OPTIMUM WATER SPRAYS FOR FIRE FIGHTING

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ABSTRACT

Water sprays are being currently used for fire suppression in the essentially two distinctive regimes: as relatively coarse sprinkler sprays, or as fine water mists. The most efficient way of fire suppression is associated with the latter mode. For an efficient delivery and heat absorption the parameters of the spray, in particular droplet size must be optimized.

In the present study, a criterion for the optimum spray dynamics is proposed, and an analytical estimation is provided for optimum droplet size in the spray as a function of Heat Release Rate of fire. Mathematical model is based on approximate solution of the Lagrangian equation for the motion of water droplets.

The present approach provides a quick estimation of optimum spray parameters for a particular fire application.

It is argued that a proper scientific definition of water mist sprays need be based on consideration of spray dynamics under specific fire conditions.

KEYWORDS: Fire fighting, Water sprays, Optimum droplet diameter

NOTATION

C_D	drag coefficient
c_p	gas specific heat
d	droplet diameter
d_0	initial droplet diameter
d_{opt}	optimum droplet diameter
$\vec{F}_g$	gravity force
g	gravity acceleration
k_{ev}	evaporation constant
k_g	gas thermal conductivity
L	latent heat of vaporization
L_f	mean flame height
m	droplet mass
$\dot{Q}$	fire Heat Release Rate
$\dot{Q}_c$	fire convective Heat Release Rate
Re_p	particle (droplet) Reynolds number
T_∞	ambient temperature
T_g	gas temperature
T_s	droplet surface temperature

t	time
U	fire plume velocity
V	droplet velocity
V_0	initial droplet velocity
z	height
$z_{\max}$	initial droplet height
$z_{\min}$	bottom point of droplet trajectory
z_0	fire plume virtual origin

Greek symbols

ν	gas kinematic viscosity
ρ	gas density
ρ_p	particle (droplet) density
ρ_∞	ambient density

INTRODUCTION

Droplet size distribution in water spray is of great importance for fire fighting. It has strong influence on spray/fire plume interaction, controls the rate of spray evaporation in the flame and eventually the efficiency of flame suppression. These features have been extensively observed in fire suppression studies[1-3]. It has been realized[3] that fire suppression by water spray can occur in the two distinctive regimes: via fuel cooling (surface suppression) or via flame cooling (gaseous suppression). Either of these strategies requires the spray parameters to be optimized.

The parameter of primary importance is droplet size in the spray. Over years, there has been a number attempts to address the issue of "optimum" droplet size for fire fighting. Definitions of the "optimum" droplet behavior vary between different investigators. Obviously, the choice of an optimum droplet size depends on a particular suppression strategy.

Several possible approaches have been discussed in the literature[4]. An optimum mean diameter of $d_{opt} \sim 350\mu m$ has been proposed[5] derived from optimizing the terminal velocity to droplet diameter ratio. Use of high-momentum sprays with the initial velocity $\sim 80\ m/s$ in conjunction with droplet sizes $\sim 70\ \mu m$ has been proposed[6] in order to achieve rapid deceleration of droplets, sufficient residence times and high evaporation rates.

Computational studies[7] relating heat absorption capacity of the spray to its initial droplet diameters indicated best extinguishment performance in the range of $300\mu m$ - $900\mu m$ droplet sizes. However, the exact droplet dynamics has not been considered in the latter paper. Droplet trajectory has been divided into two zones: above the flame and inside the flame. Detailed gas velocity profiles have not been considered in either of these two zones, and the absence of exact droplet momentum equation did not allow reasonable dynamical predictions to be made.

In the present study an alternative concept of optimum diameter is presented. It is based on a concept of flame suppression in the gaseous phase, and applies therefore, in general, to fire suppression regimes delivered by water mist systems. A major feature of the model is that estimation for the optimum diameter is derived considering exact equation of droplet motion and exact flow velocity profile in fire plume and flame. Starting from exact equations, the model however provides surprisingly simple formulas for optimum droplet diameter in fire fighting sprays.

MATHEMATICAL MODEL

Consider the basics of water droplet interaction with flame and fire plume (Fig. 1).

