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Evaporation of a Water Droplet in High-Temperature Steam

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Abstract

A modified interfacial heat transfer correlation between a dispersed water droplet and ambient superheated steam is proposed and compared with available experimental data and other correlations. Modified one overcomes the inherent deficiencies of Lee and Ryley's interfacial heat transfer correlation that ignored the effects of steam superheating which can not be neglected especially in the reflood situation of a loss-of-coolant accident. Modified one is represented by

$$Nu = \frac{x_{actual}}{x_{equilibrium}}(2 + 0.74Re_M^{1/2}Pr_f^{1/3}), \quad \text{or}$$

$$Nu = \frac{h_{fg}}{(h_v - h_f)}(2 + 0.74Re_M^{1/2}Pr_f^{1/3}).$$

In the present correlation the effect of possible subcooling of a water droplet is not taken into consideration. Comparison of the above correlation with currently available measurement data for a water droplet in high temperature gas flow shows that the proposed one correlates well with the measurement data where the degree of superheating is negligible and considerable.

Key Words : droplet, dispersed flow, interface heat transfer, reflood, LOCA

1. Introduction

Dispersed droplet flow is often encountered in the reflood phase of a loss-of-coolant accident (LOCA), spray flows to quench fire and air-fuel premixing of high-pressure combustors. Significant portions of the droplets can have Reynolds numbers on the order of 100. Emphasis is on the interface heat transfer of a water droplet during the reflood phase of a LOCA in this paper.

Dispersed droplet flow and its interfacial heat transfer is important in the reflood phase because they provides precursory cooling of fuel and steam before the quenching of nuclear core eventually takes place by the emergency core cooling water. Dispersed water droplets are in the form of a large number of discrete droplets convecting and vaporizing in a continuous steam space, and their mathematical description involves complex nonlinear couplings of mementum, energy and mass exchange. Regardless of the macroscopic complexity of the flow field, the traditional modeling approach for such a flow generally involves specifying the governing equations for a single, isolated droplet. This is often the case in the experimental measurements of interfacial heat transfer for liquid sprays also. Those approaches can be justified with respect to the fact that the void fraction of gas phase in the reflood phase of a LOCA is generally greater than 95% and the thickness of the film formed by vaporization is thin enough compared with the diameter of a water droplet. In this circumstance, interactions between the droplets are negligible and each droplet can be modeled to be isolated from neighboring droplets. The derived equations are applied to general situation of conglomerate of droplets in the steam, and sometimes its application is extended to the condition of steam bubbles in the superheated liquid as well.

Lee and Ryley [1] developed a correlation for an interfacial heat transfer between a water droplet and superheated steam, which is suspended at the tip of a fine horizontal glass fiber. The correlation is paid special attention in LOCA analysis because it is based on the evaporation of a water droplet in steam environment unlike other experiments done in air space, and because its modified form is used in the so-called best-estimate thermal-hydraulic analysis codes like RELAP5 [2] and TRAC [3]. Lee and Ryley' s original correlation can be expressed by

$$Nu_f (1+B) = 2 + 0.6\, Re_M^{1/2} Pr_f^{1/3}, \tag{1}$$

Coefficient of the second term is found to exceed 0.6 and 0.552 of Ranz and Marshall [4] and Froessling [5], respectively. This might be caused by the differences in the size and the species of the liquid droplets and other experimental conditions. Ranz and Marshall performed the experiment for a water droplet in air and Froessling for droplets of water, aniline and nitrobenzene in air. From the correlations of Lee and Ryley, Ranz and Marshall, and Froessling, it is found that the coefficient of the non-dimensional number term is dependent on the interrelationship of physical properties of liquid phase and gas phase. Degree of superheating of the steam in Lee and Ryley' s experiment was 3-34°C and Reynolds number was 64-250. In the above three correlations, characteristic length of Reynolds number was droplet diameter while other properties were evaluated at film temperature or ambient temperature. The film temperature is defined as the mean of droplet surface temperature and ambient gas temperature. Lee and Ryley do not explicitly mention whether the properties are evaluated at film temperature or ambient temperature, but the difference can be neglected because the degree of superheating is very small.

