Unlinearity of the Pressure Characteristics in Steam Firetube Boilers

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Abstract – **In the paper is investigated the unlinearity of the pressure statics and dynamics in steam firetube boilers. It is obtained and analysed transfer function coefficients of the pressure. These coefficients are changed depending on operating parameters in wide interval. The obtained results are applied for synthesis of pressure control systems adaptive towards operating conditions.**

Keywords – **Firetube Boiler, Pressure Unlinearity**

I. Introduction

The dynamic and static properties of the pressure in the steam boilers are described by unlinear ordinary differential equations. These equations can linearized in surrounding domain around starting stationary state. It has to beat in mind that linearized differential equations coefficients are functions of the parameters characterized the current state – working pressure and steam load.

The firetube boilers have a design by which all the water-steam part is lockated on one the same volume. This fact simplifies the pressure mathematical model. The pressure dynamic of the two-phases mixture in water-steam boiler tract is described by following linearized differential equation [1]:

$$T_0 \cdot \frac{d\varphi_p}{dt} + C_p \cdot \varphi_p = C_1 \cdot \varphi_{M1} - C_2 \cdot \varphi_{M2} + C_{\Theta 1} \cdot \varphi_{\Theta 1} + \varphi_Q \qquad (1)$$

where:

- φ_{M1}, φ_{M2} and $\varphi_{\theta 1}$ are undimensional input parameters – feedwater mass flow, steam mass flow and feed water temperature;
- C_1, C_2 and $C_{\theta 1}$ are undimensional transfer coefficients of relevant input parameters (gains of relevant dynamic channels);
- φ_Q and φ_P are respective undimensional control action (input heat power) and undimensional controlled output variable (steam pressure in the boiler);
- T_0 [s] is the pressure time constant;
- Cp [-] is the internal pressure self-balancing coefficient of the two-phases mixture.

Assuming zero initial conditions, and taking the Laplace transform of Eq. 1 we obtain the transfer function, described pressure dynamic without steam consumer influence. Transfer function Eq. 2 refers to dynamic channel “heat power-steam pressure”. The rest transfer functions have the same denumerator but different numerators.

$$W(s) = \frac{1}{T_0 s + C_P} \qquad (2)$$

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II. Steam Firetube Boiler Pressure Dynamic Model.

Based on Eq. 1 and 2 the dynamic model of the main controlled parameter in steam firetube boiler – pressure is represented by block diagram shown in figure 1.

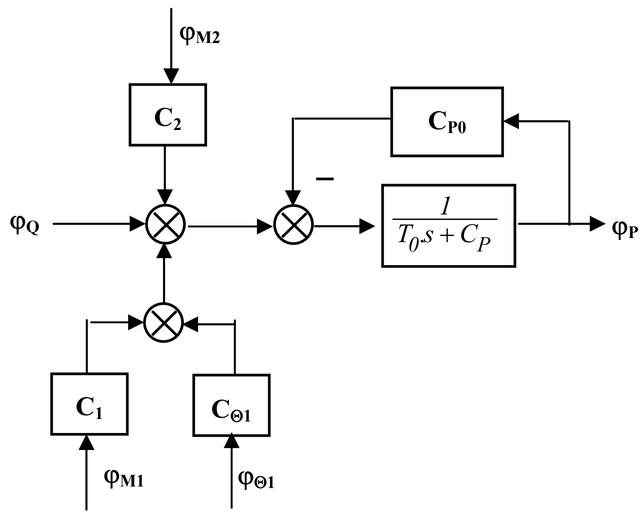

Fig. 1. Pressure model – block diagram

In the model the consumer influence is taken into consideration by including of additional structural block enveloped the transfer function from Eq. 2. This block makes negative feedback of transfer function (2) and its transfer function is:

$$W_{FB}(s) = C_{P0} \qquad (3)$$

where: Cpo is called external pressure self-balancing coefficient.

The equivalent transfer function of water-steam mixture with output signal - pressure is:

$$\Phi(s) = \frac{K}{Ts + 1} \qquad (4)$$

where:

$$K = \frac{1}{C_P + C_{P0}} \qquad (5)$$

$$T = \frac{T_0}{C_P + C_{P0}} \ \text{[s]} \qquad (6)$$

The dynamic properties of the four channels are characterized with the same time constant T (Eq. 6), but every channel has a different gain, wich is obtained from the coefficient K by following way:

⇒ Dynamic channel “heat power - pressure” (“Q-P”)

$$K_{Q\text{-}P}=K \tag{7}$$

⇒ Dynamic channel “steam mass flow - pressure” (“M2-P”)

$$K_{M2\text{-}P}=C_2.K \tag{8}$$

⇒ Dynamic channel “feed water mass flow - pressure” (“M1-P”)

$$K_{M1\text{-}P}=C_1.K \tag{9}$$

⇒ Dynamic channel “feed water temperature - pressure” (“θ1-P”)

$$K_{\theta 1\text{-}P}=C_{\theta 1}.K \tag{10}$$

III. Results for Pressure model of Firetube Boiler with Steam Capacity 12 t/h.

A. Basic data needed to obtain pressure dynamics of the steam boiler with capacity 12 t/h.

The steam firetube boilers with capacity 12 t/h (3,333 kg/s) are the most powerful representative of firetube design produced in Bulgaria. These boilers are used in industrial companies as sources of saturated steam with pressure up to 13 bar basically for technological designation and heating during the wintertime. Special feature for their working conditions is often and accidentally load change caused pressure change. The most probably intervals of operating parameter changes are: for pressure $P_0=7\div 13$ bar and for relative load $Q_0/Qn=0.5\div 1.0$.

For the boiler with steam capacity 12 t/h are presented the results concerning time constant T_0 – in table 1, about external pressure self-balancing coefficient Cpo – in table 2, and about the rest model coefficients from figure 1 – in table 3.

TABLE 1
Time constant values T_0 [s] for boiler with steam capacity 12 t/h

Po [bar]	Qo/Qn [-]					
	0,5	0,6	0,7	0,8	0,9	1,0
7	520	434	372	325	289	260
8	541	451	386	338	300	270
9	559	466	399	349	311	279
10	573	478	409	358	318	287
11	588	490	420	367	327	294
12	603	502	431	377	335	301
13	616	513	440	385	342	308

The time constant T_0 characterizes the pressure inertia which is due to accumulation of heat and mass inside the steam-water mixture. Because of the time constant depends from the pressure as well as from the relative boiler power:

$$T_0 = f\left(P_0, \frac{Q_0}{Qn}\right) \tag{11}$$

TABLE 2
Coefficient Cpo [-] values for the boiler with steam capacity 12 t/h

Po [bar]	Qo/Qn [-]					
	0,5	0,6	0,7	0,8	0,9	1,0
7	1,183	0,826	0,611	0,471	0,376	0,307
8	1,532	1,068	0,789	0,607	0,483	0,394
9	1,927	1,342	0,990	0,761	0,604	0,492
10	2,365	1,647	1,213	0,932	0,739	0,601
11	2,851	1,984	1,461	1,122	0,889	0,722
12	3,383	2,353	1,732	1,329	1,052	0,855
13	3,959	2,753	2,026	1,554	1,230	1,0

The coefficient Cpo depends also from the working pressure as well as from the relative heat power of the boiler:

$$C_{P0} = f\left(P_0, \frac{Q_0}{Qn}\right) \tag{12}$$

TABLE 3
Pressure model coefficients values for boiler with steam capacity 12 t/h

Po [bar]	Qo/Qn =0,5 ÷ 1,0			
	Cp	C_1	C_2	$C_{\Theta 1}$
7	0,0148	-0,168	-0,832	0,097
8	0,0141	-0,177	-0,823	0,097
9	0,0137	-0,185	-0,815	0,097
10	0,0129	-0,192	-0,807	0,097
11	0,0125	-0,199	-0,800	0,097
12	0,0118	-0,206	-0,794	0,097
13	0,0117	-0,212	-0,788	0,097

The coefficients Cp, C_1 and C_2 depend only from the working pressure:

$$C_P, C_1, C_2 = f(P_0) \tag{13}$$

The expressions (11) and (12), characterized the pressure inertia, are presented graphically in fig. 2 and fig. 3.