The equation of droplet motion is taken in the form[8]:

$$m\frac{d\vec{V}}{dt} = -\frac{\pi}{8}d^2\rho C_D\left|\vec{V}-\vec{U}(z)\right|\left(\vec{V}-\vec{U}(z)\right)+\vec{F}_g \qquad [1]$$

or

$$\frac{d\vec{V}}{dt} = -\left(\frac{4}{3}\frac{\rho}{\rho_p}\right)\frac{C_D}{d}\left(\vec{V}-\vec{U}(z)\right)\left|\vec{V}-\vec{U}(z)\right|+\vec{g} \qquad [2]$$

According to arrangements of Fig. 1, components of the velocities obey $V<0$; $U>0$; $V-U<0$.

Taking this into account, equation [2] in components becomes:

$$\frac{dV}{dt} = \left(\frac{4}{3}\frac{\rho}{\rho_p}\right)\frac{C_D}{d}\left(V-U(z)\right)^2 - g \qquad [3]$$

At this point, an approximation regarding the form of dependence of the drag coefficient on the particle Reynolds number is made. It is customary to characterize particle drag coefficient, for example, by the following correlation[9]:

$$C_D = \begin{cases} 27/\mathrm{Re}_p^{0.84}, & \mathrm{Re}_p < 80 \\ 0.271\mathrm{Re}_p^{0.217}, & 80 < \mathrm{Re}_p < 10^4 \end{cases} \qquad [4]$$

In the present analysis, this dependence is replaced by the following simplifying one:

$$C_D = 27/\mathrm{Re}_p, \quad \mathrm{Re}_p < 10^4 \qquad [5]$$

Comparison between the correlations [4] and [5] is presented in Fig. 2. It is seen that the approximation [5] is not unreasonable, and it will be demonstrated below that it leads to good results in the context of the present analysis.

The use of a simple universal correlation [5] greatly simplifies equation [3]. Indeed, on the RHS of [3] one has:

$$\frac{C_D}{d}\left(V-U(z)\right)^2 = \frac{27\nu(U(z)-V)^2}{d(U(z)-V)d} = 27\nu\frac{1}{d^2}(U(z)-V) \qquad [6]$$

Finally, the basic approximate equation of the droplet motion used throughout the present paper is:

$$\frac{dV}{dt} = \left(36\nu\frac{\rho}{\rho_p}\right)\frac{1}{d^2}(U(z)-V) - g \qquad [7]$$

