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Calculation of Fuel Oil Drop Burnup Time Dependence on Intensity of Flame Radiation

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Abstract: The study considers the issues of the rational organization of fuel combustion processes in TPS power boilers. Most thermal electric stations use gas as the primary fuel and fuel oil serves as the back-up fuel. Transition of boilers to fuel oil burning is usually partial and several burners as a rule, operate on the gas burning. At operation of boilers, due to features of the flame formation when fuel oil burning and gas burning, the issue about optimum performance conditions of the radiant heat exchange behavior in boiler furnaces is problematical. At gas burning the flame is non-luminous and at fuel oil burning the flame is luminous, except for core flame and furnace volume at the level of burners. There are differences in temperature distribution along the furnace height, width and depth when gas and fuel oil burning. Depending on the distribution of temperatures throughout the furnace volume, conditions of radiant heat exchange behavior and effectiveness of gas and fuel oil burning in steam boiler furnaces change which is relevant for the improvement of steam boilers' economic efficiency. Study of the flame interaction at combined burning of gas and fuel oil and their influence on the radiation heat exchange in boiler furnaces is also relevant for the improvement of steam boiler's economic efficiency.

Key words: Boiler, flame, intensity of flame radiation, burners, improvement

INTRODUCTION

As a fuel, the fuel oil continues to play the important part in the fuel and energy balance of our country. Its significance is rather essential at electric power stations and boiler plants. Most thermal stations use fuel oil as the back-up fuel while gas and coal are used as the primary fuel. Transition to fuel oil burning is most often a necessary measure due to the lack of the required amount of blue flame natural gas during the winter period. Also liquid fuel us used when combined gas-fuel oil burning for "highlightning" of a flame.

During transfer of boilers to combined burning, a part of burners transfer to fuel oil and several burners as a rule, operate on gas burning. Due to features of the flame formation when fuel oil burning and gas burning in boilers the mode of the optimal behavior of radiant heat exchange in boiler furnaces is a problem issue for operation. At gas burning the flame is non-luminous and at fuel oil burning the flame is luminous, except for core flame and furnace volume at the level of burners. There are also differences in temperature distribution along the furnace height, width and depth when gas and fuel oil burning. Depending on the distribution of temperatures throughout the furnace volume, conditions of radiant heat exchange behavior and effectiveness of fuel burning in steam boiler furnaces change. Study of the process of a flame interaction at combined burning of gas and fuel oil and their influence on the radiation heat exchange in boiler furnaces is relevant for the improvement of steam boiler's economic efficiency.

Main difficulties encountered during combined burning of natural gas and fuel oil in the boiler furnace are connected with the carburation of fuel oil-air mixture. Fuel oil-air mixture enters into the furnace from a burner in the form of direct-flow or swirling jets (Taimarov and Simakov,

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2011). For firing the atomized liquid fuel it is required to evaporate some of its part and heat up the mixture of fuel vapors with an oxidizing agent to a burning temperature. The velocity of flame propagation does not depend on hydrodynamic conditions but depends only on physical and chemical properties of the fuel mixture. In order to ensure a stable position in the furnace space of the ignition zone, i.e., the front of flame burning, the mixture should enter the ignition zone with the velocity equal to flame propagation velocity. Total calculation of fuel oil drop burning is complicated and is described by a system of energy and mass exchange equations for fuel and oxygen vapors. The energy equation can be simplified by introduction the concept for a fuel oil drop about a total enthalpy of steam-gas mixture:

$$i = cT + C|Q / \rho \tag{1}$$

Where:

- c = Mixture heat capacity (kJ/(kg⊕K))
- ρ = Mixture density (kg/m^3)
- C = Oxygen concentration (kg/m^3)
- | = Stoichiometric factor
- Q = Fuel combustion heat (kJ/kg)

Evaporation of a burning drop happens due to the heat molecular transfer through the stagnant boundary film near a drop surface. With drop burnup due to the surface reduction the total evaporation decreases the burning zone narrows and disappears upon complete drop burnup. In such a way proceeds the burning process of completely evaporating liquid fuel drop which rests in the environment or moves together with it with the same velocity.

