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Mathematical Modeling of the Gas Burner Functioning Process in Natural Gas Burning Furnaces

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ABSTRACT: Mathematical modeling of the processes, flowing gas burners, furnace plant and pipelines is performed. Models in the form of input-output, in the form of equations of material and thermal balances, provided that the system does not have gas leaks and heat losses to the environment, relate the parameters of the combustion products to the physical variables of natural gas and air entering the burner. Calculations of the calorific value of gas fuel are performed, stoichiometric equations for the combustion of simple gases that make up gaseous fuel, the consumption of the oxidant and the amount of products of complete combustion in theoretical conditions are given.

KEY WORDS: mathematical modeling, gas-burner, gas-burning furnaces, material and heat balance, combustion products, natural gas, calorific value.

I. INTRODUCTION

To date, the theory of combustion processes is not fully developed, which leads to the lack of accurate calculation methods. As a result, the need arises for a long experimental development of almost all furnace devices and assemblies in which the combustion process takes place before industrial operation [1]. The reasons for the current situation are, firstly, that fuel is a complex of natural organic substances of complex chemical structure; secondly, during the combustion process the steps are mandatory: creating a molecular contact between the fuel and the oxidizing agent (physical stage) and the interaction of molecules with the formation of reaction products (chemical stage). Finally, thirdly, the combustion process is fundamentally nonequilibrium. Therefore, the problems of modeling the combustion process are characterized as unsteady problems of turbulent mass and heat conduction in the presence of dynamic sources of matter and heat.

The study of combustion processes should develop along the way of compiling systems of integro-differential equations, the correspondence of which to the true course of the process should be checked by comparing the results of the reaction with the experimental data.

The organization of the fuel combustion process in any furnace is achieved using various aerodynamic techniques that determine the form of interaction between fuel and oxidizer, as well as determine the type of furnace process. The latter can be divided into flare and layered. During flaring, fuel is introduced by the gas-air flow and burns on the fly, almost without falling out of the stream. In the layered process, most of the fuel lies almost motionless on some grating, and air and gas flows penetrate the layer through the existing pores and channels.

The paper considers the main issues of the movement of gases and fuel in the combustion chambers. In this case, attention is paid to:

- movement and interaction of air-gas jets depending on the configuration of the furnace space;
- providing ignition of fresh fuel due to the supply of hot gases to it from zones of active combustion;
- ensuring the residence time of the fuel in the combustion chamber until the desired degree of burnout is achieved.

The aerodynamics of the technological furnace process inside the furnace of the first stage 30P-1 heater at the LLC «Shurtaneftegaz» and the movement of the jets in the furnace chamber were studied. When calculating the burnup of fuel particles, the motion of particles relative to the gas flow was taken into account, since this phenomenon enhances the heat transfer between the particle and the medium and has a significant effect on the entire burnout process. The relative velocity of a particle depends on the physical characteristics of the stream itself, the size and configuration of the particle, as well as on the temperature difference between the particle and the stream, that is, on the non-isothermal conditions of motion.

To develop a control system for the combustion process, mathematical models of the operation of the burner, furnace

II. FORMULATION OF THE PROBLEM

To derive a mathematical model, we write the equations of material and heat balance, provided that there are no gas leaks and heat losses to the environment.

The equation of material balance has the form:

$$g_{neq} = g_m + g_e, \quad (1)$$

where g_m and g_e are the amount of fuel and air entering the burner per unit time; g_{neq} - the amount of generated combustion products.

The heat balance equations for an infinitely small time interval:

$$dQ_{\text{bbid}} = dQ_{\text{noz}}, \quad (2)$$

where dQ_{bbid} is the amount of heat released during the combustion of $g_m dt$ fuels in time dt ; dQ_{noz} - the amount of heat absorbed by the combustion products during dt .

The amount of heat released can be determined by the formula:

$$dQ_{\text{bbid}} = \lambda_m g_m dt, \quad (3)$$

where λ_m is the calorific value of the fuel, cal/kg.

The heat absorbed by the combustion products is determined as follows:

$$dQ_{\text{noz}} = C_m g_m dt (\theta_{\text{noz}} + \theta_m) + M_{\text{noz}} C_{\text{noz}} d\theta + C_n g_n dt (\theta_{\text{noz}} - \theta_{\text{amm}}), \quad (4)$$

where C_m and θ_m are the heat capacity and temperature of the fuel entering the burner; C_n and θ_{amm} - heat capacity and air temperature; C_{noz} and θ_{noz} - the heat capacity and temperature of the combustion products in the flare; M_{noz} - the amount of combustion products contained in the torch of the burner.