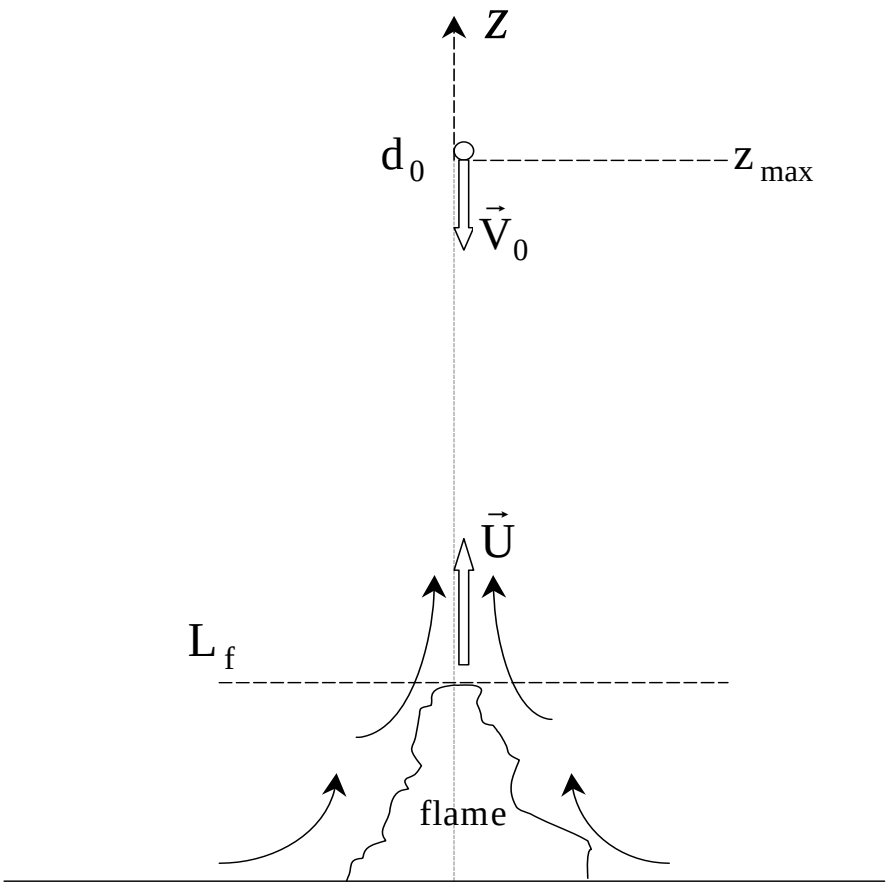

FIGURE 1. Schematic of droplet injection into fire

The profile *U(z)* in the above equation is assumed to be known, and is determined by a particular fire under consideration.

Even in the case of constant droplet diameter no analytical solutions for equation [7] are known, although the equation form itself is rather well-known. In the latter case the equation [7] belongs to the class of Abel Equations of the Second Kind. Existence of closed-form solutions for these equations depend on the form of a known function on the RHS, in our case, essentially, on the form of the profile *U(z)*. Unfortunately, the case of velocity profiles in fire plumes ($U(z) \sim z^{-1/3}$) does not fall into the classified cases which admit integration[10].

RESULTS AND DISCUSSION

Non-evaporating Droplet

To illustrate the method for estimating optimum diameter, consider movement of a non-evaporating particle first. This case illustrates essential properties of the solution of equation [7].

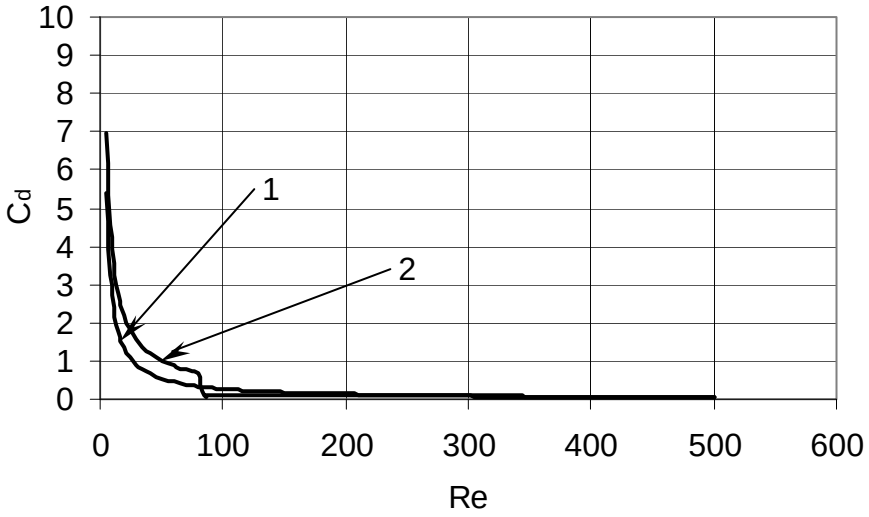

FIGURE 2. Approximation of the drag coefficient dependence on the particle Reynolds number
1 – approximate dependence [5]; 2 – experimental correlation [4]

In general, the optimum should be defined in the following way: droplet posses the optimum diameter if upon injection it evaporates exactly in the flame region (i.e. neither penetrates to the surface nor evaporates in inert fire plume). In application to a non-evaporating particle, it is sensible to impose the following criterion: droplet zero-velocity point is inside the flame. This point will also be a reversing point for a droplet trajectory, since upon achieving this point the droplet will still experience acceleration by fire plume, and will start to move upwards. The rationale for such a criterion is that if the droplet had a capability to evaporate, complete evaporation is likely to happen in the vicinity of a reversing point where the temperature is high (flame temperature) and droplet motion is slow (residence time large).

It will be demonstrated below that a similar, slightly modified criterion is suitable for a general case of evaporating droplet.

Using the identity

$$\frac{dV}{dt} = \frac{dV}{dz} \cdot \frac{dz}{dt} = V \frac{dV}{dz} \qquad [8]$$

The equation [7] can be transformed into:

$$V \frac{dV}{dz} = \left(36\nu \frac{\rho}{\rho_p} \right) \frac{1}{d^2} \left(U(z) - V \right) - g \qquad [9]$$

This equation can now be integrated between the initial and final points of the trajectory to get:

$$-\frac{1}{2} V_0^2 = \left(36\nu \frac{\rho}{\rho_p} \right) \frac{1}{d^2} \left[\int_{z_{max}}^{z_{min}} U(z) dz - \int_{z_{max}}^{z_{min}} V dz \right] - g\left(z_{min} - z_{max} \right) \qquad [10]$$

The integral term containing plume velocity profile *U(z)*.is a known function, obtained upon specification of the latter profile.

