FROUDE-MODELING-BASED GENERAL SCALING RELATIONSHIPS FOR WATER-SPRAY-FIRE-PLUME INTERACTIONS

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ABSTRACT

Based on the Froude modeling concept, Heskestad proposed a set of scaling relationships for the spray-plume interaction for high droplet Reynolds number conditions ($Re_D \geq 10$). The droplet Reynolds number is defined as the ratio of the product of droplet diameter and the absolute value of the droplet velocity relative to the gas velocity over the gas kinematic viscosity. Recently, Yu showed theoretically that the scaling methodology can be extended to low droplet Reynolds number conditions ($Re_D \leq 1$) except for the scaling requirement for droplet size. High droplet Reynolds number conditions in general prevail in sprinkler applications and low droplet Reynolds conditions usually take place in water mist applications. To bridge the scaling gap, this paper describes a generalization of the Froude modeling approach and presents a set of general scaling relationships applicable to spray-plume interactions for all droplet Reynolds number conditions. These general scaling relationships should be experimentally validated before engineering applications.

KEYWORDS: Physical scaling, Spray-plume interaction

NOMENCLATURE

A	frontal area of water droplet
C_D	drag coefficient
$C_{p,g}$	specific heat of gas
$C_{p,w}$	specific heat of water
d	droplet diameter
$\vec{F}_d$	droplet drag force vector
$\vec{g}$	gravitational acceleration
h_d	droplet heat transfer coefficient
k_g	thermal conductivity of gas
L	characteristic length
L_v	latent heat of vaporization
m_d	mass of water droplet
$\dot{m}_e$	droplet vaporization rate
$\vec{\dot{m}}''_w$	water mass flux vector
$\dot{M}_e$	total vaporization rate of droplets
$\dot{M}_w$	total water mass discharge rate
n'''	droplet number density
Nu_d	droplet Nusselt number
Pr	Prandtl number
Δp	dynamic pressure of the gas flow
$\dot{Q}_c$	fire convective heat release rate

Re_d	droplet Reynolds number
$\vec{S}$	total drag force of droplets per unit volume
t	time
T	temperature
u	magnitude of velocity vector
$\vec{u}$	velocity vector
v'''_w	total droplet volume per unit volume
$\dot{V}_w$	total volumetric water discharge rate
ρ_g	gas density
ρ_w	water density
ν_g	gas kinematic viscosity

Subscripts

c	characteristic quantities
cool	cooling
d	water droplet
g	gas medium
¥	Ambient

INTRODUCTION

Automatic water-based fire protection systems, such as fire sprinkler systems, water spray systems and water mist systems, deliver water to the fire area or the entire fire environment typically by water sprays discharged from a pre-configured sprinklers or nozzles. For each type of sprinklers and nozzles, the droplets in the discharged water sprays normally have diameters ranging in a continuous spectrum, depending on the discharging water pressure, orifice diameter and other features of the sprinklers and nozzles[1]. During air-borne, the vaporizing water droplets are constantly exchanging their momentum with the gas medium in the fire environment. The simultaneous momentum, mass and heat transfers between water droplets and fire gases continually modify the droplet trajectories, droplet sizes and the pattern of gas current. These droplet transport phenomena eventually affect the amount and distribution of water fluxes realized on the fuel surface, help reducing the oxygen concentration in the fire environment by water vapor generation, and at the same time cool the fire environment. Therefore, the water-spray-fire-plume interaction has a profound impact to the overall performance of water-based fire protection systems.

Attempts have been performed to simulate the spray-plume interaction numerically with encouraging results[2-5]. However, these numerical simulations all require the starting conditions of discharged water sprays, which are usually unknown a priori. To date, existing numerical models for spray formation are still limited to simple nozzles[6] and have not been thoroughly validated, thus are not yet ready for the industrial sprinklers and nozzles which generally have much more complex configurations. In addition to the starting water spray condition and spray-plume interaction, a numerical model for fire suppression simulation needs to be able to track the water transport on and in the storage array of combustibles and the response of combustible burning to the water application. Validated numerical models for the latter two fire suppression processes are currently unavailable to be integrated with the more mature spray-plume interaction model for reliable fire protection evaluation. Before a reliable numerical simulation tool for fire suppression is available, a physical scaling approach is believed to be a viable alternative to aid in the engineering and evaluation of water-based fire protection systems. The scaling approach helps reduce the system development cost by conducting testing in more affordable scaled-down facilities.