In case of high superheating of the free stream gas, the effect of evaporation takes place in two folds. Firstly, because of evaporation, the temperature and the composition surrounding the droplets are different from the free stream conditions; secondly, mass efflux from evaporation may affect the flow field in the vicinity of the droplet. Together, these effects can significantly alter the heat and mass transfer processes. At low free stream temperature, the effect of vapor

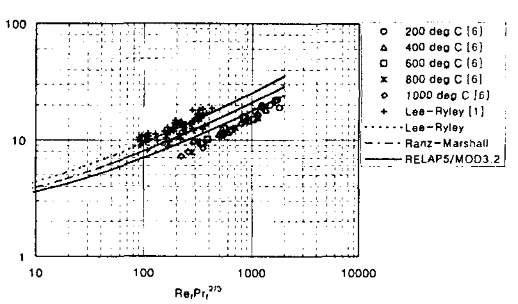

Fig. 1. Comparison of the Data of Lee-Ryley and Yuen-Chen with Other Correlations

concentration can be neglected but this is not true at higher temperatures. The effect of mass efflux is usually taken into account by the use of mass transfer number. The effect of variable properties can be taken into account by either the reference state method or the use of a correction factor. With low superheating of the free stream steam as in the experiments of Lee-Ryley and Ranz-Marshall, Reynolds and Prandtl numbers evaluated at film condition and at free stream gas condition give negligible differences. If the temperature difference between liquid phase and gas phase becomes considerable, Lee and Ryley-type correlation is necessary to be corrected. Yuen and Chen' s measurement [6] of Fig. 1 show considerable deviations from Lee and Ryley' s correlation. Yuen and Chen' s experiment was conducted with water and methanol droplets at the air temperature range of approximately 200-1000 ℃ and Reynolds number range of 200-2000. Shown in Fig. 1 are exclusively for water droplets. Yuen and Chen' s correlation is represented by

$$Nu_f(1+B) = 2 + 0.6\, Re_M^{1/2} Pr_f^{1/3}, \qquad (2)$$

regardless of droplet species, while careful examination of the data shows consistently lower values for methanol droplet. The properties were evaluated at film conditions except the free stream density in the Reynolds number. Mass transfer number $B = (h_\upsilon - h_d)/L$. A factor of $(1+B)$ is necessary to reflect the effect of gas superheating. In case of high-temperature superheated steam condition like in the experiment of Yuen and Chen, Reynolds and Prandtl numbers evaluated at free stream condition become significantly different from those evaluated at film condition. Yuen and Chen' s correlation is basically of Ranz-Marshall' s on which the correction factor is applied and Reynolds number evaluation is modified. Another correction factor of $1/(1+B_f)^{0.7}$ was proposed by Renksizbulut and Yuen [7] for freely suspended droplets of water, methanol and heptane in hot air tunnel with Reynolds number range of 25-2000. The properties were evaluated at the film condition except the free stream density in Reynolds number. Mass transfer number B_f was $(1+Q_R/Q_C)(h_\upsilon - h_d)/L$. The necessity of the exponent 0.7 comes from the data of heptane. Water and methanol data are well correlated even with the exponent 1.0, and it becomes exactly Yuen-Chen' correlation if Q_R/Q_C is neglected.

The reflood phase of a LOCA covers the steam condition of negligible and considerable superheating. The necessity of the unified equation is manifest, which correlates with both of data of negligible and considerable degree of steam superheating. Unfortunately, as shown in Fig. 1, two groups of data are separated from each other. RELAP5/MOD3.2 even reduced the coefficient of the non-dimensional parameters to 0.5 for the application to LOCA analysis, and its closeness to high-temperature data is obtained but it is inevitable to deviate from Lee-Ryley' s data. The purpose of present paper is to develop an equation for the interfacial heat transfer of exclusively a water droplet, which correlates with the data at both low-temperature and high-temperature superheating of the gas phases. On the correlation of Lee and Ryley, equation (1), a correction factor to the Nusselt number is determined and a modification of the Reynolds number is made. The correction factors of other researcher's were determined empirically. In the present paper an emphasis is on the analytical derivation of the correction factor and further on the provision of the theoretical basis for those empirical correction factors. The coefficient of the non-dimensional number term of equation (1) or (2) may have a relationship with the species of liquid and gas phases. In the present paper which has an intention to develop a correlation for the application to LOCA analysis where the interfacial heat transfer of a water droplet occurs in steam environment, the effect of species on the coefficient is not considered and the coefficient of Lee and Ryley is preferred.

Other correlations for a liquid droplet or droplets in air or steam were provided by Downing [8], Eisenkalm et al. [9], and Narasimhan and Gauvin [10]. Numerical analysis of droplet evaporation was studied by Renksizbulut and Yuen [11] and the evaluation of equilibrium and non-equilibrium evaporation models was performed by Miller et al.[12].