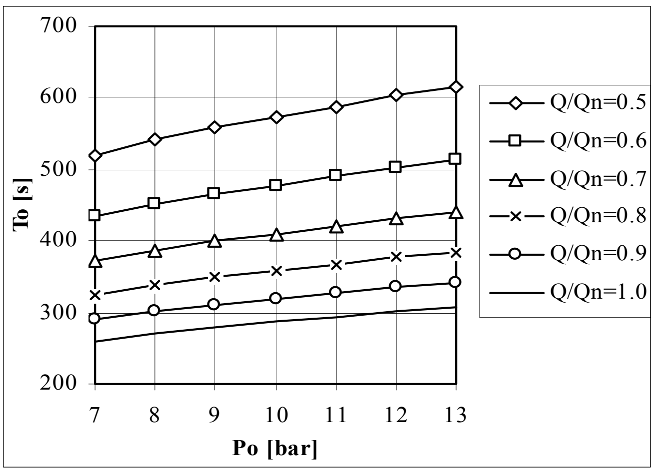

Fig. 2. Time constant T_0 as function from operating parameters

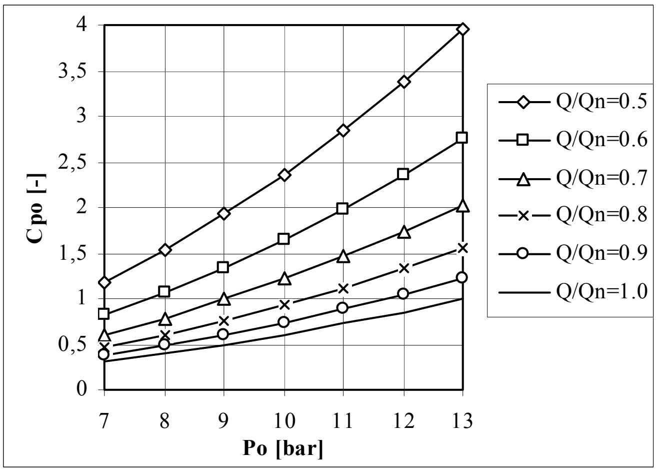

Fig. 3. Relationship of coefficient Cpo from operating parameters

The coefficient $C_{\theta 1}$, which determines the feed water temperature influence to the pressure, is independt from the initial stationary state parameters:

$$C_{\theta 1} = in\,var\left(P_0, \frac{Q_0}{Qn}\right) \tag{14}$$

B. Pressure dynamics with taking into consideration of steam consumers.

The pressure inertia of all the discussed channels is characterized with the identical time constant – the equivalent time constant T. It is calculated by Eq. 5 with the data from tables 1, 2, 3 and shown graphically in fig. 4.

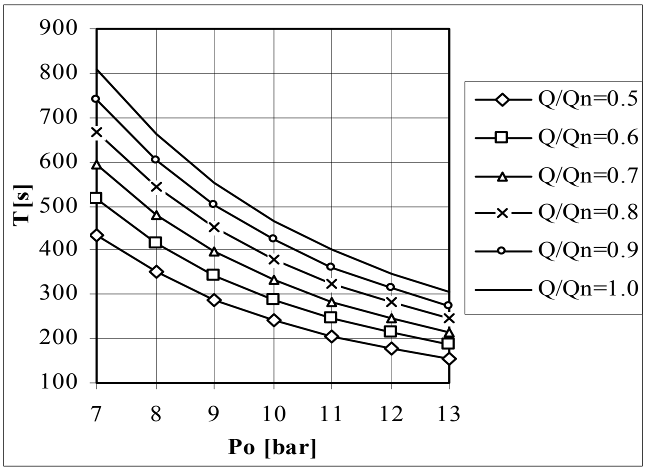

Fig. 4. Equivalent pressure time constant T of boiler with steam capacity 12 t/h and consumers.

From fig. 4. we can see that the dynamic properties of the steam pressure in the boiler are changed in wide intervals.

The time constant T_0 does not have constant values in the defined intervals of parameters change (fig. 2). The reason is an accumulation of different quantity of heat and mass in the boiler volume by different stationary pressures (P_0). Because the steam-phase part decreases if the pressure increases (the water level in the boiler is constant) then the relationship between the time constant T_0 and the steam pressure P_0 diverts from the linear relation.

When the boiler works commonly with steam consumers, they bring in its equivalent time constant T a significant unlinearity (fig. 4). The reason can be explained with the character of the external pressure self-balancing coefficient Cpo (table 2 and fig. 3). As result of it, the four dynamic channels have better dynamic properties (they have more quickness) in case of higher working pressure and bigger steam load.

C. Static properties of the steam pressure in the boiler.

The influence of the four input forces on the steam pressure when the boiler is in a stationary state, is defined from the respective transfer coefficients (channel gains), which can be calculated using Eq. 7, 8, 9, 10.

The relationship of the "power-pressure" channel gain – Kq-p from the operating parameters is presented graphically in fig. 5.

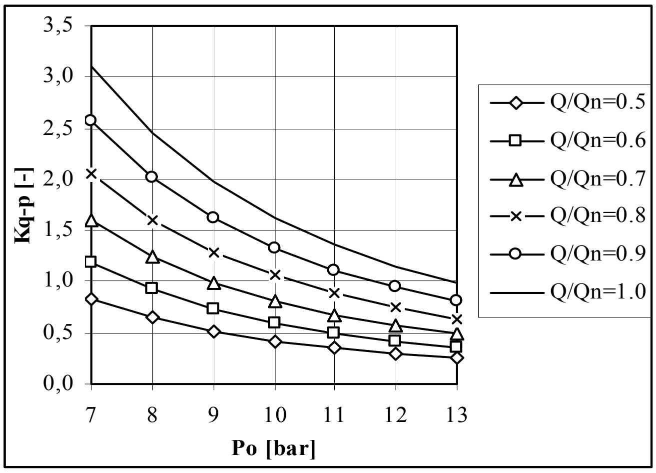

Fig. 5. Gain of the dynamic channel "power-pressure"

The coefficient Kq-p is actually the gain of the control action channel. It appears the pressure sensibility towards the control action. From the results, which are presented in fig. 5, may be see that the pressure becomes more sensitive towards the control action if the working pressure is lower and the power is higher.

