THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAŢI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING,
ISSN 1221- 4566, 2012

DYNAMIC MODEL OF A STEAM BOILER FURNACE

Ion V. Ion, Florin Popescu

"Dunărea de Jos" University of Galaţi, Thermal Systems and Environmental Engineering
ion.ion@ugal.ro

ABSTRACT

Variation in fuel flow rate and load demand of a steam boiler leads to variation of gas-dynamic characteristics of furnace. Based on the furnace dynamic model, the furnace temperature and pressure and flue gas mass flow rate are predicted when variation in fuel flow rate occurs. The simulated variation of furnace pressure and temperature is higher for natural gas fired boiler than coal fired boiler due to higher combustion reaction rate of natural gas.

KEYWORDS: boiler furnace, mathematical model, air-gas circuit control system.

1. INTRODUCTION

A power utility boiler has an unsteady state operation due to the variation in power demand. During the unsteady operation of the boiler steam a pulsatory flow of the flue gas is created. This pulsatory flow allows the occurrence of certain pressure rhythmic variations inside the furnace leading to negative effects upon the air-flue gas circuit safety and efficiency in operation.

Pressure rhythmic variations cause fluctuations of combustion, affecting its efficiency and increasing air pollution, and alternative mechanical stress upon the furnace walls (in case it has been equipped with membrane walls) which may reduce in time the outfit's durability and even destroy it.

The causes of the pressure rhythmic variations inside the furnace may fall into two distinct categories [11]:

- *external causes:*

- pulsatory inlet flow of the fuel into the furnace when burning solid fuel, caused by variations of the fuel heating value and malfunction of the coal mills;
- pulsatory inlet flow of the air into furnace, caused by fluctuations of the fuel flow;
- lack of the synchronization between the air blowers and exhausters when fluctuations of the flow rate air supply occurs.

- *internal causes:*

- flame turbulence and/or difference between the combustion speed and the admission speed of the air-fuel mixture.

In practice, the pressure rhythmic variations inside the furnace may be a result of both internal and external causes, the interference phenomena making difficult the identification of the each type of causes.

Knowing the dynamic characteristics of the furnace is useful to develop its control system. The most practical way to know the dynamic properties of the furnace is simulation. Performing test runs is almost impossible because of the safety and economic reasons [14]. The simulation model is based on the mass, heat and momentum conservation principles. The present paper is an extension of the paper [1].

2. MODEL OF THE FURNACE DYNAMICS

To develop the mathematical model so as to simulate the dynamic behavior of the furnace, we take into account the working chart in figure 1. The input quantity, which varies in time, is the fuel mass flow rate, $\dot{m}_f$ and the output value is the pressure inside the furnace, p_f. The model includes the mass, energy, and momentum balances, the heat transfer from hot flue gases to water and steam model and the flue gas flow through the boiler model:

- combustion heat balance:

$$V_f \frac{d(\rho_g \cdot h_g)}{d\tau} = \dot{m}_a \cdot h_a + \dot{m}_{fb} \cdot LHV - \dot{m}_g \cdot h_g - \dot{Q}_f - \dot{Q}_l \text{ [kW]} \quad (1)$$

- combustion mass balance:

$$V_f \cdot \frac{d\rho_g}{d\tau} = \dot{m}_{fb} + \dot{m}_a - \dot{m}_g \text{ [kg/s]} \quad (2)$$

- flue gas flow through the boiler [12]:

$$\dot{m}_g = k_f \cdot p_f \text{ [kg/s]} \quad (3)$$

- furnace gas pressure:

$$p_g = R_g \cdot \rho_g \cdot T_g \ \text{[N/m}^2\text{]} \tag{4}$$

- combustion dynamics:

$$\dot{m}_{fb} = \dot{m}_f \left(1 - e^{\frac{-\tau}{T_f}}\right) \tag{5}$$

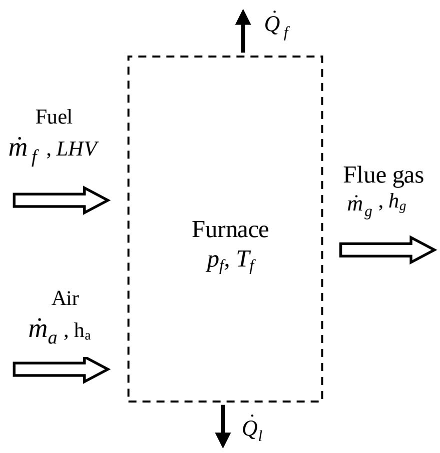


Fig. 1. *Physical model of the boiler furnace.*

where:
V_F [m^3] - furnace volume;
ρ_g [kg/m^3] – flue gas density;
$\dot{m}_f$ [kg/s] - fuel mass flow rate;
$\dot{m}_{fb}$ [kg/s]– burning fuel mass flow rate;
$\dot{m}_a$ [kg/s]–air mass flow;
$\dot{m}_g$ [kg/s]–exhaust gas mass flow;
LHV [kJ/kg] - fuel lower heating value of the fuel;
$\dot{Q}_f$ [kW] –heat transferred by radiation to vaporizer [11]:

$$\dot{Q}_f = c_R \cdot S \cdot \left(T_g^4 - T_{rt}^4\right) \approx c_R \cdot S \cdot T_g^4 \tag{6}$$

$\dot{Q}_l$ [kW] – lost heat through furnace walls;
T_g [k] – flue gas temperature;
h_g [kJ/kg] – flue gas enthalpy [12]:

$$h_g = c_{pg} \cdot \left(T_g - T_{ref}\right) + h_{ref} \tag{7}$$

T_{ref} [K] –reference exhaust gas temperature;
c_{pg} [kJ/kg K] – flue gas specific heat at constant pressure;
h_a [kJ/kg] - air specific enthalpy;
c_{pa} [kJ/kg K]-air specific heat at constant pressure;
T_a [K]–air temperature;
h_{ref} [kJ/kg]- flue gas reference enthalpy;
R_g [kJ/kg K] - gas constant for flue gas;
c_R [kW/m^2·K^4] – the coefficient of mutual heat transfer between flame and wall;
S [m^2]–radiation heat transfer surface of vaporizer;
T_{rt} [K] – vaporizer metal tube temperature;
k_f [m·s] – a friction coefficient.

3. SIMULATION OF THE FURNACE DYNAMICS

To be quickly implemented within a simulation tool environment the developed mathematical model is presented in a block diagram form. Figure 2 depicts the furnace block diagram representation in Simulink (Matlab).

The dynamic behavior of the furnace has been found out introducing certain variation laws of the control input which stands for the fuel mass flow rate $\dot{m}_f$ and specifying the time variation of the gas pressure inside the furnace (the maximum risk and maximum stress conditions for control system are those which have a suddenly variation of the fuel flow rate, such as the blockage of one mill or in an extremely case the total blockage of the fuel supply).

The furnaces of two energy steam boilers have been analyzed: pulverized coal fired boiler (type C4) and natural gas fired boiler (type TGM89). The steady state operating conditions are presented in table 1. The simulation results are shown in figures 3 and 4.

Table 1. Steam boiler working parameters.

Parameters	Measure unit	Steam boiler C4	Steam boiler TGM 89
$\dot{m}_f$	kg/s	12.928	6.193
$\dot{m}_a$	kg/s	138.55	115.5
h_a	J/kg	260000	287000
V_F	m^3	2813	1770
LHV	J/kg, J/m^3_N	24704000	35523000
T_{ref}	K	1273	1473
h_{ref}	J/kg	1662538	1923738
k_f	m·s	0.001514	0.001217
c_R	W/m^{2}K^4	$4.1 \cdot 10^{-8}$	$3.62 \cdot 10^{-8}$
$\dot{Q}_l$	W	28361000	614000
S	m^2	1200	1350
ρ_g	kg/m^3	0.3927	0.2265
p_g	N/m^2	10^5	10^5

4. CONCLUSIONS

From figures 3 and 4 it can be concluded that:

– the pressure variation inside the furnace, caused by variations of the fuel flow is higher inside the natural gas fired boiler, because, as compared to coal, natural gas has a higher combustion rate;

– due to the low gas dynamic resistance of the boiler, the phenomenon occurs very fast.

The control system of the air-gas circuit may be developed on the basis of these characteristics. This system requires that the flue gas pressure at the end of furnace should be measured and in consequence the opening angle of the gas blower’s guide blades must be ordered in accordance with the obtained results.

