

# Influence of dispersion degree of water drops on efficiency of extinguishing of flammable liquids

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**Abstract.** Depending on the size of water drops, process of fire extinguishing is focused either in a zone of combustion or on a burning liquid surface. This article considers two alternate solutions of a heat balance equation. The first solution allows us to trace decrease of temperature of a flammable liquid (FL) surface to a temperature lower than fuel flash point at which combustion is stopped. And the second solution allows us to analyze decrease of burnout rate to a negligible value at which steam-air mixture becomes nonflammable. As a result of solve of a heat balance equation it was made the following conclusion: water drops which size is equal to 100  $\mu\text{m}$  will completely evaporate in a zone of combustion with extent of 1 m if the flying speed of drops is even 16 mps (acc. to Stokes  $v = 3$  mps); whereas drops of larger size will evaporate only partially.

## 1 Introduction

In automatic fire extinguishing systems as dispersive devices it is usually used drenchers and sprinklers which provide coarse-particle dispersion of water with the average diameter of drops about 2 mm [1-3]. Dispersive devices are installed on ceiling overlaps therefore the finely dispersed fraction of sprayed stream evaporates in heated combustion products.

It is supposed that drops of large sizes practically don't evaporate in a gas phase as because of high flying speed of drops so of its small specific heat-exchange surface. In this case suppression of FL with flash point more than 90 ° C is occurs due to cooling of its surface to a temperature at which the speed of evaporation of a flammable liquid is insufficient for forming of concentration of fuel in gas-air mixture required for combustion. The process of suppression in this case is reduced to following aspects:

- cooling of the surface,
- absorption of the heat flow, moving from flame jet to a surface of flammable liquid, by water drops.

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As the main parameters of fire seat - burning liquid - defining the balance of heat and mass in the process of suppression by water it is considered:

- burnout rate (evaporation) of FL;
- temperature in a zone of combustion (flame jet);
- temperature of a liquid surface;
- water use ratio (during suppression) [4-6].

Depending on the size of water drops extinguishing process is focused either in a zone of combustion or on a burning liquid surface. Drops smaller than 150  $\mu\text{m}$  completely evaporate in combustion zone decreasing its temperature to a critical value called the temperature of extinction [7-11]. Decrease of temperature in combustion zone leads to reduction of the input rate of fuel vapors in it [12].

## 2 Heat balance equation

Flow of fuel vapors in a gas phase, when the surface temperature is close to the boiling point, is possible to determine by Stephen formula:

$$u_m^0 = \frac{D_0}{RT_0} \left( \frac{T_F}{T_0} \right)^m \frac{P_a}{\delta} \ln \left( \frac{P_a - P_1}{P_a - P_s} \right), \quad (1)$$

where:  $u_m^0$  — specific mass burnout rate of a flammable liquid (FL) in a steady mode of burning,  $\text{kg} \cdot \text{m}^2/\text{s}$ ;  $D_0$  — diffusion coefficient of FL molecules in a gas phase at a normal temperature of  $T_0$ ,  $\text{m}^2/\text{s}$ ;  $R$  — universal gas constant,  $\text{J} / (\text{mol} \cdot \text{K})$ ;  $T_F$  — flame jet temperature,  $^{\circ}\text{C}$ ;  $P_a$  — atmospheric pressure, Pa;  $\delta$  — thickness of diffusion layer, m;  $P_1$  — pressure FL vapors in surroundings at the distance from the surface equal to diffusion layer thickness  $\delta$ , Pa;  $P_s$  — pressure of a FL saturated steam at temperature of a surface  $T_s$ , Pa.

The  $m$  exponent in a formula (1) for hydrocarbons is approximately equal 2. This ratio considers the molar-convective nature of movement of vapor from an evaporation surface.

Accepting that change of FL evaporation rate is caused by decrease of a flame jet temperature  $T_F$ , and considering that for the short period of extinguish of a flame by high dispersive water the surface temperature will not change appreciably, we should find an expression of FL burnout rate in stationary conditions  $u_m$  of the extinguishing process:

$$u_m = u_m^0 (T_F/T_0)^2 \quad (2)$$

The heat balance equation for a FL extinguishing process by impact of sprayed water on a combustion zone can look as follows:

$$\rho C_p V dT_F = (n u_m^0 S_0 Q_1 - Q_w q_f) d\tau \quad (3)$$

where:  $\rho$  — density of combustion product,  $\text{kg}/\text{m}^3$ ;  $C_p$  — heat capacity of combustion product,  $\text{kJ}/(\text{kg} \cdot \text{K})$ ;  $V$  — volume of a combustion zone which height is accepted as equal to the luminous part of flame or the distance from sprayer to a combustion surface,  $\text{m}^3$ ;  $n$  — coefficient considering heat losses in process of emission;  $n = 0,6$ ;  $S_0$  — combustion surface area,  $\text{m}^2$ ;  $Q_1$  — low heat value of FL,  $\text{kJ}/\text{kg}$ ;  $Q_w$  — specific quantity of heat taken by water from surface layer of FL during suppression,  $\text{kJ}/\text{kg}$ ;  $q_f$  — mass rate of flow,  $\text{kg}/\text{s}$ ;  $\tau$  — time of extinguish, sec.

## 3 Two variants of solution of the heat balance equation

Let us consider two alternate solutions of a thermal balance equation. The first solution

allows us to trace the decrease of a flammable liquid surface temperature to a temperature lower than fuel flash point at which combustion is stopped. And the second solution allows us to analyze the decrease of burnout rate to a negligible value at which steam-air mixture becomes nonflammable.

### 3.1 The first embodiment of the heat balance equation solutions

The first alternate solution can look as follows. We express  $u_m$  through the temperature in combustion zone. For this purpose we use a formula for heat-mass exchange in a stationary mode:

$$u_m^0 = \frac{\alpha(T_F - T_s)}{Q_{fl}} \quad (4)$$

$\alpha$  — heat transfer coefficient,  $\text{kg}/(\text{m}^2 \cdot \text{K})$ ;  $Q_{fl}$  — specific heat of FL evaporation,  $\text{kJ}/\text{kg}$ .

If we substitute an expression for specific mass burnup rate (4) into the thermal balance equation (3), we will get:

$$\frac{\rho C_p V dT_F}{d\tau} = \frac{n\alpha Q_{fl} S_0 (T_F - T_s)}{Q_l} - q_f Q_w \quad (5)$$

$$q_f/S_0 \equiv J, \quad (6)$$

we should rewrite the formula (5):

$$\frac{\rho C_p h dT_F}{d\tau} = \frac{n\alpha Q_{fl} S_0 (T_F - T_s)}{Q_l} - JQ_w \quad (7)$$

$J$  — intensity of water supply,  $\text{kg}/\text{m}^2 \cdot \text{s}$ ;  $h$  — height of the luminous part of flame over FL surface,  $\text{m}$ .

We reduce the equation (7) into the form suitable for integration:

$$d\tau = \frac{\rho C_p h Q_{fl}}{n\alpha Q_l} \frac{dT - JQ_w Q_{fl} g (T_F - T_s) n\alpha Q_l}{JQ_w Q_{fl} (T_F - T_s) n\alpha Q_l} \quad (8)$$

We integrate formula (8) ranging from  $\tau = 0$  to  $\tau = \tau_T$  and from  $T_F^0$  to  $T_F$ :

$$\tau_T = \frac{\rho C_p h}{n\alpha Q_l} \ln \frac{J - J_{cr} \alpha (T_F - T_s)}{J - J_{cr}} \quad (9)$$

where  $T_F^0$  — temperature in combustion zone before extinguishing,  $^{\circ}\text{C}$ .

The critical condition of extinguishing when the time of suppression become endless, i. e.  $\tau_T \rightarrow \infty$ , is expressed so:

$$J = J_{cr} = g \frac{n\alpha Q_l (T_F - T_s)}{Q_w Q_{fl}} \quad (10)$$

At the same time  $\alpha(T_F - T_s)/Q_{fl} = u_m^0$ , therefore

$$J_{cr} = g \frac{nQ_{fl} u_m^0}{Q_w} \quad (11)$$

If we enter expression for  $J_{cr}$  (12) into the formula (11) we will get:

$$\tau_T = \frac{\rho C_p h}{n\alpha Q_l} \ln \frac{J - (T_F - T_s)n\alpha Q_l / Q_w Q_{fl}}{J - J_{cr}} \quad (12)$$

### 3.2. The second embodiment of the heat balance equation solutions

Now we consider the second alternate solution.

Using the formula (4) we get:

$$dT_F = \frac{Q_{fl}}{\alpha} du_m \quad (13)$$

Now we substitute the expression (13) into equation of thermal balance (3):

$$\frac{\rho C_p h Q_{fl}}{\alpha} du_m = (nu_m Q_{fl} - JQ_w) d\tau \quad (14)$$

We solve the equation within such limits: from  $\tau = 0$  to  $\tau = \tau_T$  and from  $u_m = u_m^0$  to  $u_m = 0$ .

