should be conducted at the minimum steam mass flow rate $\dot{m}_p$, ensuring the appropriate cooling of the superheater tubes.

6. CONCLUSIONS

The model of the dynamics of the boiler evaporator, presented in this paper, can be used for the determination of the heat flow rate, transferred from the flue gases in the combustion chamber to the boiler evaporator, which is required to warm up the boiler evaporator at the assumed rate of medium temperature change. The fuel mass flow rate $\dot{m}_{pal}$ which ensures the prescribed rates of the medium temperature changes in the evaporator is determined from the combustion chamber calculations. Fuel consumption during the boiler start up process, necessary for heating the boiler evaporator from the initial to the design temperature has been determined. The heating of the boiler drum is conducted at the maximum allowable rate with respect to the stresses, caused by pressure and thermal load, which occur at the boiler drum-downcomer junction. In order to limit the consumption of the expensive oil during the boiler start up, the process should be conducted at the minimum steam mass flow rate ensuring the appropriate cooling of the superheaters. The excess air number should be kept at the minimum value. The results of the analysis conducted in the paper can be used to formulate the optimum procedure for the boiler start up process.

7. REFERENCES:

[1] Staff Report, **Dealing with cycling: TRD 301 and the Euro Norm compared**, Modern Power Systems, Vol 27, No. 5, 2007, pp. 33-38.

[2] TRD 301, **Zylinderschalen unter innerem Überdruck**, Technische Regeln für Dampfkessel (TRD), Köln – Berlin: Heymanns Beuth, 2001.

[3] European Standard, EN 12952-3, **Water-tube boilers and auxiliary installations** – Part 3: Design and calculation for pressure parts, CEN – European Committee for Standarization, rue de Stassart 36, B-1050 Brussels, 25. July 2001.

[4] P. Profos, **Die Regelung von Dampfanlagen**, Berlin: Springer, 1962.

[5] M.A. Styrykovich, K.J. Katkovskaia, E.P. Sierov, **Steam Boilers**, Moscow, Gosenergoizdat, 1959 (in Russian).

[6] E.P. Sierov, B.P. Korolkov, **Dynamics of Steam Boilers**, Second Edition, Moscow, Energia, 1981 (in Russian).