For a good working of the regulating system it is required that the measurement of the pressure at the end of furnace, should be done in all four sides of the furnace and all four values should be calculated together to find out their mean value, which will be used further on by the regulating system.

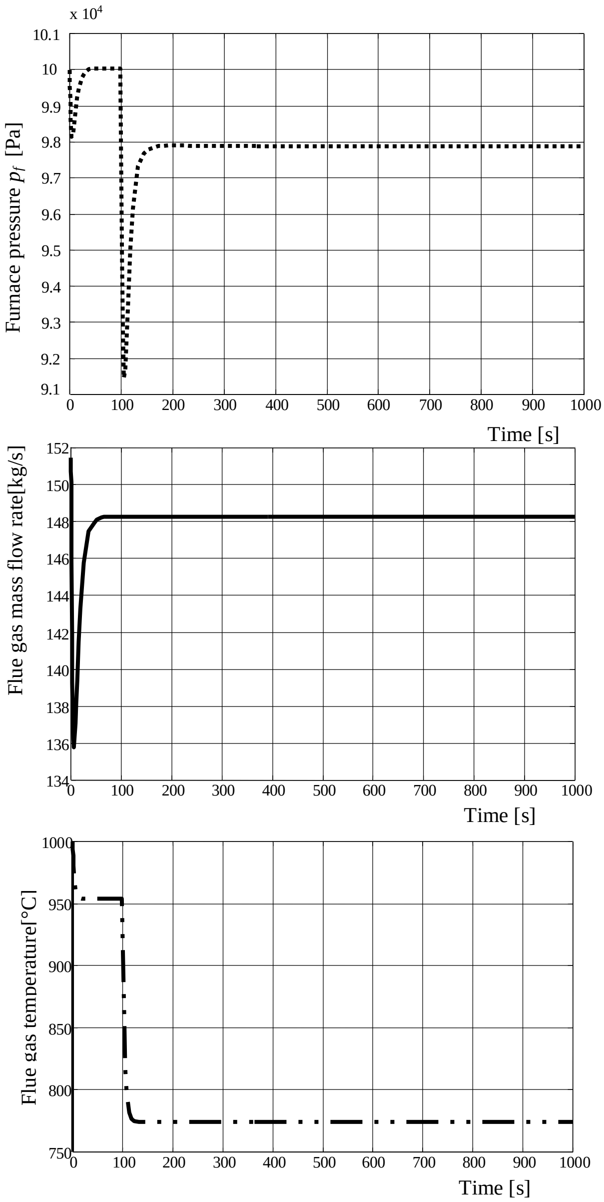
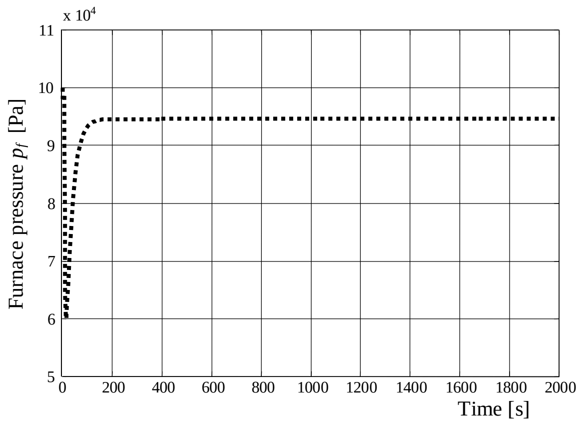