MATERIALS AND METHODS

The amount of oxygen diffusing to the spherical surface under other equal conditions is proportional to its squared diameter therefore, installation of the burning zone at some distance from a fuel oil drop conditions a higher burning rate in comparison with the same solid fuel particle, during burning of which the chemical reaction proceeds virtually on the surface itself. Since, fuel oil drop burning rate is determined by the evaporation rate, the time of its burnup can be calculated on the basis of the heat balance equation of its evaporation due to the heat obtained from the combustion zone:

$$qFd| = -\rho\left[c_{av}(t_b - t_0) + \lambda_v\right]dv \tag{2}$$

Where:

- q = The amount of heat obtained from the combustion zone by a drop surface unit per unit time (kW/m^2)
- F = Drop surface at the current time moment (m^2)
- τ = Time of drop complete burnup (sec)
- ρ = Fuel oil density (kg/m^3)
- c_{av} = Average fuel oil heat capacity (kJ/(kg-K))
- t_b and t_0 = Boiling temperature and initial temperature of oil fuel (°C)
- λ_v = Evaporation heat (kJ/kg)
- dV = Fd| = Reduction of drop volume during dτ time period
- r and r_0 = Current and initial drop radii (m)

The time of fuel oil drop complete burnup can be determined by Eq. 2:

$$\tau = -\int_{r_0}^{0} \frac{\rho\left[(t_b - t_0)c_{av} + \lambda_v\right]}{q}.dr \tag{3}$$

Use of Eq. 3 for calculation of the time of fuel oil drop complete burnup is connected with difficulties in determining heat flow q coming from the combustion zone to the drop surface.

In the diffusion theory of fuel oil drop burning in respect to burning in the stationary environment or in the flow at zero relative velocity of a drop an idea about a reduced boundary spherical dr film near the drop surface is used within which only molecular transfer takes place in the presence of sharp change in temperature and reacting substances concentration (Taimarov *et al*., 2011). Beyond this conditional boundary film the flow is uniform in terms of temperature and concentration conditions due to the intensive molecular transfer. The combustion zone in the form of the spherical surface is formed around the drop. The heat portion generated in the combustion zone enters the drop surface and is utilized for evaporation and heating of fuel oil vapor to the temperature of the combustion zone. During the burning process this heat is returned.

Fuel oil vapors are transferred by the molecular diffusion into the combustion zone from the inside from the drop surface and from the outside-oxygen from the external surface of the reduced film. It is accepted that burning proceeds in the diffusion area, i.e., the chemical reacting in the combustion zone is performed so quickly, that the lead time can be neglected in comparison with the diffusion time.

This allows considering that the combustion zone is the surface whereon concentrations of fuel oil vapors and oxygen are equal to zero as a result of virtually momentary reacting of diffusion fluxes of these air-fuel mixture components entering into the combustion zone with a stoichiometric quantitative ratio between them. Combustion products generated in the combustion zone diffuse into the outside environment and the space between the burning zone and the drop and the released heat is removed into the external environment by molecular heat conduction. Combustion products and fuel oil vapors are located in the inner part of the reduced film, oxidizing agent and combustion products are located outside.

RESULTS AND DISCUSSION

The following equations are derived for the calculation of the burnup process for each of these two parts of the reduced film: the heat balance equation and the material balance equation.

