Pressure Self-balancing in Steam Firetube Boilers

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Abstract – **In the paper is investigated an important property of the main process parameter in steam firetube boilers – self-balancing of the steam pressure. Its taking into consideration in the pressure model is done through initiating of external pressure self-balancing coefficient, for which is found theoretical formula.**

Keywords – **Firetube boiler, pressure self-balancing coefficient.**

I. INTRODUCTION

The transfer function of the dynamic channel "input heat power-steam pressure in the boiler" has the form [1]:

$$W_{Q-P}(s) = \frac{1}{T_0 s + C_P} \tag{1}$$

where:

- T_0 [s] is the dynamic channel time constant;
- Cp [-] is the pressure self-balancing coefficient.

That coefficient can calculate using the expression:

$$C_P = \left[\left(\frac{\partial i''}{\partial p}\right)_0 - \left(\frac{\partial i_{fw}}{\partial p}\right)_0\right]\frac{M_0 P_0}{Q_0} \tag{2}$$

where:

- M_0, P_0 and Q_0 are mass flow, pressure and heat power of the boiler, such as "$_0$" subscript represents the stationary regime, for which is made the calculation;
- i'' and i_{fw} are enthalpy of steam and feed water.

The coefficient Cp characterizes the ability for self-balancing of the pressure in the boiler without taking into consideration the steam consumers influence. Because of it is called internal pressure self-balancing coefficient. This coefficient has values aproximaly to zero in pressure operating range of the industrial steam boilers.

Without taking into consideration of the steam consumers influence on the steam pressure in the boiler, the dynamic channel "input heat power-steam pressure" does not have the property self-balancing of the pressure.

II. EXTERNAL SELF-BALANCING PRESSURE COEFFICIENT

When steam firetube boiler works commonly with steam consumers, every pressure changing by reason of input heat power changing has back action. The operation mode of this feedback is: for example if the steam pressure increases, the steam mass flow to consumers increases too (the consumers hold their configuration) and more steam flow brings out of the boiler more heat power, which compensates a part of increased input power. This back action can be taken into consideration through including a hard feedback in the model with transfer coefficient *Cpo*, called external pressure self-balancing coefficient:

$$C_{PO} = \frac{\Delta Q / Q_0}{\Delta P / P_0} \tag{3}$$

where Q_0 is the heat power and P_0 is the pressure, both in starting stationary regime; with "Δ" is symbolized their incrementings.

Regarding the described action mode, the coefficient *Cpo* can be written in form:

$$C_{PO} = \frac{\Delta M / M_0}{\Delta P / P_0}\frac{\Delta Q / Q_0}{\Delta M / M_0} = C_{P1} . C_{P2} \tag{4}$$

The first multiplicatived term (C_{P1}) which presents the mass flow changing caused from steam pressure changing, can be obtained from the mass flow expression:

$$M_0 = K_S\sqrt{\rho_0'' P_0} \tag{5}$$

where:

- M_0 [kg/s] is steam mass flow to consumers in starting stationary regime;
- K_S [m^2] is equivalent cross-section area of the steam consumers;
- ρ_0'' [kg/m^3] is steam density in saturation state in starting stationary regime.

Incrementing the variables in Eq. (5) leads to a new stationary regime, where it has the form:

$$M_0 + \Delta M = K_S\sqrt{(\rho_0'' + \Delta\rho'')(P_0 + \Delta P)} \tag{6}$$

After subtraction of Eq. (5) from Eq. (6) and ignoring the high-order mathematical terms we obtain:

$$2\frac{M_0}{K_S^2}.\Delta M = \rho_0''.\Delta P + P_0.\Delta\rho'' \tag{7}$$

from which equation by dividing of ΔP we obtain the dimensional coefficient:

$$\frac{\Delta M}{\Delta P} = \frac{K_S^2}{2.M_0}\left[\rho_0'' + P_0\left(\frac{\partial\rho''}{\partial P}\right)_0\right] \tag{8}$$

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To do Eq. 8 undimensional we have to multiply it by P_0/M_0. As result we obtain the first searched coefficient:

$$C_{P1} = \frac{\Delta M / M_0}{\Delta P / P_0} = \frac{P_0 K_S^2}{2 M_0^2}\left[\rho_0'' + P_0\left(\frac{\partial \rho''}{\partial P}\right)_0\right] \qquad (9)$$

The second coefficient *(C_{P2})* indicates what part of input heat power is used to compensate the increased steam mass flow. It can be obtained from the energy balance expression:

$$\eta Q_0 = M_0\left(i_0'' - i_{fw}\right) \qquad (10)$$

where: η [-] is the boiler efficiency; i_0'' [kJ/kg] is steam enthalpy in saturation state; i_{fw}[kJ/kg] is feed water enthalpy.