Fig. 3. *Pulverized coal fired boiler - 25% step in fuel flow rate.*



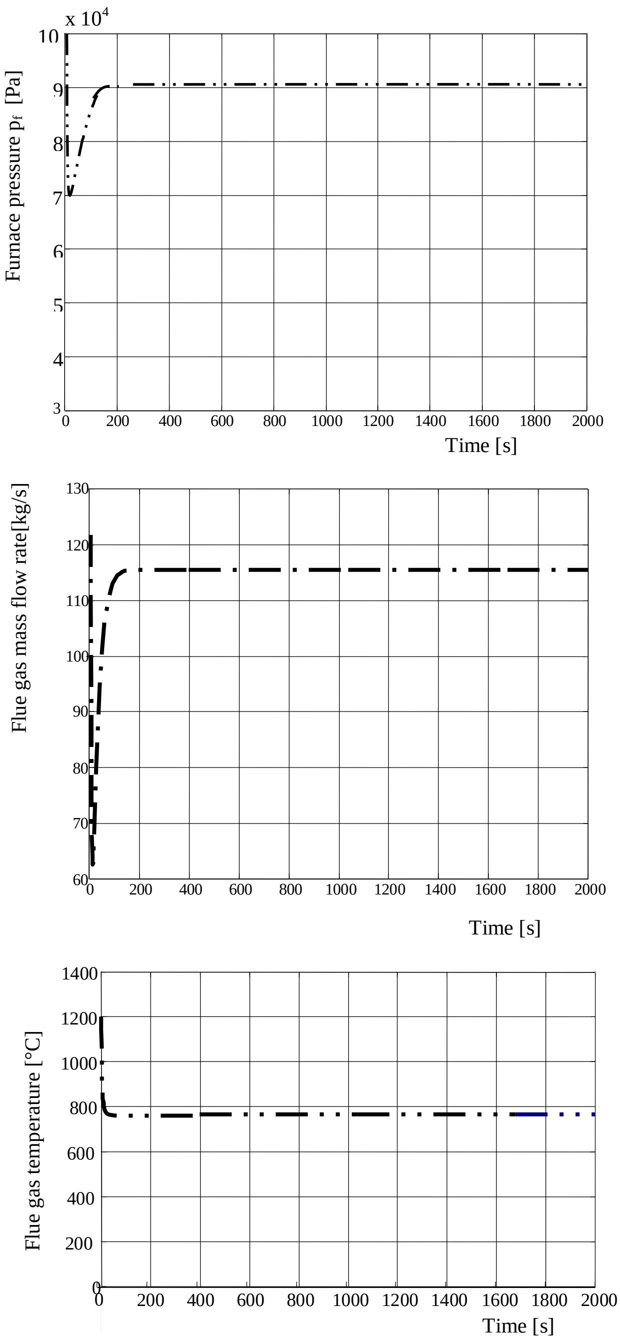


Fig. 4. *Natural gas fired boiler- 100% step in fuel flow rate.*

References

[1] **Ion V.I., Craciun S.,** *Simulation of the boiler furnace’s dynamic operation*, Modelling and Optimization in the Machines Building Field MOCM-99, Vol. 2, Bacău 2003, pp. 143-148.

[2] **Adam E.J., Marchetti L.,** *Dynamic simulation of large boilers with natural recirculation*, Computers and Chemical Engineering, 1999; 23, pp. 1031–1040.

[3] **Borman G.L., Ragland K.W.**, *Combustion engineering*, Singapore, McGraw-Hill Inc., 1998.

[4] **Chien K.L., Ergin E.I., Ling C., Lee A.**, *Dynamic analysis of a boiler*, Transactions of ASME, 1958; 80, pp. 1809–1819.

[5] **de Mello F.P.**, *Boiler models for system dynamic performance studies*, IEEE Transactions on Power Systems, Vol 6, No. 1, 1991, pp. 753–761.

[6] **Elmegaard B.,** *Simulation of boiler dynamics - Development, Evaluation and Application of a General Energy System Simulation Tool***,** Ph.D. Thesis, Technical University of Denmark, 1999.

[7] **Falcetta M.F., Sciubba E.,** *A Computational, Modular Approach to the Simulation of Powerplants*, Heat Recovery Systems and Combined Heat and Power Production, 1995, Vol.15, pp.131–145.

[8] **Gaba R., Gaba A.,** *Mathematical model and computation program of the chamber furnace of boilers for air pollution reduction*, Environmental Engineering and Management Journal March 2012, Vol.11, No. 3, pp. 557-565.

[9] **Maffezzoni C.,** *Dinamica dei generatori di vapore*, Masson, Milano, 1989.

[10] **Maffezzoni C.,** *Issues in modeling and simulation of power plants*, Proceedings of IFAC symposium on control of power plants and power systems, Vol. 1, 1992, pp. 19–27.

[11] **Neaga C., et al.,** *Modelarea funcţionării cu pulsaţii de presiune a focarului cazanului de 420 t/h Nr.1 de la C.E.T. Braşov* (*The modelling of the furnace working with pressure variations for 420 t/h steam boiler No. 1 from CET Braşov*), Lucrările Conferinţei Naţionale de Termotehnică, 23-24 Mai, 1997, Braşov, pp. 243-250.