To simplify the task it is considered (Khzmalyan and Kagan, 1976) that the temperature of liquid drop surface is equal to the boiling temperature and the following heat balance equation of drop evaporation during burning process is taken as the basis for calculation:

$$q = -g\left[\lambda_v + c_v (T - T_b)\right] = -\lambda \frac{dT}{dx} \qquad (4)$$

Where:

q = Specific heat flux to the surface

g = Specific vapor flow from the surface of liquid per time unit

λ_v = Fuel oil evaporation heat

c_v = Fuel oil heat capacity

T_b, T = Temperature of fuel oil surface accepted equal to boiling temperature and fuel oil vapor temperature, respectively

λ = Gas medium heat conduction factor

Integration of the Eq. 4 gives:

$$q = g\frac{1}{\Delta}\int_{T_b}^{T_c} \frac{\lambda dT}{\lambda_v + c_v (T - T_b)} \qquad (5)$$

Where:

Δ = Reduced film thickness

T_c = Temperature in the combustion zone

The temperature in the combustion zone required for calculations by Eq. 5 is determined from the ratio of heat fluxes from the combustion zone into the environment and oxygen from the environment into the combustion zone through the reduced film. On the assumption that under the conditions of the boiler furnace, heat losses from radiation into the environment are relatively small and coefficients of diffusion and temperature conductivity are equal to each other. Neglecting stephan flux due to its smallness we get that the temperature on the burning surface is equal to the theoretical temperature of burning in the medium of the same composition and with the initial temperature equal to the temperature of environment at excess air factor $\alpha = 1$.

To demonstrate the determining role of evaporation in proceeding of drop burning process and the dependence of evaporation on heat conditions the limit case is considered when burning of vapors does not limit the process and heat conditions are assigned irrespective of the process of vapors burning near the drop surface (Taimarov and Taimarov, 2007).

In case of small drops, the method of determination of heat amount obtained by a moving drop is based on the assumption that takes place heat exchange of drops with the environment only by convection. In this case, the heat flux perceived by the drop is equal to:

$$q = \alpha_0 (T - T_e) \qquad (6)$$

Where:

α_c = Factor of convective heat exchange

T_e = Temperature of the environment

The value of heat exchange factor α_c depends on the condition of the medium movement and is calculated by dependence of Nu criterion on Re value determined experimentally. For small drops moving in the flow with a very low relative velocity (Re<100), criterion, $Nu = \alpha_c d/\lambda = 2$ wherefrom:

$$\alpha_c = \frac{2\lambda}{d} = \frac{\lambda}{r} \qquad (7)$$

Having substituted Eq. 6 for q, taking into account Eq. 7 in Eq. 3 and having integrated it we will receive:

$$\tau = \int_0^{r_0} \frac{\rho\left[(t_b - t_0)c_{av} + \lambda_v\right]}{\lambda (T_e - T_b)}.rdr = \frac{\rho\left[(t_b - t_0)c_{av} + \lambda_v\right]}{2\lambda (T_e - T_b)} \qquad (8)$$

According to the Eq. 8, the duration of burnup of a small drop which evaporates in the process of convective heating in the carrying gas flow is proportional to the square value of its initial radius.

According to the law on linear dependence of the diameter square of small drop which is evaporating or burning in diffusion mode, on the time, the following burning factor is accepted as a characteristic value for drop burning:

$$k = \frac{d_0^2 - d^2}{\tau} \qquad (9)$$

were, d_0 d-initial and current drop diameters, respectively, m. When burning in air with the temperature of 800-900°C and drop's flow-around velocities of up to 1 m/sec for benzene k =1.3÷1.5; for kerosene k = 1-1.3 mm^2/sec. For fuel oil and diesel fuel oil k value is approximately the same. k factor increases with increase in the medium temperature and oxygen concentration those results in the increase of temperature in the combustion zone as well as with increase in drop flow-around velocity that results in the increase of Nu criterion.

The experimental data coincide with the calculation data according to the diffusion theory as well as show that Eq. 8 qualitatively correctly describes the dependence of burnup on the drop diameter and medium parameters.

Along with that the experimental data shows that burning of drops does not always have a diffusion character. Semenov criterion is the characteristic of deviation from diffusion burning:

$$Se = \frac{\sqrt{KD}}{\alpha_d} \quad (10)$$

where, **K**, D, α_d-constant of reaction rate, molecular diffusion factor and diffusion exchange factor, respectively.