The term involving unknown profile of the particle velocity *V(z)* needs, however, be estimated.

This integral term can be written (using [8] again) as:

$$\int_{z_{\max}}^{z_{\min}} V dz = \int_{z_{\max}}^{z_{\min}} V^2 dt \qquad [11]$$

and the simplest estimation (mean value theorem) yields:

$$\int_{z_{\max}}^{z_{\min}} V^2 dt \approx V(z_*) \int_{z_{\max}}^{z_{\min}} V dt = V(z_*)\left[z_{\min} - z_{\max}\right] \approx -\frac{|V_0|}{2}\left[z_{\min} - z_{\max}\right] = \frac{|V_0|}{2}\left[z_{\max} - z_{\min}\right] \qquad [12]$$

Therefore, the equation [10] gives:

$$-\frac{1}{2}V_0^2 = \left(36\nu\frac{\rho}{\rho_p}\right)\frac{1}{d^2}\left[\int_{z_{\max}}^{z_{\min}} U(z)dt - \frac{|V_0|}{2}\left(z_{\max} - z_{\min}\right)\right] - g\left(z_{\min} - z_{\max}\right) \qquad [13]$$

$$\frac{1}{d^2}\left[\int_{z_{\max}}^{z_{\min}} U(z)dz - \frac{|V_0|}{2}\left(z_{\max} - z_{\min}\right)\right] = \frac{1}{\left(36\nu\frac{\rho}{\rho_p}\right)}\left[g\left(z_{\min} - z_{\max}\right) - \frac{1}{2}V_0^2\right] \qquad [14]$$

and

$$d_{opt}^2 = \left(36\nu\frac{\rho}{\rho_p}\right)\frac{\left[\int_{z_{\max}}^{z_{\min}} U(z)dz - \frac{|V_0|}{2}\left(z_{\max} - z_{\min}\right)\right]}{\left[g\left(z_{\min} - z_{\max}\right) - \frac{1}{2}V_0^2\right]} \qquad [15]$$

Finally, one arrives at the estimation:

$$d_{opt} = \left[\left(36\nu\frac{\rho}{\rho_p}\right)\frac{\int_{z_{\max}}^{z_{\min}} U(z)dz - \frac{|V_0|}{2}\left(z_{\max} - z_{\min}\right)}{g\left(z_{\min} - z_{\max}\right) - \frac{1}{2}V_0^2}\right]^{1/2} \qquad [16]$$

At this point, plume velocity profile must be specified. The reference fire used for calculations is a methanol pool fire, which exhibits nearly constant burning rate over a wide range of pool diameters.

For a particular fire HRR, a corresponding pool diameter can be found from the burning rate assuming complete combustion of the fuel. Then, flame heights, virtual origin position, and plume velocity profile can be predicted by well-known correlations of Heskestad[11]. The plume profile, in particular, is given as:

$$U(z) = 3.4\left(\frac{g}{c_p T_\infty \rho_\infty}\right)^{1/3} \dot{Q}_c^{1/3} (z - z_0)^{-1/3} \qquad [17]$$

Velocity distribution in the flame zone is different. Velocity is nearly constant in the intermittent zone, and falls to zero following square-root dependence in the continuous zone[11]. Intermittent zone typically covers about *60%* of the total flame height[11]. Based on these estimations, velocity profile [17] can be extended into the flame zone as:

$$U(z) = \sqrt{\frac{5}{2}} U(L_f)\left(\frac{z}{L_f}\right)^{1/2} ; \qquad z \le \frac{2}{5} L_f \qquad [18]$$

$$U(z) = U(L_f); \qquad \frac{2}{5} L_f \le z \le L_f \qquad [19]$$

This procedure uniquely relates HRR to the plume geometry and thermal properties.

In the present example, half height of the flame is taken as a trajectory reverse point, i.e. $z_{min}=L_f/2$.