When writing equation (4), it was assumed that the temperature was distributed throughout the volume uniformly due to intense mixing. This assumption is accepted in order to obtain a simpler mathematical model of the burner.

After the transformations we get

$$\lambda_m g_m dt = C_m g_m dt (\theta_{\text{noz}} + \theta_m) + M_{\text{noz}} C_{\text{noz}} d\theta + C_n g_n dt (\theta_{\text{noz}} - \theta_{\text{amm}}). \quad (5)$$

Dependence (5) is a burner model recorded in physical variables. To convert it to the form accepted in control theory, we divide into both sides of equation (5) and give similar terms. As a result, we obtain:

$$M_{\text{noz}} C_{\text{noz}} \frac{d\theta_{\text{noz}}}{dt} + (C_m g_m + C_e g_e) \theta_{\text{noz}} = C_m g_m \theta_m + C_e g_e \theta_{\text{amm}} + g_m + \lambda_m. \quad (6)$$

We introduce the following notation:

$$T_{\text{zop}} = \frac{M_{\text{noz}} C_{\text{noz}}}{C_m g_m^0 + C_e g_e^0}; K_{\theta,T} = \frac{g_m^0 C_m}{C_m g_m^0 + C_e g_e^0}; K_{g,T} = \frac{g_m^0 \lambda_m}{C_m g_m^0 + C_e g_e^0}; K_{\theta,amm} = \frac{g_e^0 C_e}{C_m g_m^0 + C_e g_e^0},$$

where T_{zop} - is the time constant; $K_{\theta,T}; K_{g,T}; K_{\theta,amm}$ - burner transfer coefficients; $g_m^0; g_e^0$ - nominal values of fuel and air consumption.

Taking into account the introduced notation, equation (6) will take the form:

$$T_{zop} \frac{d\theta_{noz}}{dt} + \theta_{noz} = K_{g,T} g_m + K_{\theta,T} \theta_m + K_{\theta,amm} \theta_{amm}. \quad (7)$$

With the designations introduced, the input action-control is the fuel consumption g_m - entering the burner. By changing its value, you can change the temperature of the combustion products, which allows you to control the combustion process. Equation (7) is the desired burner model in the input-output form.

III. CALCULATIONS OF THE PROCESS OF BURNING GAS FUEL

The following indicators are used to calculate the calorific value of gas fuel:

1. The calorific value of dry gas, kcal.m³

$$Q_b^c = 30,5H_2 + 30,2CO + 95CH_4 + 166C_2H_6 + 236,9C_3H_8 + 307C_4H_{10} + 377,2C_5H_{12} + 150,4C_2H_4 + 219,4C_3H_6 + 290C_4H_8 + 359,8C_5H_{10}, \quad (8)$$

where H₂, CO, CH₄ and etc. - volume fractions of the components included in the gas mixture, %.

2. The calorific value of dry gas lower, kcal/m³

$$Q_h^c = 25,8H_2 + 30,2CO + 85,5CH_4 + 152,3C_2H_6 + 218C_3H_8 + 283,4C_4H_{10} + 348,9C_5H_{12} + 141,1C_2H_4 + 205,4C_3H_6 + 271,1C_4H_8 + 336,5C_5H_{10}. \quad (9)$$

3. The calorific value of wet gas is lower at a pressure p and temperature t other than normal, kcal/m³:

$$Q_{h(t,p)}^p = Q_h^c * p T_0 / (760 * T) [1 - \varphi P_c / p (1 + 18600 / 22,4 Q_h^c)], \quad (10)$$

where Q_h^c - is the net calorific value at 0°C and 760 mm.hg., kcal/m³; $T_0 = 273^0K$; $T = 273 + t^0$; φ - relative humidity; P_c - the elasticity of saturated steam, mm.hg.

4. The amount of air theoretically necessary for combustion, m³/m³:

$$L_T = 0,0456(0,5H_2 + 0,5CO + 2CH_4 + 3C_2H_4 + 3,5C_2H_6 + 4,5C_3H_6 + 5C_3H_8 + 6C_4H_8 + 6,5C_4H_{10} + 8C_5H_{12} + 1,5H_2S - O_2), \quad (11)$$

where H₂, CO, CH₄ and etc. - volume fractions of the components included in the combustible gas, %.

5. Actual air consumption during gas combustion, m³/m³:

$$L_D = \alpha * L_T, \quad (12)$$

where L_D - the amount of air theoretically necessary for the combustion of 1 m³ of combustible gas, m³; α - coefficient of excess air.