With the improvement of diffusion conditions when reduction of the drop's size and increase in the velocity of their flow-around by flow, i.e., transition to modes which are characterized by smaller values of semenov criterion, the role of vapor's burning within the boundary film decreases and the amount of vapors removed into the environment increases. At Se→0.4, burning of vapors within the boundary film of very small drops can be neglected. Liquid fuel vapors which are brought away into the gas volume, burn according to the laws of liquid mixtures burning. Large values of criterion Se→∝ correspond to the diffusion burning of vapors within the boundary film.

In case of large drops, the distance from the drop surface to the combustion zone increases as a result of which the role of convective heat exchange with a drop decreases and transfer of heat by radiation q_r from the combustion zone begins to prevail. In this case, the heat flux q perceived by a drop can be accepted:

$$q = q_r \quad (11)$$

where, q_r-intensity of diffusion flame radiation perceived by a drop on the surface. At burning from a free surface, the intensity of diffusion flame radiation does not depend on the size and shape of the evaporation surface.

Table 1: Burnup time τ (sec) of a fuel oil drop with the initial radius of 12.7 um depending on q_r

Incident flux q_r (kW/m^2)	Burnup time of fuel oil drop (τ sec)
100	0.047
150	0.031
200	0.023
250	0.019

Therefore, q_r values obtained for burning from a free surface can be used to calculate the liquid fuel drop burnup. Having substituted q value according to Eq. 11 into Eq. 8 we get the equation for calculation of the drop burnup time:

$$\tau = \frac{\rho\left[(t_b - t_0)c_{av} + \lambda_v\right]}{q_r} r_0 \quad (12)$$

Where:

- τ = Time of drop complete burnup (sec)
- ρ = Fuel oil density (kg/m^3)
- c_{av} = Average fuel oil heat capacity (kJ/kg-**K**)
- t_b and t_0 = Fuel oil boiling temperature and initial temperature, respectively (°C)
- λ_v = Heat of fuel oil evaporation (kJ/kg)
- r_0 = Initial radius of a drop (m)
- q_r = Intensity of flame radiation perceived by a fuel oil drop on a surface (kW/m^2)

Calculation results of the burnup time τ (sec) of a fuel oil drop with the initial radius of 12.7 um depending on q_r are given in Table 1. Within the present work we have developed the mathcad program for determination of the fuel oil drop burnup time depending on q_r.

As it is seen from Table 1 with growth of an incident flux from the flame, time τ of the fuel oil drop burnup greatly decreases however, according to the kinetic theory, the time of fuel oil drop burnup is 0.05 sec.

Studies of incident fluxes were conducted on the operating TGM-84B boiler under different loads and flow rates of gas and fuel oil. Obtained measurement results are presented in Table 2. Figure 1 shows layout of TGM-84B boiler furnace sections for analysis of the experimental results on incident heat fluxes.

This boiler has 6 burners arranged in 2 tiers. level 7.2 m-burners from 1-4; level 10.2 m-burners No. 5 and No. 4. This boiler has 16 hatches: at level 6.6 m (hatches from 1-4b); at level 11.2 m (hatches from 5-12), at elevation 22.3 m (hatches 13, 14). Figure 1 conditionally presents two sections in depth of burners: section No. 1 passes through hatches of the left screen (hatch No. 1-at level 6. 6 m, No. 5-at level 11. 2 m) and through hatches of the right screen (No. 12-at level 11. 2 m, No. 4-b-at level 6.6 m); section No.2 passes through hatches of the left screen (hatch No. 1-at level 6. 6 m, No. 6 -at level 11. 2 m) and through hatches of the right screen (No. 11-at level