Upon integration of the profile [17]-[19], the following expression is obtained:

$$\int_{z_{\max}}^{L_f/2} U(z)dz = \frac{51}{10}\left(\frac{g}{c_p T_\infty \rho_\infty}\right)^{1/3} \dot{Q}_c^{1/3}\left[(L_f - z_0)^{2/3} - (z_{\max} - z_0)^{2/3}\right] - \frac{1}{2}U(L_f)L_f \approx$$

$$\approx \left(\frac{g}{c_p T_\infty \rho_\infty}\right)^{1/3} \dot{Q}_c^{1/3}\left[5\left[(L_f - z_0)^{2/3} - (z_{\max} - z_0)^{2/3}\right] - 1.7(L_f - z_0)^{-1/3} L_f\right] \qquad [20]$$

Equations [16] and [20] provide the estimation of the optimum droplet diameter.

Quality of prediction is tested against numerical solution of the equation of the droplet motion, coupled to the mass transfer equation. Description of the Lagrangian method of particle (droplet) tracking is widely available in the literature, e.g.[1,2].

Droplet initial velocity was kept constant in the computations at $V_0=20$ *m/s*. Initial droplet height was *3 m* for the present case, and *5 m* for the evaporating droplet analysis (below).

Prediction results for a non-evaporating droplet are presented in Fig. 3. There is an excellent agreement between the analytical estimation and the solution obtained from numerical analysis.

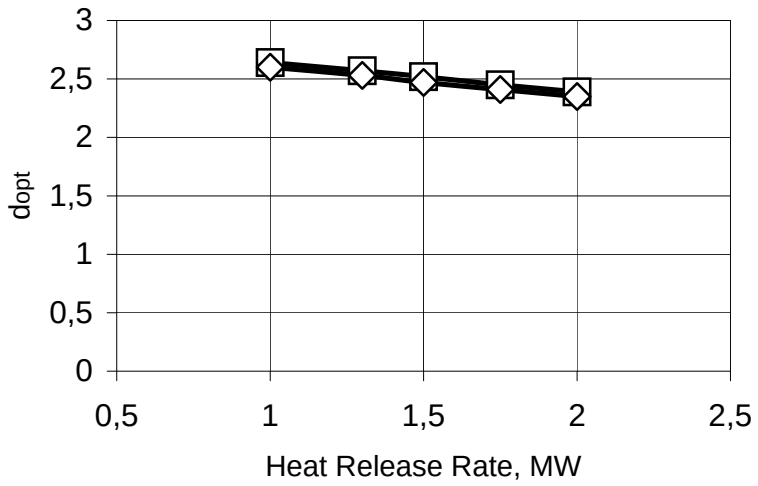

FIGURE 3. Comparison between optimum droplet diameters predicted by analytical formulae (16, 20) and by numerical analysis
□ - analytical; ◇ - numerical

Evaporating Droplet

Similar ideas are applicable for the droplet experiencing evaporation in fire plume and flame.

The optimum is defined in the following way: droplet trajectory ends at the surface of the material due to complete evaporation. This ensures, first of all, that droplet is delivered into the flame zone and completely evaporates in this zone, i.e. is not carried away by the plume. Secondly, major part of evaporation process is expected to occur in the flaming zone, since droplet will decelerate before it disappears at the surface. (Note that the point of complete evaporation is always also a point of zero velocity for the droplet trajectory). Therefore, the droplet will have large residence time in the flame. Strict mathematical proof of the above criterion is yet to follow.

Equation [9] is slightly modified to give:

$$d^2 V \frac{dV}{dz} = \left(36\nu \frac{\rho}{\rho_p} \right) \left(U(z) - V \right) - d^2 g \qquad [21]$$

For the droplet diameter history, a d^2-*law* of evaporation is assumed. This is a good approximation in most cases, including droplets moving in fire plumes, as can be confirmed, for example, by numerical analysis of the droplet motion.