Condition when  $\tau = \tau_T$  at  $u_m = 0$  is real only for suppression of flammable liquids with high flash point. As practically all water evaporates in a gas phase, the surface temperature of FL during suppression does not change appreciably; therefore the executed earlier transformation in a formula (14) is reasonable for a case of FL suppression.

The solution of an equation (14) will be the formula

$$\tau_T = \frac{\rho C_p h}{n\alpha Q_l} \ln \frac{J}{J - \left(\frac{n\alpha Q_l}{Q_w Q_{fl}}\right)} \quad (15)$$

We should find the value of critical intensity, when  $\tau_T \rightarrow \infty$ :

$$J = J_{cr} = g \frac{nQ_{fl} u_m^0}{Q_w} \quad (16)$$

By substituting the value of critical intensity (16) into (15) formula we can get:

$$\tau_T = \frac{\rho C_p h}{n\alpha Q_l} \ln \frac{J}{J - J_{cr}} \quad (17)$$

The formula (14) considers parameters of highly flammable liquid better and the ratio (17) is suitable for description of the extinguishing process of high-boiling FL and solid combustible materials (SCM) which surface temperature is close to  $T_F$ .

It is necessary to define how the specific burnup rate is changing during extinguishing.

On the basis of interrelation of  $u_m$  and  $T_F$  parameters through the ratio (4) we constitute

the equation of thermal balance for combustion zone which width and height are defined by fire seat diameter:

$$\frac{\rho C_p h Q_{fl} du_m}{\alpha d\tau} = nu_m Q_{fl} - J Q_w \quad (18)$$

And now we execute an integration of differential equation (18) ranging from  $\tau = 0$  to  $\tau = \tau_T$  and from  $u_m = u_m^0$  to  $u_m = 0$ :

$$d\tau = \frac{\rho C_p}{J Q_w - n Q_{fl} u_m} \quad (19)$$

$$\tau_T = \tau_0 \ln \frac{J}{J - J_{cr}} \quad (20)$$

We should take into account that the quantity of water evaporating in process of suppression is reduced as the temperature in combustion zone is decreased.

We make an equation of thermal balance:

$$h \rho C_p dT_F = [nu_m Q_{fl} - \frac{\alpha f_{\Sigma}}{S_0} (T_F - T_s)] d\tau \quad (21)$$

where  $f_{\Sigma}$  — total surface area of water drops participating in heat exchange,  $m^2$ .

We can take the thermal balance equation for process of suppression by impact of sprayed water on combustion zone:

$$\rho C_p V dT_F = (nu_m S_0 Q_{fl} - Q_w q_t) d\tau. \quad (22)$$

Now we can find an expression for critical rate of supply of sprayed water:

$$J_{cr} = 2/3 \frac{\rho r_k^2 n Q_{fl} u_m^0}{T_F^0 \tau_0} \quad (23)$$

This formula takes into account dispersion of an initial water stream.

It is necessary to define part of water evaporated in a flame jet.

To define the stay time of water drop in a zone with increased gas temperature it is necessary to calculate the speed of its falling. If we regard a drop as a solid ball than with small Reynolds numbers (Re) the steady falling speed of a drop is determined by Stokes formula

$$v = 2/9 g r_k^2 \frac{\rho_v - \rho_g}{\eta} \quad (24)$$

where:  $\rho_g$  — gas density,  $kg/m^3$ ;  $\eta$  — gas dynamic viscosity,  $Pa \cdot s$ ;  $g$  — gravitational acceleration,  $m/s^2$ .

If the water drop with an initial radius  $r_0$  heats up while passing through the gas layer, heated up to the temperature of flame jet  $T_F$  in this case, changes of drop temperature in time can be determined by this ratio

$$\frac{4\pi r_0^3 \rho_v C_w dT_0}{3d\tau} = 4\pi r_0^3 \alpha (T_F - T_0) \quad (25)$$

where  $C_w$  — heat capacity of water, kJ/kg-K;  $T_0$  — initial temperature of drop, °C.