In the 1970s, Heskestad proposed a set of scaling relationships for the interaction of water sprays and fire plumes in geometrically similar spaces[7]. These scaling relationships were developed by maintaining constant Froude number in the buoyancy-induced gas flow, preserving dynamic interactions between water droplets with the gas flow, and conserving scalar variables in the physical domain. The scaling relationships derived by Heskestad are specifically for sprays with a significant inertia compared to the gas flow (as typically for sprinkler systems): a high droplet Reynolds number condition ($Re_D \geq 10$). This condition leads to the requirement that droplet size be scaled with ½-power of physical dimension. Recently, the aforementioned scaling relationships were satisfactorily tested with fire suppression experiments conducted in open space under high droplet Reynolds number conditions where high droplet velocity relative to gas velocity was prevalent [8,9].

By flooding an entire enclosure with water mist, the water mist tends to move closely with the circulating gas current, rendering low droplet Reynolds number situations ($Re_D \leq 1$). Theoretical analysis showed that the scaling relationships for high Reynolds number conditions could be broadly extended to low Reynolds number conditions, except that the droplet size should be scaled with a ¼-power of length scale, instead of the ½-power found for high Reynolds number conditions.[10] A series of fire suppression experiments was subsequently conducted to verify the validity of such a modeling extension[11].

It is apparent that another set of scaling relationships is required for situations where the droplet Reynolds numbers range between 1 and 10. Instead of developing a specific new set of scaling requirements to fill the gap, it is desirable that general scaling relationships could be derived for any droplet Reynolds number conditions. This set of general scaling relationships for spay-plume interaction can then be integrated with the fire-scaling techniques similar to those described previously[12-14] for the evaluation of fire suppression performance in scaled-up or scaled-down fashions. This paper describes the derivation of these general scaling relationships for spray-plume interaction based on the Froude modeling concept.

DERIVATION OF THE GENERAL SCALING RELATIONSHIPS

Before the derivation, two dimensionless parameters need to be defined: one is the droplet Reynolds number and the other is the Froude number.

As mentioned above, the droplet Reynolds number is defined as:

$$\mathrm{Re}_d = \frac{d\left|\vec{u}_d - \vec{u}_g\right|}{\nu_g} \quad , \qquad [1]$$

where d and $\vec{u}_d$ are the droplet diameter and droplet velocity vector, and $\vec{u}_g$ and ν_g are the gas velocity vector and gas kinematic viscosity, respectively.

On the other hand, the Froude number is defined as:

$$\mathrm{Fr} = \frac{\rho_g u_g^2}{gL(\rho_\infty - \rho_g)} \quad , \qquad [2]$$

where ρ_g and ρ_∞ are fire gas temperature and ambient temperature, respectively, g is gravitational acceleration, L is the characteristic dimension of the fire environment, and u_g is the scalar value of the gas velocity vector $\vec{u}_g$.

As proposed by Heskestad[7], to properly scale the interaction of water droplets and buoyancy-induced flow in geometrically similar spaces, three factors have to be preserved: 1) Froude number of the buoyancy-induced gas flow, 2) momentum transfer characteristics between the water droplets and the gas flow, and 3) droplet vaporization characteristics.

By conserving gas temperature, a constant Froude number leads to the following requirements for the characteristics of buoyancy-induced gas flows:

$$u_{g,c}^2 \propto L \Rightarrow u_{g,c} \propto L^{1/2} \quad [3]$$

$$t_c \propto \frac{L}{u_{g,c}} \propto L^{1/2} \quad [4]$$

$$\Delta p \propto \rho_g u_{g,c}^2 \propto (L^{1/2})^2 \propto L \quad [5]$$

and

$$\dot{Q}_c \propto \rho_g u_{g,c} (T_g - T_\infty) L^2 \propto L^{1/2} L^2 \propto L^{5/2} \quad [6]$$

where $\dot{Q}_c$ is the convective heat release rate of the fire and other symbols are defined in the Nomenclature Listing.