6. Excess air ratio

$$\alpha = \frac{1}{1 - 3,76 \frac{O^1_2 - 2CH_4 - 0,5(CO^1 + H^1_2)}{N^1_2 - N_2 / Vcr}}, \quad (13)$$

where O^1_2 , CH^1_4 , CO^1 and N^1_2 - volume fractions of components of the products of combustion, %; N_2 - volumetric nitrogen content in a combustible gas, %; Vcr - the volume of dry combustion products of 1 m³ of combustible gas, m³.

7. The volume of gas combustion products with a theoretical amount of air, m³/m³:

$$V = V_{CO_2} + V_{H_2O} + V_{N_2}, \quad (14)$$

where V_{CO_2} , V_{H_2O} , V_{N_2} are, respectively, the volumes of carbon dioxide, water vapor and nitrogen in the products of combustion of 1 m^3 of combustible gas, m^3 .

8. The volume of carbon dioxide in the products of gas combustion, m^3/m^3 :

$$V_{CO_2} = 0,01 (CO_2 + CO + CH_4 + 2C_2H_6 + \dots + mC_mH_n), \quad (15)$$

where CO_2 , CO , CH_4 , $2C_2H_6$, ... mC_mH_n - are the components of the combustible gas, % vol.

9. The volume of water vapor in the products of gas combustion, m^3/m^3 :

$$V_{H_2O} = 0,01[H_2 + 2CH_4 + 2C_2H_4 + \dots + n/2C_mH_n + 0,124(d_r + Lrd_b)], \quad (16)$$

where H_2 , CH_4 ..., C_mH_n - are components of a combustible gas containing hydrogen, % vol; d_r and d_b - humidity of combustible gas and air, g/m^3 .

10. The volume of nitrogen in the products of gas combustion, m^3/m^3 :

$$V_{N_2} = 0,79 LT + 0,01N_2, \quad (17)$$

where: N_2 - is the nitrogen content in the combustible gas, % vol.

11. The volume of gas combustion products is actual (taking into account the coefficient of excess air), m^3/m^3 :

$$V_D = V_{CO_2} + V_{H_2O} + V_{N_2}^1 + V_{O_2}^1, \quad (18)$$

where: V_{CO_2} and V_{H_2O} are the volumes of carbon dioxide and water vapor obtained by burning in a theoretical amount of air, m^3/m^3 ; $V_{N_2}^1$ and $V_{O_2}^1$ - are the volumes of nitrogen and oxygen in the combustion products, taking into account the coefficient of excess air, m^3/m^3 .

12. The volume of nitrogen in the products of gas combustion is real (taking into account the coefficient of excess air), m^3/m^3 :

$$V_{N_2} = 0,79 \alpha LT + 0,01 N_2, \quad (19)$$

where N_2 - is the nitrogen content in the combustible gas, % vol.

13. The oxygen volume in the gas combustion products is real (taking into account the coefficient of excess air), m^3/m^3 :

$$V_{O_2}^1 = 0,21 (\alpha - 1)LT. \quad (20)$$

14. The actual volume of gas combustion products, m^3/m^3 :

$$V_D^C = \frac{CO_2 + CO + CH_4 + 2(C_2H_4 + C_2H_6) + \dots + mC_mH_n}{CO_2' + CO' + CH_4'}, \quad (21)$$

where CO_2 , CO , CH_4 , ... C_mH_n - are the carbon-containing components of dry combustion products, % vol.

15. The density of the gas mixture at 0^0 C and 760 mm.hg . kg/m^3 :

$$P^0_{cm} = (P_1V_1 + P_2V_2 + \dots + P_nV_n) / 100, \quad (22)$$

where: P_1 , P_2 , P_n - density of individual gases, kg/m^3 ; V_1 , V_2 , V_n - the content of individual gases in the mixture, volumetric.

16. The density of the mixture of gases, kg/m^3 :

$$P^{t,p}_{cm} = P^0_{cm} \frac{273 \bullet (760 + p)}{(273 + t) \bullet 760}, \quad (23)$$



where P_{cm}^0 - the density of gases at 0^0 C and 760 mm.hg, kg/m^3 ; P - the pressure of the mixture is excessive, mm.hg; t – the temperature of the mixture, 0C .