2. Derivation of a Correction Factor

Evaporating water droplet is assumed to be surrounded by a thin boundary layer of saturated steam as in the Lee and Ryley. The heat transferred from the superheated steam to the droplet must suffice to heat the droplet surface to saturation temperature, to evaporate liquid to supply this boundary layer, and also, thereafter, to superheat the vapor contained therein. During the reflood of a LOCA, droplet temperature is generally at saturation temperature except the entrance region of the core. In this paper, the subcooling of the droplet is not taken into consideration and the droplet temperature is assumed to be at saturation condition. For the small values of superheat, the heat to superheat the vapor contained in the boundary layer is comparatively small and does not materially affect the result and was neglected by Lee and Ryley. If the degree of superheat becomes high enough as in reflood situation of a LOCA, however, the heat to superheat the evaporated steam to superheated condition can not be neglected. In case of typical reflood condition of 0.3 MPa, for example, this heat exceeds 50 % of the latent heat of vaporization when the superheated steam temperature is 1000K. In order to find a correction factor in highly superheated steam condition, this heat is taken into consideration. Hence the heat transfer from the superheated steam to the droplet can be expressed by

$$\frac{dQ}{dt} = \pi d^2 h(T_v - T_s) = \pi dkNu(T_v - T_s). \qquad (3)$$

Also,

$$\frac{dQ}{dt} = [h_{fg} + (h_v - h_g)]\frac{dm}{dt}. \qquad (4)$$

Equations (3) and (4) have 3 unknowns of *dQ /dt*, *Nu*, *dm / dt*, and can not be solved directly. But a meaningful relationship is obtained if they are combined to give

$$\frac{dm}{dt} = \left(\frac{\pi dk(T_v - T_s)}{h_{fg} + (h_v - h_g)}\right)Nu. \qquad (5)$$

In order to derive the relationship between *Nu* and $Nu_{Lee\text{-}Ryley}$, the same amount of heat as in the Lee and Ryley's experiment is considered, then the heat supply is

$$\frac{dQ}{dt} = \pi dkNu_{Lee\text{-}Ryley}(T_v - T_s). \qquad (6)$$

Then *dm/dt* in highly superheated steam is

$$\frac{dm}{dt} = \left(\frac{\pi dk(T_v - T_s)}{h_{fg} + (h_v - h_g)}\right)Nu_{Lee\text{-}Ryley}. \qquad (7)$$

Re-writing,

$$\frac{dm}{dt}=\left(\frac{\pi dk(T_v-T_s)}{h_{fg}}\right)Nu_{Lee-Ryley}\left(\frac{h_{fg}}{h_{fg}+(h_v-h_g)}\right). \qquad (8)$$

Equation (8) can be rearranged in two ways. One is to show the ratio of vapor generations and another is to show the ratio of Nusselt numbers in low and high superheated steam conditions. Equation (8) can be written to give the rate of vapor generations as

$$\frac{dm}{dt}=\left(\frac{dm}{dt}\right)_{Lee-Ryley}\left(\frac{h_{fg}}{h_{fg}+(h_v-h_g)}\right). \qquad (9)$$

Vapor generation in highly superheated steam is less than that calculated by Lee and Ryley' s correlation by a factor of enthalpy difference ratio. Ratio of Nusselt numbers can be deduced if the equation (8) is re-written as

$$\frac{dm}{dt}=\left(\frac{\pi dk(T_v-T_s)}{h_{fg}}\right)Nu, \qquad (10)$$

where $Nu=Nu_{Lee-Ryley}\left(\frac{h_{fg}}{h_{fg}+(h_v-h_g)}\right). \qquad (11)$

Recalling that the heat supply is calculated by equation (6) and considering that *Nu* is a portion of $Nu_{Lee\text{-}Ryley}$ as shown in equation (11), equation (10) shows that the vapor generation in highly superheated steam is calculated by a portion of heat transfer divided by the latent heat of vaporization. The portion of heat transfer across the interface only to produce dm/dt is the numerator of equation (10). The amount of heat necessary to superheat the generated steam is not included in equation (10). Therefore, Nu in equation (10) or in equation (11) represents exactly the Nusselt number for the interfacial heat transfer in highly superheated steam.