Assuming that vaporizing droplets are subject to only gravitational force and drag force, the equation of motion of a single water droplet is expressed by:

$$\frac{d(m_d \vec{u}_d)}{dt} = m\vec{g} - \frac{1}{2} C_D A \rho_g \left|\vec{u}_d - \vec{u}_g\right| (\vec{u}_d - \vec{u}_g), \quad [7]$$

where the mass of the droplet is:

$$m_d = \frac{\pi}{6} \rho_w d^3, \quad [8]$$

and C_D and A are the drag coefficient and the frontal area of the droplet, respectively.

For a spherical particle, the drag coefficient[15] can be expressed with power-law functions of the droplet Reynolds number such as:

$$C_D = \begin{cases} \dfrac{24}{Re_d} & \text{for} \quad Re_D \le 1 \\ \dfrac{27}{Re_d^{0.8}} & \text{for} \quad 1 < Re_D \le 10 \\ \dfrac{12}{Re_d^{0.5}} & \text{for} \quad 10 < Re_D \le 500 \end{cases} \quad [9]$$

It has been reported that the drag coefficient for a vaporizing droplet is very close to that for a non-vaporizing droplet[16]. Therefore, it is reasonable that Eq. [9] is used to estimate the drag coefficient of a vaporizing droplet in the respective ranges of droplet Reynolds numbers.

It was pointed out in the INTRODUCTION that the droplet size has been shown to scale differently with the physical dimension for $Re_D \le 1$ and $10 < Re_D \le 500$ although the scaling requirements for other system parameters are identical [8,10]. It is desirable that a common set of scaling relationships for

any droplet Reynolds number conditions could be obtained and the scaling gap for $1 < Re_D \leq 10$ can thus be bridged.

In general, the drag coefficient can be expressed by:

$$C_D = \frac{k}{Re^x} \qquad [10]$$

where k and x are constants which give the best regression of C_D for a range of droplet Reynolds numbers.

Substituting Eq. [8], Eq. [10] and $A = \pi d^2/4$ into Eq. [7], we have

$$\frac{d\vec{u}_d}{dt} + 3\vec{u}_d \frac{\frac{dd}{dt}}{d} = \vec{g} - \frac{3}{4}\frac{k\nu_g^x \rho_g}{\rho_w} d^{-(1+x)} \left|\vec{u}_d - \vec{u}_g\right|^{1-x} (\vec{u}_d - \vec{u}_g) \qquad [11]$$

The droplet velocity can be expressed with

$$\vec{u}_d = \frac{L}{t_c}\frac{d(\frac{\vec{X}_d}{L})}{d(\frac{t}{t_c})} \qquad [12]$$

where L and t_c are the characteristic length and time associated with the gas flow in a control volume.

So the acceleration of the droplet can be expressed with

$$\frac{d\vec{u}_d}{dt} = \frac{L}{t_c^2}\frac{d^2(\frac{\vec{X}_d}{L})}{d(\frac{t}{t_c})^2} \qquad [13]$$

Substituting Eqs. [12] and [13] into Eq. [11], we have

$$\frac{d^2(\frac{\vec{X}_d}{L})}{d(\frac{t}{t_c})^2} + 3\frac{d(\frac{\vec{X}_d}{L})}{d(\frac{t}{t_c})}\frac{d(d/\Lambda)}{d(t/t_c)} = \frac{t_c^2}{L}\vec{g} - \frac{3}{4}\frac{k\nu_g^x \rho_g}{\rho_w}\frac{t_c^2}{L} u_{g,c}^{2-x} d^{-(1+x)} \left|\frac{L}{t_c u_{g,c}}\frac{d(\frac{\vec{X}_d}{L})}{d(\frac{t}{t_c})} - \frac{\vec{u}_g}{u_{g,c}}\right|^{1-x} \left(\frac{L}{t_c u_{g,c}}\frac{d(\frac{\vec{X}_d}{L})}{d(\frac{t}{t_c})} - \frac{\vec{u}_g}{u_{g,c}}\right) \qquad [14]$$

where $u_{g,c}$ is the characteristic buoyancy-induced gas velocity. In Eq. [14], Λ is a self-fulfilling scaling parameter in the second term on the left-hand side of the equation. As a result, the function of Λ in terms of characteristic quantities has to be derived from the similarity conditions required in the other terms of Eq. [14] so that the scaled spray pattern will be invariant in different model scales.