The procedure for finding the coefficient C_{P2} is the same as for the coefficient C_{P1}. Equation 10, written in the new stationary regime (after incrementing of the variables) is:

$$\eta\left(Q + \Delta Q\right) = \left(M_0 + \Delta M\right)\left(i_0'' + \Delta i'' - i_{fw}\right) \qquad (11)$$

The incremental equation, obtained after subtraction of Eq. 10 from Eq. 11 and ignoring high-order terms has the form:

$$\eta \Delta Q = \left(i_0'' - i_{fw}\right)\Delta M + M_0 \Delta i'' \qquad (12)$$

from which through dividing by $\eta.\Delta M$ we obtain the dimensional coefficient:

$$\frac{\Delta Q}{\Delta M} = \frac{Q_0}{M_0} + \frac{M_0}{\eta}\left(\frac{\partial i}{\partial P}\right)_0 \frac{\Delta P}{\Delta M} \qquad (13)$$

By obtaining of Eq. 13 is taken into consideration that:

$$\frac{i_0'' - i_{fw}}{\eta} = \frac{Q_0}{M_0} \qquad (14)$$

If we substitute $\Delta P/\Delta M$ from Eq. 8 in Eq. 13, then Eq. 13 has the form:

$$\frac{\Delta Q}{\Delta M} = \frac{Q_0}{M_0} + \frac{2 M_0^2}{\eta K_S^2}\left(\frac{\partial i}{\partial P}\right)_0 \frac{1}{\rho_0'' + P_0\left(\frac{\partial \rho''}{\partial P}\right)_0} \qquad (15)$$

from which after undimensioning (multiplying the both sides by M_0/Q_0) we obtain for C_{P2} the expression:

$$C_{P2} = \frac{\Delta Q / Q_0}{\Delta M / M_0} = 1 + \left(\frac{\partial i''}{\partial P}\right)_0 \frac{2 M_0^3}{\eta Q_0 K_S^2\left[\rho_0'' + P_0\left(\frac{\partial \rho''}{\partial P}\right)_0\right]} \qquad (16)$$

Regarding Eq. (4) finally we obtain for C_{P0} :

$$C_{P0} = \frac{P_0}{2}\left(\frac{K_S}{M_0}\right)^2\left[\rho_0'' + P_0\left(\frac{\partial \rho''}{\partial P}\right)_0\right] + \frac{P_0}{\eta}\frac{M_0}{Q_0}\left(\frac{\partial i''}{\partial P}\right)_0 \qquad (17)$$

III. Results concerning external pressure self-balancing coefficient.

Regarding Eq. 17 the external pressure self-balancing coefficient depends from:

- operational boiler parameters in starting stationary regime:
  - boiler heat power;
  - steam mass flow to consumers;
  - steam pressure in the boiler;
  - boiler efficiency.
- hydroresistans of the consumers, defined as equivalent cross-section area;
- thermodynamical properties of saturated steam and their changes by variation in the neighborhood of starting stationary state.

In table 1 are presented the results for boiler with steam capacity 12 t/h by changing its relative power between 0.5 and 1.0 and its operational pressure between 4 and 13 bar.

TABLE 1
External pressure self-balancing coefficient C_{P0}

Q/Qn [-] P_o [bar] ↓	0.5	0.6	0.7	0.8	0.9	1
4	0,407	0,288	0,216	0,169	0,137	0,114
5	0,621	0,436	0,324	0,252	0,202	0,167
6	0,879	0,615	0,456	0,353	0,282	0,231
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

IV. Conclusion.

The coefficient Cpo increases if the pressure increases, i.e. the property self-balancing of the pressure is more expressive by higher pressures in the boiler. It is obliged to the unlinear relationship between the steam mass flow and the pressure .

If the pressure is constant but the power increases the coefficient Cpo decreases. The explain is: from the fixed starting pressure, the steam mass flow changings are limited from the consumers, and corresponding bring out power is limited too, which compensates relative less heat power by bigger stationary boiler power, i.e. Cpo becomes less.

The obtained relationship and results for the coefficient Cpo give a possibility to have a mathematical model of the dynamic channel in real cases (with steam consumers) when the pressure and the power are changed in all operation ranges.

References

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