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A Study on the Correlations Development for Film Boiling Heat Transfer on Spheres

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ABSTRACT

Film boiling is the heat transfer mechanism that can occurs when large temperature differences exist between a cold liquid and hot material. In the nuclear reactor safety analysis, film boiling has become an important issue in recent years. During severe accident, hot molten corium fall into relatively cool water, and fragment into spheres or sphere-like particles. If the steam explosion is triggered, the thermal energy of corium is converted into the mechanical energy that can threaten the integrity of reactor vessel or reactor cavity. One of the important concerns in the heat transfer analysis during pre-mixing stage is the film boiling heat transfer between the corium and water/steam two-phase flow. Until now, considerable works on film boiling have been performed. However, there is no available correlation adequate for severe accident analysis. In this study, film boiling heat transfer correlations have been developed, and their applicable ranges have been enlarged and their prediction accuracy has been enhanced.

I. INTRODUCTION

When severe accident occures, there is some probability of violent fuel-coolant interaction named steam explosion at inside of vessel or outside of the vessel (on the reactor cavity floor). Through the initial stage of steam explosion especially pre-mixing stage the temperature difference between hot molten fuel and water is sufficiently large for film boiling. Therefore, film boiling heat transfer coefficient has to be given to analyze the pre-mixing stage of steam explosion. Especially, the heat transfer coefficient of sphere is needed because the shape of fragmented molten fuel is sphere or sphere-like shape. Until now, considerable works have been devoted to film boiling on sphere or cylinder. As a result of these studies, many film boiling heat transfer correlations have been developed and suggested. However, the prediction capabilities of the developed correlations are not good. In this study, film boiling correlations for sphere under single- and two-phase flow conditions have been developed with enlarged applicable ranges and enhanced prediction capabilities.

In this paper, review of the previous work is presented in Chapter 2 and film boiling correlation development is described in Chapter 3. Conclusion for overall this study and recommendation are given in Chapter 4.

II. BACKGROUND

2.1 Natural convection film boiling heat transfer correlations

Bromley (1950) developed the correlation for the pool film boiling at saturated condition first. By an analysis that is similar to the Nusselt's analysis for condensation, he obtained correlation, which had 1/4 power form. After this many authors have been developed correlations which have 1/4 power term.

Through research that concerns the pool film boiling from spheres in cryogenic liquids or in some organic liquids which have small capillary length, the correlations with 1/3 power term were developed.

2.2 Forced convection film boiling heat transfer correlations

Bromley et al. (1953) carried out an analysis, which is based on Bernoulli's theorom, and they obtained two dimensionless groups and correlated them according to their experimental data. On the other hand, Kobayashi (1966) developed different correlation following the analysis used by Bromley (1953).

III. CORRELATION DEVELOPMENT FOR FILM BOILING HEAT TRANSFER ON SPHERES

3.1 Film Boiling Data Base

The film boiling data base of Liu and Theofanous (1994) used in correlation development is described in table 3.1 and 3.2.

3.2 Correlation Development

In all the correlations for heat transfer on sphere with no phase change, Nusselt number is expressed as a function of Reynolds number and Prandtl number. Therefore if we consider phase change by evaporation, Nusselt number can be expressed as a function of Reynolds number and Prandtl number of liquid and vapor.

$$Nu = C_1 \mathrm{Re}_v^{C_2} \mathrm{Pr}_v^{C_3} \mathrm{Re}_l^{C_4} \mathrm{Pr}_l^{C_5}$$

3.2.1 Saturated single-phase flow

Using the vapor drift velocity, vapor Reynolds number is modified like this:

$$\mathrm{Re}_v = \frac{\rho_v (u_l + 0.878) d}{\mu_v}$$

The final form of correlation is as follows:

$$Nu_{sat} = 2.634 \mathrm{Re}_v^{0.614} \mathrm{Pr}_v^{-0.4}$$

Reynolds number and Prandtl number of liquid is omitted, because the liquid velocity is already considered in modified vapor Reynolds number, and the liquid Prandtl number is constant at saturated condition.

3.2.2 Subcooled single-phase flow

By adding some subcooling term to the correlation for saturated condition, the correlation for subcooled condition has been developed as follows:

$$Nu_{sub} = Nu_{sat} + 4.612 \left[\frac{C_{pl} \Delta T_{sub}}{C_{pv} \Delta T_{sup}} \right]^{1.136} \mathrm{Re}_l^{0.750} \mathrm{Pr}_l^{-1.646}$$

3.2.3 Upward two-phase flow

The correlation has been developed as follows:

$$Nu_{up} = 4.697 \mathrm{Re}_v^{0.469} \mathrm{Pr}_v^{0.66}$$

Because the exponent of liquid Reynolds number is very small according SAS regression, it has been dropped. And the liquid Prandtl number is also omitted because it is constant under two-phase condition.

3.2.4 Downward two-phase flow

The correlation has been developed as follows:

$$Nu_{down} = 0.03013\,\mathrm{Re}_v^{0.055}\,\mathrm{Pr}_v^{-4.902}\,\mathrm{Re}_l^{0.5973}\,\alpha^{-1.188}$$

The liquid Prandtl number is omitted because it is constant.