In order to reproduce the same relative droplet trajectory pattern in different model scales, the following coefficients in Eq. [14] have to be invariant:

$$\frac{t_c^2}{L} = \text{constant}, \qquad [15]$$

$$\frac{k\nu_g^x \rho_g}{\rho_w} \frac{t_c^2}{L} u_{g,c}^{2-x} d^{-(1+x)} = \text{constant} \qquad [16]$$

and

$$\frac{L}{t_c u_{g,c}} = \text{constant} \qquad [17]$$

Based on Eqs. [3] and [4], both conditions required in Eqs. [15] and [17] and self-fulfilled. In Eq. [16], the gas and water properties do not change between different model scales because the temperatures are conserved, per the modeling requirement. Therefore, to satisfy Eq. [16], the functional relationship for droplet size has to be

$$d \propto u_{g,c}^{(2-x)/(1+x)} \propto L^{(2-x)/2(1+x)} \qquad [18]$$

The modeling requires not only that the relative spray patterns in different scales have to be reproduced, but also that the similarity of the gas flow patterns has to be maintained. As water droplets travel in the gas medium, they exchange momentum with the gas current via the interacting drag force between the droplets and gas medium. Assuming that the frictional loss is negligible, the total force exerted by the droplets to the gas medium per unit volume is:

$$\vec{S} = \frac{\vec{F}_d \left| \dot{\vec{m}}_w'' \right|}{m_d \left| \vec{u}_d \right|} \qquad [19]$$

where

$$\vec{F}_d = \frac{1}{2} C_D A \rho_g \left| \vec{u}_d - \vec{u}_g \right| (\vec{u}_d - \vec{u}_g) \qquad [20]$$

and $\dot{\vec{m}}_w''$ is the water mass flux vector.

After combining Eqs. [10], [19] and [20], we have

$$\bar{S} = \left(\frac{3\rho_g}{4\rho_w}\right) k\nu_g^x d^{-(1+x)} \frac{\left| \vec{u}_d - \vec{u}_g \right|^{1-x} \left| \dot{\vec{m}}_w'' \right|}{\left| \vec{u}_d \right|} (\vec{u}_d - \vec{u}_g). \qquad [21]$$

To reproduce the gas flow pattern in different model scales under water discharge, the absolute value of Eq. [21] has to be proportional to the characteristic pressure gradient of the gas flow. Since ν_g is invariant, we have

$$d^{-(1+x)} \frac{\left|\vec{u}_d - \vec{u}_g\right|^{2-x} \left|\vec{\dot{m}}''_w\right|}{\left|\vec{u}_d\right|} \propto \frac{u_{g,c}^2}{L} \qquad [22]$$

Equation [12] indicates that $\vec{u}_d$ is scaled with $L^{1/2}$. As a result,

$$\left|\vec{\dot{m}}''_w\right| \propto \frac{d^{(1+x)} \left|\vec{u}_d\right| \left|\vec{u}_d - \vec{u}_g\right|^{x-2} u_{g,c}^2}{L} \propto L^{1/2} \qquad [23]$$

Equation [23] states that the water fluxes in different physical scales are scaled with the square root of the characteristic lengths. As a result, the number of droplets per unit volume is scaled with

$$n''' = \frac{\left|\vec{\dot{m}}''_w\right|}{m_d \left|\vec{u}_d\right|} \propto L^{3(x-2)/2(1+x)} \qquad [24]$$

Consequently, the total volume of water droplets per unit volume is scaled with

$$v'''_w \propto n''' d^3 \propto L^0 \qquad [25]$$

which states that the total volume of water droplets per unit volume is conserved in different scales as the gas temperature is.

The total water mass discharge rate can be calculated by integrating the water fluxes under no fire conditions with

$$\dot{M}_w = \oint_A \vec{\dot{m}}''_w \bullet d\vec{A} \qquad [24]$$

where A is the total surface area of the control volume. Therefore,

$$\dot{V}_w = \frac{\dot{M}_w}{\rho_w} \propto L^{1/2} L^2 \propto L^{5/2} \qquad [25]$$

which states that the total volumetric water discharge rate has to be scaled with $L^{5/2}$.