Transforming the inside of the parenthesis of equation (11) into quality ratio using

$$h_{mix}\cong x_{actual}h_v+(1-x_{actual})h_f, \qquad (12)$$

and

$$x_{equilibrium}\cong\frac{h_{mix}-h_f}{h_g-h_f}. \qquad (13)$$

Here also, the subcooling of the water droplet is neglected consistently. Combining equation (12) and (13),

$$\left(\frac{h_g-h_f}{h_v-h_f}\right)=\left(\frac{h_{fg}}{h_{fg}+(h_v-h_g)}\right)\cong\frac{x_{actual}}{x_{equilibrium}}. \qquad (14)$$

Then, equation (11) becomes

$$Nu=Nu_{Lee-Ryley}\left(\frac{x_{actual}}{x_{equilibrium}}\right). \qquad (15)$$

As the degree of superheating reduces, h_v and $x_{equilibrium}$ approach h_g and x_{actual}, respectively, resulting in the correction factor of unity. Then, *Nu* reproduces $Nu_{Lee\text{-}Ryley}$.

Yuen and Chen [5] give a correction factor of 1/(1+B) and B is calculated by

$$\mathrm{B}=\frac{h_v-h_d}{L}, \qquad (16)$$

where h_d is the free stream enthalpy at droplet surface temperature. If the droplet surface temperature is assumed to be at saturation temperature neglecting the subcooling of the droplet, h_d is replace by h_g. Then,

$$\frac{1}{1+\mathrm{B}}=\frac{1}{1+\frac{h_v-h_d}{L}}=\frac{h_g-h_f}{(h_g-h_f)+(h_v-h_d)}$$
$$=\frac{h_g-h_f}{h_v-h_f}, \qquad (17)$$

which coincides with the correction factor of equation (14).

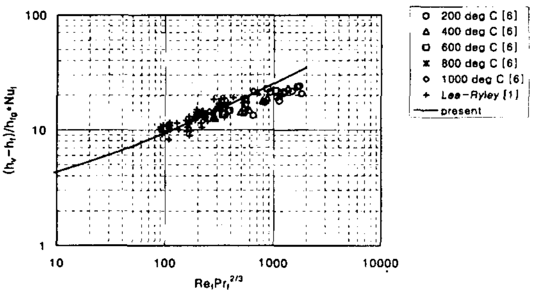

Fig. 2. Comparison of the Present Correlation with the Data of Lee-Ryley and Yuen-Chen

3. Discussions

In order to analyze the effect of free stream temperature on the interfacial heat transfer of a water droplet, the data of Lee-Ryley [1] and the data for water droplets of Yuen-Chen [6] are chosen. Even though Renksizbulut and Yuen [7] and Eisenkalm et al. [9] also provided measurements for water droplets, their data are not taken into consideration because no temperature dependency are provided and the Reynolds numbers were too low, respectively. The data of Eisenklam et al. covers the Reynolds numbers roughly between 1 and 10 while the order of magnitude of the Reynolds numbers in most engineering cases is 100 [6]. Lee-Ryley' s data and Yuen-Chen' s data are apparently separated as shown in Fig. 1. Yuen-Chen' s data show that the increase of the Nusselt numbers is several times as the ambient temperature decreases from 1000°C to 200°C. In other words, the interface heat transfer can be over-predicted by several times unless the high-temperature superheating is appropriately considered. The Nusselt number consistently decreases as the free stream temperature increases. Lee-Ryley' s data were of lower temperature but it deviates from the trend of temperature dependency of Yuen-Chen' s data. This is caused by the differences of the droplet sizes and the steam properties. Both data are of water droplets, and it can be seen that the effect of free stream velocity is to increase the Nusselt number.

Lee-Ryley' s correlation over-predicts the Nusselt numbers of high-temperature gas condition and Ranz-Marshall' s correlation goes through the intermediate of Lee-Ryley' s and Yuen-Chen' s measurements. The correlation used in RELAP5/MOD3.2 approaches Yuen-Chen' s data rather than Lee-Ryley' s even though it is based on the Lee-Ryley' s correlation. This is due to the reduction of the coefficient of the non-dimensional numbers of equation (1) from 0.74 to 0.5. With respect to the fact that the primary concern of LOCA analysis is a peak clad temperature which occurs at high-temperature superheated steam, this reduction can be justified in some sense. But the loss of accuracy at low or mild superheating condition results in the incorrect prediction of the superheated steam temperature in turn.

Fig. 2 shows the comparison of the present correlation with the experimental data. The present one correlates both of the data with reasonable accuracy. Careful examination of Fig. 2 reveals that the over-prediction of the present correlation compared with the Yuen-Chen data becomes obvious as the ambient temperature decreases. This might be caused by the ignorance of water subcooling in the present correlation. The effect of droplet subcooling on interfacial heat transfer is apparently larger in low ambient temperature because the difference between saturation temperature and subcooled temperature becomes considerable portion of the temperature difference between ambient steam and droplet temperature, than in high ambient temperature. If the surface temperature of the droplet is available, T_s of equation (3) can be replaced by T_d and further improvement of the correlation is possible.