17. Average volumetric heat capacity of a mixture of gases, $kcal/(m^3 * ^0C)$:

$$C_{CM}=(V_1C_1 + V_2C_2+...+ V_nC_n)/100, \tag{24}$$

where V_1, V_2, \dots, V_n – is the content of the individual components of the mixture, % volume; C_1, C_2, \dots, C_n - is the average volumetric heat capacity of the individual components of the mixture, $kcal / (m^3 * ^0C)$;

18. The ignition limits of the gas mixture is the upper or lower (approximately, with a low content of ballast impurities), % of the volume of gas in the mixture with air:

$$L = \frac{V_1 + V_2 + \dots + V_n}{V/l_1 + V_2/l_2 + \dots + V_n/l_n}, \tag{25}$$

where V_1, V_2, \dots, V_n – is the content of individual combustible components of the gas mixture, % volume; l_1, l_2, \dots, l_n – the content of individual combustible components of the gas mixture, respectively, with the upper or lower ignition limits, % vol.

19. The maximum speed of propagation of the flame of a combustible gas mixture, m/s:

$$g_{pn.cm} = L_M \frac{V_1g_{pn1}/l_1 + V_2g_{pn2}/l_2 + \dots + V_n g_{pn.n}/l_n}{V_1 + V_2 + \dots + V_n}, \tag{26}$$

where V_1, V_2, \dots, V_n – the content of the mixture components, % volume; $g_{pn1}, g_{pn2}, \dots, g_{pn.n}$ - maximum flame propagation speed of individual gases in the air mixture, m/s; l_1, l_2, \dots, l_n – is the content of individual gases in a mixture with air, giving the maximum speed of flame propagation, % vol.

The stoichiometric equations of combustion of simple gases constituting a gaseous fuel, the consumption of an oxidizing agent and the amount of products of complete combustion under theoretical conditions are shown in Table 1.

TABLE I. STOICHIOMETRIC EQUATIONS FOR THE COMBUSTION OF SIMPLE GASES, THE CONSUMPTION OF AN OXIDIZING AGENT AND THE AMOUNT OF PRODUCTS OF COMPLETE COMBUSTION IN THEORETICAL CONDITIONS

Gas	Equations	Consumption, m^3/m^3		The amount of combustion products, m^3/m^3			
		oxygen	air	CO ₂	H ₂ O	N ₂	Total
Hydrogen	$H_2+0,5O_2=H_2O+2580$	0,500	2,381	-	1,000	1,881	2,881
Carbon monoxide	$CO+0,5O_2=CO_2+3020$	0,500	2,381	1,000	-	1,881	2,881
Methane	$CH_4+2O_2=CO_2+H_2O+8550$	2,000	9,524	1,000	2,000	7,524	10,524
Acetylene	$C_2H_2+2,5O_2=2CO_2+H_2O+13400$	2,500	11,905	2,000	1,000	9,405	12,405
Ethylene	$C_2H_4+3O_2=2CO_2+2H_2O+14100$	3,000	14,286	2,000	2,000	11,286	15,286
Ethane	$C_2H_6+3,5O_2=2CO_2+3H_2O+15200$	3,500	16,667	2,000	3,000	13,167	18,167
Propylene	$C_3H_6+4,5O_2=3CO_2+3H_2O+20500$	4,500	21,429	3,000	3,000	16,929	22,929
Propane	$C_3H_8+5O_2=3CO_2+4H_2O+21800$	5,000	23,810	3,000	4,000	18,810	25,810
Butylene	$C_4H_8+6O_2=4CO_2+4H_2O+27100$	6,000	28,572	4,000	4,000	22,572	30,572
Butane	$C_4H_{10}+6,5O_2=4CO_2+5H_2O+28300$	6,500	30,959	4,000	5,000	24,453	33,453
Penten	$C_5H_{10}+7,5O_2=5CO_2+5H_2O+37700$	7,500	35,715	5,000	5,000	28,215	38,215
Pentane	$C_5H_{12}+8O_2=5CO_2+6H_2O+34900$	8,000	38,096	5,000	6,000	30,096	41,096
Benzene	$C_6H_6+7,5O_2=6CO_2+3H_2O+33500$	7,500	35,715	6,000	3,000	28,215	37,215
Hydrogen sulfide	$H_2S+1,5O_2=SO_2+H_2O+5600$	1,500	7,143	1,000**	1,000	5,643	7,643

* Thermal effects ($kcal/m^3$) are given in rounds; **SO₂=1,000 m^3/m^3 .



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IV. CONCLUSION

The resulting mathematical model will be used in the future when developing a control system for the combustion process inside the furnace of the first stage heater 30P-1 at the LLC «Shurtanneftegaz» in order to increase its economic efficiency.

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