Under different Reynolds number conditions, the Reynolds analogy for heat transfer gives the following general relationship[17],

$$Nu_d = \frac{h_d d}{k_g} \propto Pr\, Re_d^{1-x} \qquad [26]$$

where Nu and Pr are Nusselt number and Prandlt number, respectively, h_d is the heat transfer coefficient on the droplet surface and k_g is the thermal conductivity of the gas medium.

Assuming that the droplet is heated up uniformly, the droplet temperature in the initial heat-up period is approximated with

$$m_d C_{p,w} \frac{dT_d}{dt} \cong A h_d (T_g - T_d) \qquad [27]$$

By normalizing Eq. [27], we have

$$\frac{d(\frac{T_d}{T_\infty})}{d(\frac{t}{t_c})} \propto t_c d^{-2} \mathrm{Re}_d^{1-x} \propto L^0 \qquad [28]$$

which states that the instantaneous droplet temperature is reproduced in different physical scales, consistent with the scaling requirement that the scalar variables is conserved.

Since both the droplet temperature and gas temperature are conserved, the droplet vaporization rate per droplet, $\dot{m}_e$, is proportional to

$$\dot{m}_e \propto h_d d^2 \propto \mathrm{Re}_d^{1-x} d \propto L^{(5-4x)/(2+2x)} \qquad [29]$$

When the droplet velocity relative to the gas velocity is small, the quasi-steady droplet vaporization rate is proportional to $d(k_g/C_{p,g})\ln(1+B)$[18], where $B = (C_{p,g}/L_v)(T_g-T_d)$. Since $C_{p,g}$ and L_v are approximately constant and temperature is conserved in the modeling, B can be regarded as constant; thus, the droplet vaporization rate is only proportional to the droplet diameter for $\mathrm{Re}_d \le 1$.

When $\mathrm{Re}_d \le 1$, the value of x is 1 according to Eq. [9]. As a result, Eq. [29] leads to that the droplet vaporization rate is proportional to droplet size, consistent with the expectation for situations where the relative velocity between the droplet and gas is small. On the other hand, $x = 1/2$ for $500 \ge \mathrm{Re}_D > 10$. Equation [29] gives that $\dot{m}_e \propto \mathrm{Re}_d^{1/2} d$, which reproduces the functional relationship previously reported for $\mathrm{Re}_d > 20$.[19]

The total vaporization rate in the control volume, $\dot{M}_e$, is the product of number of droplets per unit volume, domain volume, and vaporization rate per droplet. Therefore,

$$\dot{M}_e = \int_V n''' \dot{m}_e dV \propto L^{(3x-6)/(2+2x)} L^{(5-4x)/(2+2x)} L^3 \propto L^{5/2} \qquad [30]$$

Consequently, the total cooling rate, $\dot{Q}_{cool}$, in the control volume is scaled with

$$\dot{Q}_{cool} \propto L^{5/2} \qquad [31]$$

Furthermore, the droplet lifetime, t_d, is:

$$t_d = \frac{m}{\dot{m}_e} \propto \frac{d^3}{\dot{m}_e} \propto \frac{L^{3(2-x)/2(1+x)}}{L^{(5-4x)/(2+2x)}} \propto L^{1/2} \qquad [32]$$

which is consistent with the dependence of time scale on length scale for the gas flow, as shown earlier.

Finally, it is worth mentioning that the individual gas concentrations are also conserved in different physical scales. Since the convective heat release rate of the fire is proportional to the chemical heat

release rate for the same fuel, the rates of produced combustion products are expected to be proportional to $L^{5/2}$. Since the water vapor generation rate is scaled with $L^{5/2}$, the total water vapor generation rate in the control volume from both combustion and vaporization is therefore proportional to $L^{5/2}$. Since the entrainment rate to the fire is proportional to the product of the surface area ($\propto L^2$) and the entrainment velocity ($\propto L^{1/2}$), the rate of air entrained to the fire is therefore proportional to $L^{5/2}$. Since the concentration is proportional to the ratio of the generation rate and the entrainment rate, the gas concentrations are therefore conserved.

Table 1 summarizes the general scaling relationships derived above and the scaling relationships obtained previously for $Re_D \leq 1$ and $10 < Re_D \leq 500$. As shown, all the scaling relationships are identical except for drop number density and drop size. By using the corresponding *x* values, the scaling power indexes for $Re_D \leq 1$ and $10 < Re_D \leq 500$ can be obtained accordingly from the general scaling relationships.