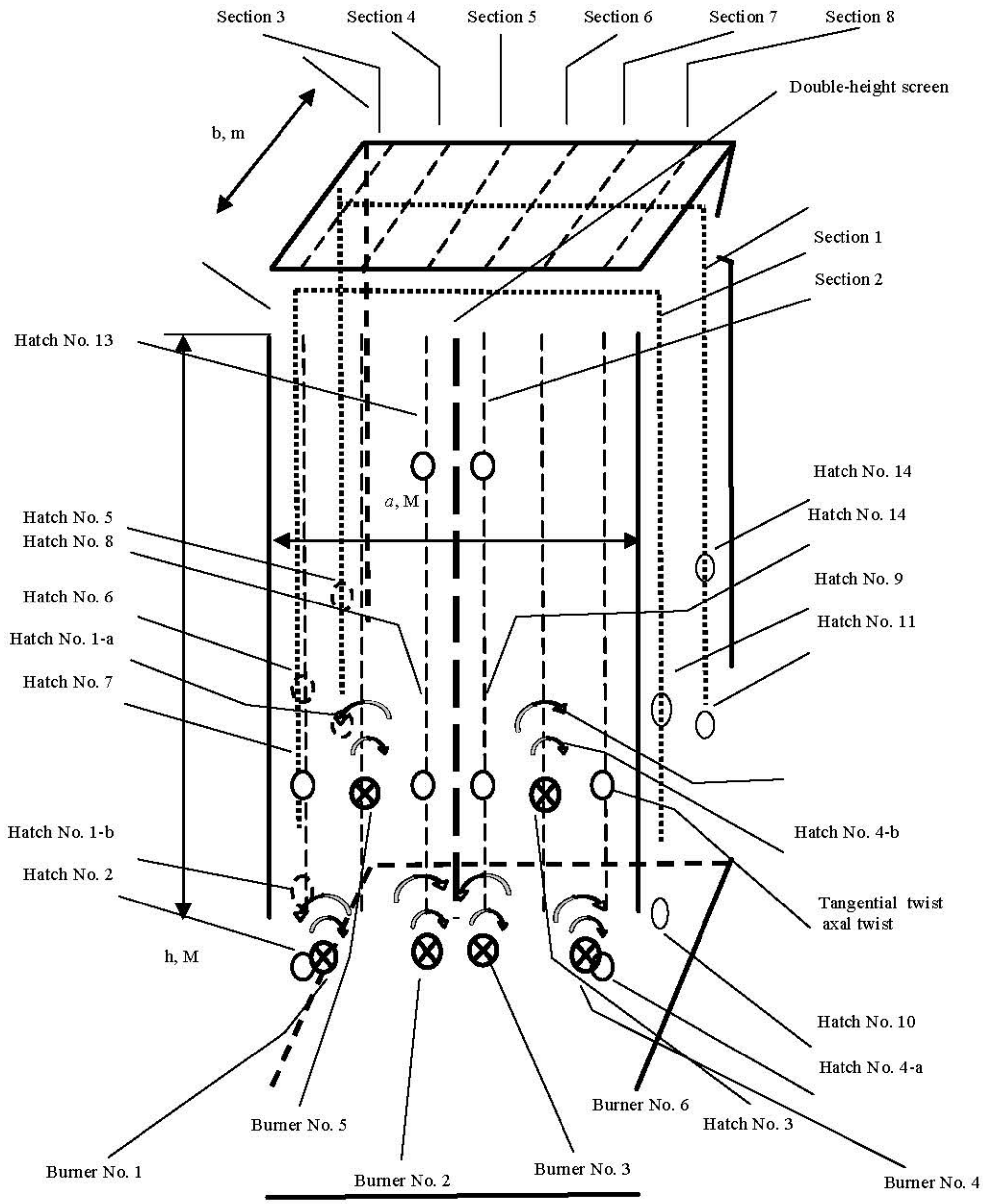

Fig. 1: Layout of TGM-84B boiler furnace sections at the analysis of flame temperature measurement results (O- burners of the furnace chamber front wall, ⊗-hatches)