Specifically, the d^2-*law* implies that the droplet surface area diminishes at a constant rate:

$$d_0^2 - d^2(t) = k_{ev} \cdot t \qquad [22]$$

which is equivalent to:

$$\frac{d}{dz}\left(d^2 \right) = -\frac{k_{ev}}{V} \qquad [23]$$

The evaporation constant, k_{ev}, is estimated as follows[12]:

$$k_{ev} = \frac{8k_g}{\rho_p c_p} \ln\left(1 + \frac{c_p}{L}\left(T_g - T_s\right)\right) \qquad [24]$$

Integration of equation [21] from the initial point down to the fuel surface gives:

$$-\frac{1}{2}V_0^2 d_0^2 + \frac{k_{ev}V_0}{4} = \left(36\nu\frac{\rho}{\rho_p}\right)\left[\int_{z_{\max}}^{0} U(z)dz - \int_{z_{\max}}^{0} V(z)dz\right] - g\int_{z_{\max}}^{0} d^2(z)dz \qquad [25]$$

It should be noted that integration by parts is performed on the LHS, with the relation [23] being taken into account.

Estimating the last two integrals on the RHS of [25] gives:

$$-\frac{1}{2}V_0^2 d_0^2 + \frac{k_{ev}V_0}{4} = \left(36\nu\frac{\rho}{\rho_p}\right)\int_{z_{\max}}^{0} U(z)dz + \left(36\nu\frac{\rho}{\rho_p}\right)\frac{V_0}{2}z_0 - gz_0\frac{d_0^2}{2} \qquad [26]$$

and, finally;

$$d_{opt} = \left[\left(36\nu\frac{\rho}{\rho_p}\right)\frac{\left[-\frac{V_0 z_0}{2} + \frac{k_{ev}V_0}{4} + \int_{z_{\max}}^{0} U(z)dz\right]}{\frac{V_0^2}{2} - \frac{gz_0}{2}}\right]^{1/2} \qquad [27]$$

The integrated gas velocity profile for the present case takes the following form:

$$\int_{z_{\max}}^{0} U(z)dz = \frac{51}{10}\left(\frac{g}{c_p T_\infty \rho_\infty}\right)^{1/3} \dot{Q}_c^{1/3}\left[\left(L_f - z_0\right)^{2/3} - \left(z_{\max} - z_0\right)^{2/3}\right] - \frac{13}{15}U\left(L_f\right)L_f \approx$$

$$\approx \left(\frac{g}{c_p T_\infty \rho_\infty}\right)^{1/3} \dot{Q}_c^{1/3}\left[5\left[\left(L_f - z_0\right)^{2/3} - \left(z_{\max} - z_0\right)^{2/3}\right] - 25.6\left(L_f - z_0\right)^{-1/3}L_f\right] \qquad [28]$$

Comparison with the numerical integration results are presented in Fig. 4 for a range of fire sizes spanning nearly order of magnitude in HRR. The agreement is particularly good for smaller fires (*~1 MW*) with the optimum diameter starting to be slightly underpredicted for larger fires. Overall, deviation of the analytical estimation from "exact" (numerical) solution does not exceed 13%.

Of the particular interest is a dependence of an optimum diameter on the fire HRR. The rate of the diameter increase with fire size is easily deducible from [27] in the form:

$$\frac{d}{d\dot{Q}}\left(d^2\right) \propto \dot{Q}^{-9/30} = \dot{Q}^{-0.3} \tag{29}$$

In reality, the rate is slightly bigger, as suggested by Fig. 4. It is intended to perform more sophisticated analysis of the equation [21] in order to improve predictions.

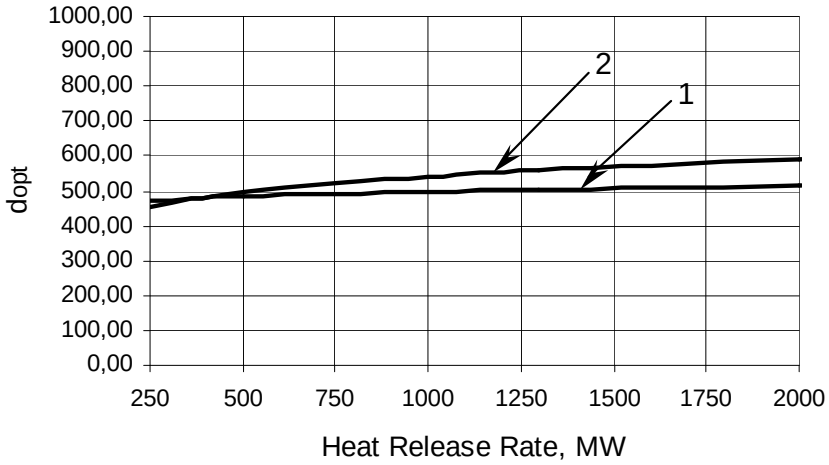

FIGURE 4. Comparison between optimum droplet diameters predicted by analytical formulae [27], [28] and by numerical analysis (1 - analytical; 2 - numerical)