VALIDATION OF SCALING RELATIONSHIPS

As discussed above, the Froude modeling is based on the view point of fluid mechanics, which does not include factors such as fire radiation and combustion. However, since the Froude modeling preserves the relative fire environment and water spray pattern in different model scales, it is expected that fire suppression results could also be closely reproduced. However, the modeling approach should be thoroughly validated before being applied to engineering applications. Since radiation transmission in fire environment cannot be exactly scaled under atmospheric conditions, it is imperative to determine the range of scale ratios in which acceptable scaling results are obtained. Besides fire radiation, the impact of air vitiation and the fuel surface effect on fuel pyrolysis should also be evaluated.

TABLE 1. Comparison of scaling relationships

Scaling Parameters	**$Re_d \leq 1$**	**$10 < Re_d \leq 500$**	**Any Re_d**
Drag Coefficient	Re_d^{-1}	$Re_d^{-1/2}$	Re_d^{-x}
Dimension	L^1	L^1	L^1
Time	$L^{1/2}$	$L^{1/2}$	$L^{1/2}$
All Scalar Parameters except Drop Number Density	L^0	L^0	L^0
Drop Number Density	$L^{-3/4}$	$L^{-3/2}$	$L^{(3x-6)/(2+2x)}$
Velocity	$L^{1/2}$	$L^{1/2}$	$L^{1/2}$
Ventilation rate	$L^{5/2}$	$L^{5/2}$	$L^{5/2}$
Fire Convective Heat Release Rate	$L^{5/2}$	$L^{5/2}$	$L^{5/2}$
Total Water Discharge Rate	$L^{5/2}$	$L^{5/2}$	$L^{5/2}$
Water Flux	$L^{1/2}$	$L^{1/2}$	$L^{1/2}$
Total Cooling Rate	$L^{5/2}$	$L^{5/2}$	$L^{5/2}$
Drop Size	$L^{1/4}$	$L^{1/2}$	$L^{(2-x)/(2+2x)}$

To date, the Froude modeling presented above has been partially validated with experiments[8,9,11]. As mentioned in the INTRODUCTION, Heskestad tested the modeling applicability for fire extinguishment in open space under high drop Reynolds number conditions. In Ref. 9, Heskestad demonstrated experimentally that for a constant ratio of nozzle height above the burner versus effective orifice diameter, for methane sand-burner fires in 10-to-1 scale ratio, the water discharge rate and the fire size at extinction can be correlated using the modeling approach. Later on in Ref. 10, he

extended the fire extinction correlation to different nozzle-height-to-orifice-diameter ratios for methane fires. He also showed that the correlation trend for heptane pool fires is consistent with that for methane fires, except that the heptane pool fires require higher water discharge rate at fire extinction for the same fire heat release rate.

A series of fire cooling experiments was conducted to evaluate the validity of the scaling relationships derived for low drop Reynolds number conditions. These experiments, conducted under fire products collectors, quantified the water mist cooling of fire gases in open space. Three methane burners with 1, 3 and 9 scale ratios were used and three sets of corresponding water mist nozzles were selected to produce water mist discharges closely meeting the scaling requirements. The water mist was introduced into the fire plume by entrainment to reproduce the low drop Reynolds number flow scenario. The experimental results showed that, under this scenario, the water mist cooling of fire gases was scaled with 2.5 power of the scale ratio, as expected for low drop Reynolds number conditions.

CONCLUSIONS

A set of general scaling relationships for spray-plume interaction based on the Froude-modeling concept is presented in this paper, which is applicable to any drop Reynolds number conditions. These general relationships are consistent with those developed previously for high droplet Reynolds number conditions where $Re_D \geq 10$, and the low Reynolds number conditions where $Re_D \leq 1$. High droplet Reynolds number conditions in general prevail in sprinkler applications, low droplet Reynolds number conditions typically occur in fire suppression/extinguishment applications where water mist is delivered to the shielded fires by suspending water mist in gas current. The general relationships bridge the current scaling gap between $1 < Re_d \leq 10$. These relationships have been partially validated experimentally. However, additional validation work is required before applying this modeling technique to engineering applications.

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