11.2 m, No. 4-a-at level 6.6 m). There are also conditionally shown 6 sections across the width of burners: section No. 3 passes through hatches (No. 2-at level 6.6 m, hatch No. 5-at level 11. 2 m); section No. 4 passes through burner No. 5 at level 10.2 m); section No. 5 passes through burner No. 2 at level 7. 2m, hatch No. 8-at level 11. 2 m and hatch No. 13-at elevation 22. 3 m); section No. 6 passes through burner No. 3 at elevation 7.2 m, hatch No. 9-at level 11. 2 m and hatch No. 14-at level 22. 3 m; section No. 6 passes through burner No. 6 at level 10. 2 m); section No. 8 passes through hatches (No. 3 at level 6.6 m, hatch No. 5-at level 11. 2 m). The analysis carried out above showed that burning of fuel oil is followed by very complex physical and chemical behavior. It is virtually impossible to divide processes by the flow time of reactions and their sequence: therefore they are considered in general. In practice, the main role in determining optimal modes of fuel oil burning belongs to the experimental research of heat fluxes which incident from flame, throughout the furnace volume.

Table 2: Results of experimental studies at burning of gas and fuel oil in TGM-84B boiler

	Value of incident fluxes (kW/m²)					
Variables	1	2	3	4	5	6
Place of incident fluxes sampling	Load 290 t/h Gas, 22 t.m³/h Oil fuel, 310 t/h	Load 300 t/h Gas, 18 t.m³/h Oil fuel,6 t/h	Load 310 t/h Gas, 10 t.m³/h Oil fuel,13.5 t/h	Load 300 t/h 0 Oil fuel,21.7 t/h	Load 322 t/h Gas, 10.3 t.m³/h Oil fuel, 22.3 t/h	Load 350 t/h Gas, 17 t.m³/h Oil fuel,3.5 t/h
burners operating on gas	1, 2, 3, 4, 5, 6	1, 4, 5, 6	1, 4		1, 4	1, 2, 3, 4
burners operating on fuel oil	-	2, 3	2, 3, 5, 6	1, 2, 3, 4, 5, 6	2, 3, 5, 6	5, 6
Hatch No. 1-a	219.90	109.7	107.4	102.8	98.18	176.2
Hatch No. 1-b	151.00	341.6	107.4	77.5.0	121.1	132.3
Burner No. 1	146.40	132.6	151.0		137.2	151.0
Burner No. 3	125.70	-	-	-	-	-
Burner No. 2	116.50	-	-	-	-	-
Burner No. 4	128.00	130.30	105.10		100.500	118.80
Hatch No. 4-a	141.80	194.60	72.900	95.880	79.8100	114.30
Hatch No. 4-b	275.00	258.90	123.40	100.50	132.600	258.90
Hatch No. 5	291.10	252.00	194.60	153.30	146.400	132.80
Hatch No. 6	98.180	123.40	75.200	56.850	52.2600	84.400
Burner No. 5	146.40	153.30	-	155.60	-	-
Burner No. 6	141.80	148.70	-	-	-	-
Hatch No. 11	66.000	82.100	105.10	75.2200	52.2600	66.0400
Hatch No. 12	144.10	176.20	100.50	134.900	114.300	169.400
Hatch No. 13	89.0000	63.700	54.600	52.3600	47.6700	43.0700
Hatch No. 14	116.5.0	59.200	54.600	36.1100	68.3300	56.8500
Total value of incident fluxes	2397.38	2226.3	1253.2	1041.02	1150.61	1504.06

CONCLUSION

The growth of heat fluxes on the level of burners leads to a significant drop in temperature in the rest furnace volume which negatively effects economic efficiency and reliability of the boiler operation. Fuel oil drops are mainly heated up due to radiation fluxes which are incident from the combustion products. In this connection, the experimental research of optimal distribution conditions of incident heat fluxes throughout the furnace chamber is relevant for the improvement of fuel oil burning effectiveness.

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