Unfortunately, however, detail analysis of the temperature distribution inside the droplet is not practical and not economical in the analysis of a LOCA and most of the best-estimate thermal hydraulic codes calculate only the mean temperature of the liquid droplet. From the fact that Lee-Ryley' s data are well represented by the present correlation, a conjecture that the degree of subcooling of a water drop in their experiment was negligible is possible. Actually they assume the temperature potential for the interfacial heat transfer as the degree of steam superheating, which implies that the temperature of the water droplet is of nearly saturation temperature.

Recalling that the Reynolds number is the ratio of inertial force to viscous force, it is more appropriate to define the inertia force as $\rho_v u^2$ rather than $\rho_f u2$ where ρ_f is the density evaluated at film temperature [6, 7]. The data of Lee-Ryley or Ranz-Marshall have negligible differences between ρ_v and ρ_f, and their data agree well with their correlations even if the properties are evaluated at other conditions. In order to correlate both data of Lee-Ryley and Yuen-Chen, Reynolds number Re_M is substituted for Re_f in Fig. 3. The present correlation using Re_M fits the data more accurately. The mean and the standard deviation of measured-to-predicted ratios are now 0.98 and 0.13 respectively, instead of previous 0.94 and 0.14. The effect of the ignorance of the subcooling is still observed and further study is necessary. When the coefficient of 0.6 from Ranz and Marshall is substituted for 0.74 of Lee and Ryley, it generally under-predicts the experimental data as shown in Fig. 3. The mean and the standard deviation of measured-to-predicted ratios are 1.17 and 0.15 respectively. While the coefficient of 0.6 is widely accepted for the free stream species of air, it is clear that the coefficient of 0.74 is more preferable for steam species. Different coefficients of 0.552, 0.6 and 0.74 of the correlations from Froessling, Ranz and Marshall, and Lee and Ryley, respectively, seem to originate from different diffusion behaviors between liquid species and gas species. Experimental data obtained in high-temperature steam environment is hardly available because most of the spray flow experiments are for the application to the mixing of air and liquid fuel in the combustors. Reduction of the coefficient from 0.74 to 0.5 in RELAP5/MOD3.2 has no analytical or experimental bases. The effect of high-temperature steam in interfacial heat transfer during the reflood phase of a LOCA should be expressed by a correction factor as discussed rather than by an arbitrary reduction of the coefficient itself.

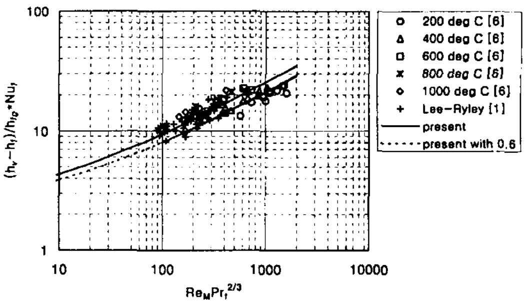

Fig. 3. Further Improvement of the Present Correlation Using ReM Instead of Ref

4. Conclusions

From simple heat balance between a water droplet and ambient steam, a new correlation of the interfacial heat transfer, especially for water droplets in steam is proposed and it is shown that the new correlation fits experimental data regardless of the degree of superheating with reasonable accuracy. The correlation overcomes the inherent deficiency of the correlations of Lee and Ryley and Ranz and Marshall in high-temperature steam and provides an analytical correction factor to their correlations without the detail analysis of the inside temperature distribution of a water droplet. Above all, the advantage of the present correlation is that it correlates both of the data that were obtained at nearly saturated and highly superheated steam.

Nomenclature

B,	$= (h_v - h_d)/L$, mass-transfer number;
d,	diameter of droplet;
dm/dt,	mass flux;
h,	heat transfer coefficient;
h,	enthalpy per unit mass;
L,	$= h_{fg}$, latent heat of vaporization per unit mass;
Nu,	$= hd/k$, Nusselt number;
Pr,	$= C_p\mu/k$, Prandtl number;
Q,	heat transfer;
Re,	$= \rho ud/\mu$, Reynolds number;
Re_M,	$= \rho_v ud/\mu_f$;
T,	temperature;
u,	velocity;
x,	quality.

Greek symbols

μ,	viscosity;
ρ,	density.

Subscripts

C,	convection;
d,	droplet surface;
f,	film;
f,	saturated water;
g,	saturated steam;
mix,	two-phase mixture;
R,	radiation;
s,	saturation;
v,	superheated steam.

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