In fig. 6 is shown the relation of the gain of general disturbance channel "steam mass flow – steam pressure" – K_{M2-P} from the operating parameters. The gain K_{M2-P} is calculated by Eq. 8 and nevertheless the coefficient C_2 depends only from the pressure then the general disturbance gain depends from the pressure as well as from the heat power.

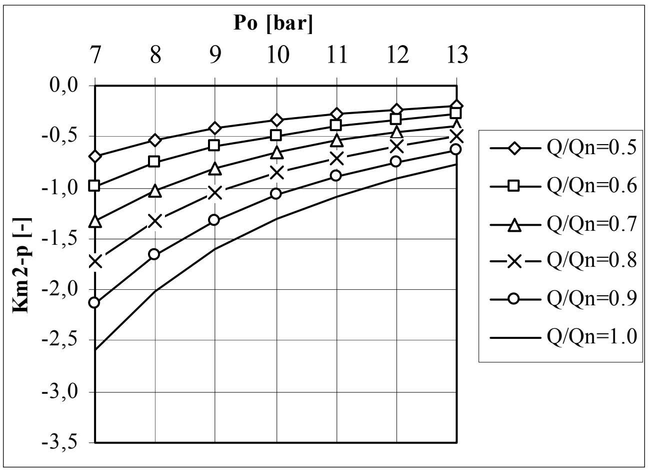

Fig. 6. Gain of the general disturbance channel "steam mass flow-pressure"

From the results for the gain $K_{M2\text{-}P}$, presented in fig. 6, can be done the identical conclusion as that one about the gain Kq-p, - namely the pressure sensitivity along the general disturbance channel becomes bigger if the pressure is in the low range and the power is in the upper range. The different between control action channel and general disturbance channel consists in: firstly the influence direction of the input action over the pressure – the general disturbance action has an opposite influence direction over the pressure and second the less values of the general disturbance channel gain as totally.

Whereas the unlinearity of control action channel is important for the optimal parameters setting of the pressure controller, the general disturbance channel unlinearity has a practical importance in case of stepwise shutting off of the steam load.

In table 4 is presented the pressure progress in case of steam load shut down with absolute amplitude ΔM_2 = - 0,6 t/h from four initial states. These states are combinations of the limit values of the two operating parameters – relative power (0.5 and 1.0) and steam pressure (7 bar and 13 bar).

TABLE 4

EXAMPLE DEMONSTRATED THE UNLINEARITY OF DYNAMIC CHANNEL "STEAM MASS FLOW-PRESSURE"

Initial state	Input- Steam flow		Channel gain	Output- Steam pressure	
Q/Qn; Po	Abs.	Rel.	$K_{M2\text{-}P}$	Rel.	Abs.
0,5; 7bar	-0,6 t/h	-0,10	-0,690	0,0690	0,483 bar
1,0; 7bar	-0,6 t/h	-0,05	-2,587	0,1293	0,905 bar
0,5; 13bar	-0,6 t/h	-0,10	-0,197	0,0197	0,256 bar
1,0; 13bar	-0,6 t/h	-0,05	-0,788	0,0394	0,512 bar

Regarding presented in table 4 results if the initial pressure is in vicinity of maximal working pressure (13 bar), then the same steam mass flow change causes more pressure change in case of boiler operation with more relative power. It is very important if the boiler shuts down its steam load from initial state identical with nominal state (relative power 1.0 and steam pressure 13 bar). Then the steam pressure increases and in presented example its absolute stationary increasing is 0.512 bar. When the boiler shuts off steam load more then 0.6 t/h from nominal initial state, the absolute pressure increment will be more considerable, and the pressure control system should have the needed quickness to recover the pressure. In an opposite case the protection system will activate and stop the boiler by reason of "unallowable high pressure".

IV. CONCLUSION

The energy plants are characterized with an unlinearity of their control variables from the operating parameters. The industrial steam boiler with firetube design work on conditions of often changes of the steam load and the steam pressure in wide ranges. The unlinearity of their properties in wide ranges should take into consideration when is carried out the synthesis of the control system.

The control systems, which are created with taking into consideration of the properties unlinearity, get possession of adaptivity. As a result they have the needed dynamic exactness in case of transients, therefore they work with maximum efficiency in case of such transient situation.

REFERENCES

[1] Chermak I., V. Peterka, I. Zavorka. Dinamika reguliruemih sistem v teploenergetike i himii, Mir, M., 1972.