[12] **Ordys A.W., Pike A.W., Johnson M.A., Katebi R.M., Grimble M.J**., *Modelling and Simulation of Power Generation Plants*, London, Springer-Verlag, 1994.

[13] **Saastamoinen J.J**., *Modelling of dynamics of combustion of biomass in fluidized beds*, Thermal Science: Vol. 8 (2004), No. 2, pp. 107-126.

[14] **Tuomas Kataja, Yrjö Majanne**, *Dynamic Model of a Bubbling Fluidized Bed Boiler*, 14th Nordic Process Control Workshop, Sirkka-Liisa Jämsä-Jounela (ed.), August 2007. pp. 58-61.

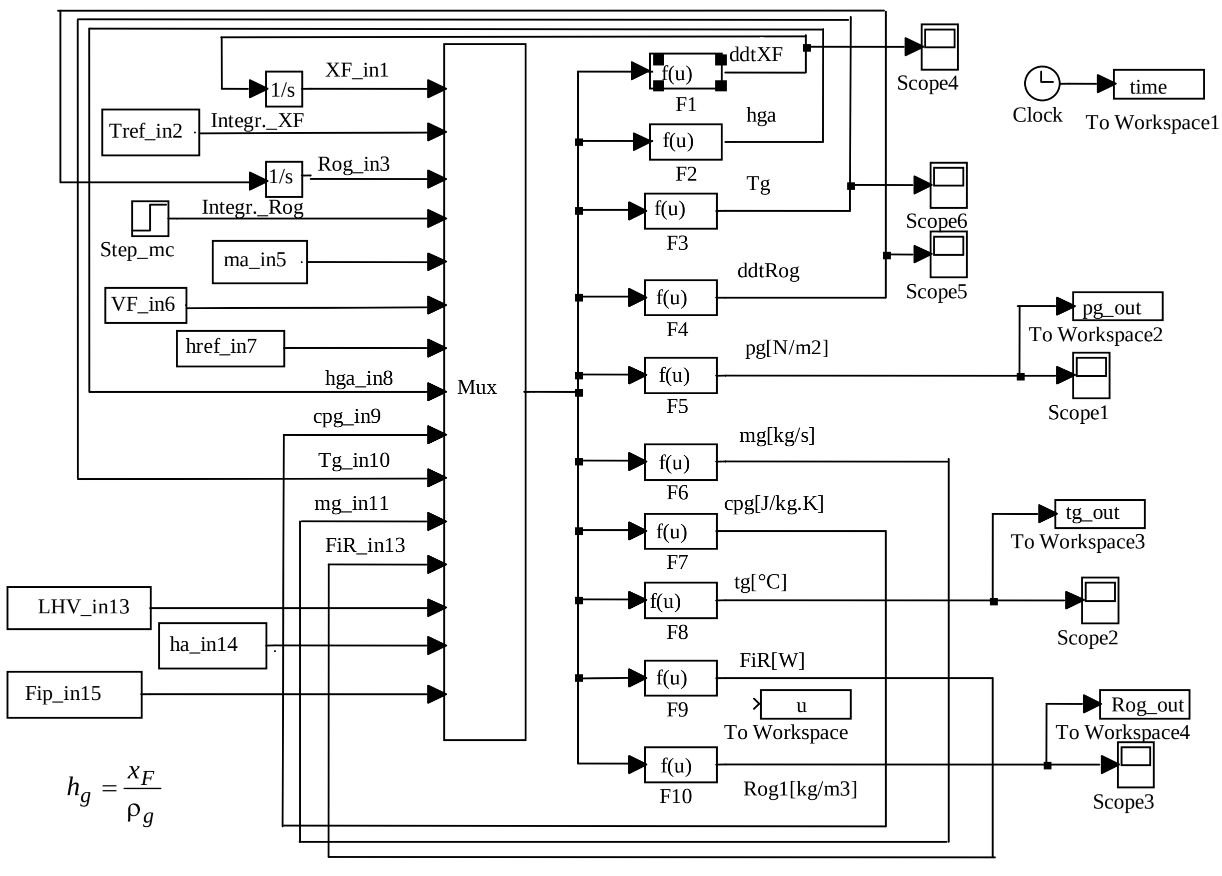


Fig. 2. *SIMULINK-furnace model block diagram.*