The proposed concept of optimum droplet diameter allows scientifically clear definition of water mist to be proposed. At the present, definitions used in the literature are rather arbitrary. One can define water mist spray as such that aims at gaseous flame suppression, rather than surface suppression. In this mode, droplets will evaporate above the surface of burning material. If such a definition is adopted then it becomes clear that the actual droplet size in water mist spray cannot be specified without referring to a particular fire. Indeed, minimum diameter of droplets penetrating through the flame towards surface is a function of fire Heat Release rate (Fig. 4). With the help of the estimation of optimum droplet diameter proposed in the present paper, one can quantitatively define water mist spray for a particular fire with a specific HRR as such that droplet diameters in the spray satisfy

$$d \le d_{opt}\left(\dot{Q}\right) \tag{30}$$

CONCLUSIONS

Equations of droplet motion and evaporation in fire plumes do not admit exact solutions. Despite of this, it is not difficult to derive a range of useful quantitative results in an analytical manner. One possible application of the analysis, demonstrated in the present paper, is the concept of an optimum droplet diameter for fire fighting.

A new concept of an optimum diameter has been proposed, based on the strategy of complete droplet evaporation in the flame. Such definition would be of particular importance for water mist suppression systems, relying on gaseous flame suppression.

The proposed definition of the optimum droplet requires analysis of the droplet motion and evaporation within fire plume and flame. The analysis has been performed using well-established

equations of the droplet dynamics. Despite the absence of exact solutions, the nature of applied optimum criterion allowed quantitative results to be derived.

An optimum diameter has been predicted for the fires in the range from *250* to *2000 kW* to within 13%. An optimum diameter has turned out to be a weak function of the fire Heat Release Rate. The form of the latter dependence has been established.

Results are encouraging in a sense that a rather complicated problem has been solved with a good accuracy by fairly simple considerations. It is planned to perform more sophisticated analysis in order to improve results further.

REFERENCES

1. Novozhilov, V., Harvie, D.J.E., Green, A.R. and Kent, J.H., "A Computational Fluid Dynamics Model of Fire Burning Rate and Extinction by Water Sprinkler", Combustion Science and Technology, 123:1-6, 227-245, 1997.
2. Novozhilov, V., Harvie, D.J.E., Kent, J.H., Apte, V.B. and Person, D., "A Computational Fluid Dynamics Study of Wood Fire Extinguishment by Water Sprinkler", Fire Safety Journal, 29:4, 259-282, 1997.
3. Novozhilov, V., "Fundamentals and Application of Fire Suppression Modeling", Proceedings of the Second NRIFD Symposium – Science, Technology and Standards for Fire Suppression Systems, 195-215.
4. Grant, G., Brenton, J. and Drysdale, D., "Fire Suppression by Water Sprays", Progress in Energy and Combustion Science, 26, 79-130, 2000.
5. Herterich, O., Water as an Extinguishing Agent, Alfred Hüthig Publishing Company, Heidelberg, 1960.
6. Ohkubo, H. and Nishio, S., "Study on Accurate Prediction of Heat Transfer Characteristics of Mist Cooling", International Journal of Japanese Society of Mechanical Engineers, Series II, 33:2, 326-332, 1990.
7. Kaleta, A., "Effect of Drop Size on Extinguishing Effectiveness of a Water Spray", Archiwum Combustionis, 6:3-4, 201- 212, 1986.
8. Kuo, K.K., Principles of Combustion, pp. 1-760, Wiley, New York, 2005.
9. Dickerson, R.A. and Schuman, M. D., Journal of Spacecraft, 99, 1960.
10. Polyanin, A.D. and Zaitsev, V.F., Exact Solutions for Ordinary Differential Equations, 2nd ed., pp. 1-787, Chapman & Hall/CRC, Boca Raton, 2003.
11. Karlsson, B. and Quintiere, J.G., Enclosure Fire Dynamics, pp. 1-315, CRC Press, Boca Raton, 2003.
12. Lefebvre, A., Atomization and Sprays, Hemisphere, New York, 1989.