Now we find relation of an evaporation time to a time of drop heating:

$$\frac{\tau_T}{\tau_l} = \frac{3Q_w}{2C_w(T_F - T_k)} / \ln \frac{(T_F - T_0)}{T_F - T_k} \quad (26)$$

Specific heat of water evaporation  $Q_w = 2,35 \cdot 10^6$  J/kg. Specific heat capacity of water  $C_w = 4,2 \cdot 10^3$  J/(kg·K);  $T_F - T_k = 1100$  K;  $\ln[(T_F - T_0)/(T_F - T_k)] = 0,068$ ;

$$\frac{\tau_u}{\tau_h} = \frac{2,35 \cdot 10^6}{2 \cdot 4,2 \cdot 10^3 \cdot 1100 \cdot 0,068} = 3,8.$$

Therefore, time of drop evaporation is in 3,8 times more than time of its heating while passing through a flame jet. If we suppose that the drop motion speed can exceed in 150 times the speed calculated for conditions of falling without initial impulse ( $v = 3,0$  m/s — steady speed), i.e. it will be 15 m/s, than heat transfer coefficient should be determined by a formula (52) if  $T_F = 1500$  K,  $v = 225 \cdot 10^{-6}$  m/s,  $\rho = 0,27$  kg/m<sup>3</sup>,  $d_k = 1 \cdot 10^{-4}$  m,  $Re = 9,4$ , from where  $\alpha_2 = 1,35\lambda/r_0$ . Therefore, increase of drop motion speed in 150 times changes the  $\alpha$  value in 1,35 times and increase the time of heating and evaporation of water drop in a flame jet equally.

If the distance from sprayer to a burning surface is 1 m than the drop flying time at a speed of 16 m/s makes  $\tau = 0,065$  s, and at a steady speed —  $\tau = 0,33$  s.

## Conclusion

Thus, drops with size of 100  $\mu$ m will evaporate completely in a burning zone with a length of 1 m if the flying speed is even 16 m/s (by Stokes  $v = 3$  m / s).

Water drops have an influence on different area of a burning object depending on their size. Finely dispersed water with an average drop size smaller than 100  $\mu$ m has predominant influence on combustion zone. Water drops which size is larger than 0.5 mm are only partially evaporate in a gas phase and have influence mainly on a burning surface of solid combustible materials or flammable liquids.

The first solving method of the thermal balance equation of process of suppression of a flammable liquid by supplying of dispersed water into combustion zone allows us to determine the limiting temperature at which combustion is stopped. The second solving method allows us to determine the blowout rate which decreased to a negligible value when steam-air mixture becomes nonflammable.

It is possible to conclude that the formula (14), in case of solving of the thermal balance equation by first method, has better accounting of FL parameters, whereas the ratio (17) is fully describes the process of suppression of a high-boiling FL and solid combustible materials, which surface temperature is close to a flame jet temperature while burning.

## References

1. P. Nash Fire Prev. No. **118**. 21–45 (1977)

2. D. A. Korolchenko, V. Yu. Gromovoy, O. O. Vorogushin Vestnik MGSU — Proceedings of Moscow State University of Civil Engineering, **1-2**, 331–335 (2011)
3. R.S. Volkov, Kuznetsov G.V., Strizhak P.A. Journal of Applied Mechanics and Technical Physics. **56(2)** 248-256 (2015)
4. V. I. Blinov, Khudyakov G. N. *Diffuzionnoye gorenije zhidkostey [Diffusion burning of liquids]*. (Moscow, Russian Academy of Sciences Publ., 1961)
5. Ya. B. Zel'dovich, et al. *Matematicheskaya teoriya gorenija i vzryva [Mathematical theory of burning and explosion]*. Moscow, Nauka Publ., 480 p. (1980)
6. Rasbash D. J. The extinction of fire with plain water: a review // Fire Safety Science. —**Vol. 1.** — P. 1145–1163. DOI: 10.3801/iafss.fss.1-1145 (1986)
7. Frolov Yu. G. *Kurs kolloidnoj khimii. Poverkhnostnyye javleniya i dispersnyye sistemy [The course of dispersoidology. Surface phenomena and disperse systems]*. Moscow, Khimiya Publ. 400 p. (1982)
8. Semenov P. The Russian Journal of Applied Physics, **14**, **7–8**, 427–437 (1994)
9. Friedrichsberg D. A. *Kurs kolloidnoj khimii [The course of dispersoidology]*. Leningrad, Khimiya Publ., 352 p. (1974)
10. A.F: Sharovarnikov, et al. Pozharovzryvobezопасnost — Fire and Explosion Safety, **22**, **no. 12**, 69-74 (2013)
11. D. A. Korolchenko Pozharovzryvobezопасnost — Fire and Explosion Safety, **vol. 21**, **no. 5**, pp. 79-80 (2012)
12. N.M. Kovalchuk, et al. Advances in Colloid and Inter-face Science, **210**, 65-71, doi:10.1016/j.cis.2014.04.003 (2014)