V. CONCLUSION AND RECOMMENDATIONS

A series of film boiling correlations on sphere under saturated or subcooled single-phase flow and upward or downward two-phase flow have been developed to estimate the heat transfer rate during the process of fuel-coolant interaction (steam explosion). Important findings are summarized as follows:

(a) The correlations for film boiling heat transfer on spheres have been developed, and they predict well the film boiling heat transfer under single- and two-phase flow within ±20% error bounds.
(b) Above correlations can predict natural convection film boiling data within ±20% error bounds also (Fig. 3.5)
(c) Above correlations can predict film boiling heat transfer in cryogenic liquid within ±20% error bounds
(d) The film boiling model for sphere that can cover the natural and forced convection is need in this field.
(e) More film boiling experiments with various sphere diameters under two-phase flow conditions are needed, because in severe accident case two-phase flow condition may be given.

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Table 2.1 Previous works on natural convection film boiling on spheres in saturated liquid

	1/4 power form	1/3 power form
First work	Bromley (1950)	Frederking and Clark (1963)
	$Nu = 0.62[Ar/Sp']^{1/4}$	$Nu = 0.14[Ar/Sp']^{1/3}$
Related works	Berenson (1961)	Merte and Clark (1964)
	Frederking and Clark (1963)	Frederking et al. (1965)
	Dhir and Purohit (1978)	Rhea and Nevins (1969)
	Klimenko (1981)	Farahat and Nasr (1978)
	Tso et al. (1990)	Klimenko (1981)
	Sakuri et al. (1990)	
Limitations	-	D > 20 mm, cryogenic liquids

Table 2.2 Previous works on natural convection film boiling in subcooled liquid

	Addition form	Ratio form
First work	Hamill and Baumeister (1967)	Shih and El-Wakil (1981)
	$h_t \approx h_{sat} + 0.88 h_r + 0.12 \frac{h_{nc} \Delta T_{sub}}{\Delta T_{sup}}$	$\frac{Nu}{Nu_{sat}} = 1 + 13.91 \left[\frac{ScAr}{Gr} \right]^{0.39}$
Related works	Siviour and Ede (1970)	Michiyoshi et al. (1988)
	Farahat et al. (1972)	Tso et al. (1990)
	Dhir and Purohit (1978)	Sakurai et al. (1990)

Table 2.3 Previous works on forced convection film boiling

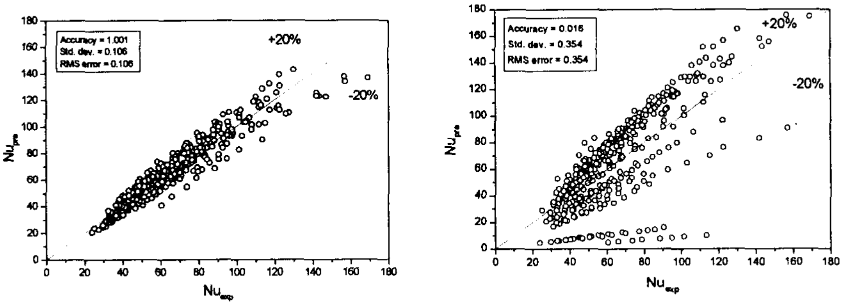
	Mode 1	Mode 2
First work	Bromley et al. (1953)	Kobayashi (1966)
	$Nu = 2.70 \mathrm{Re}_l^{0.5} \left[\frac{v_l / v_v}{Sp'} \right]^{0.5}$	$Nu = 0.393 \mathrm{Re}_l^{0.5} \left[\frac{\mu_l}{\mu_v} \right] \left[\frac{R^4 K}{Sp} \right]^{0.25}$
Related works	Siviour and Ede (1970)	Michiyoshi et al. (1988)
	Farahat et al. (1972)	Tso et al. (1990)
	Dhir and Purohit (1978)	Sakurai et al. (1990)

Table 3.1 Film boiling data base for single-phase flow

Parameters	Saturated Single-Phase	Subcooled Single-Phase
Diameter (d), mm	6.35 - 19.1	12.7
Water temperature (T_l), °C	Saturated Water	70.4 – 95.4
Water velocity (u_l), m/sec	0.01 – 2.244	0.011 – 2.208
Vapor velocity (u_v), m/sec	-	-
Reynolds number (Re_l)	225 – 97295	416 – 93247
Nusselt number (Nu)	24 – 194	44 – 402
Number of data	375	335

Table 3.2 Film boiling data base for two-phase flow

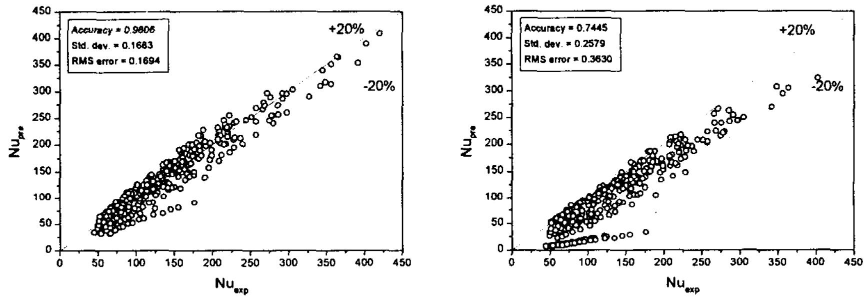
Parameters	Upward Two-Phase	Downward Two-Phase
Diameter (d), mm	12.7	12.7
Water temperature (T_l), °C	Two-Phase	Two-Phase
Water velocity (u_l), m/sec	0.69 – 2.838	1.948 – 6.475
Vapor velocity (u_v), m/sec	3.218 – 7.886	1.129 – 8.343
Reynolds number (Re_l)	29795 – 122485	84055 – 279444
Void fraction (α)	0.215 – 0.679	0.72 – 0.969
Nusselt number (Nu)	63 – 131	37 – 147
Number of data	443	708



(a) This study

(b) Liu and Theofanous (1994)

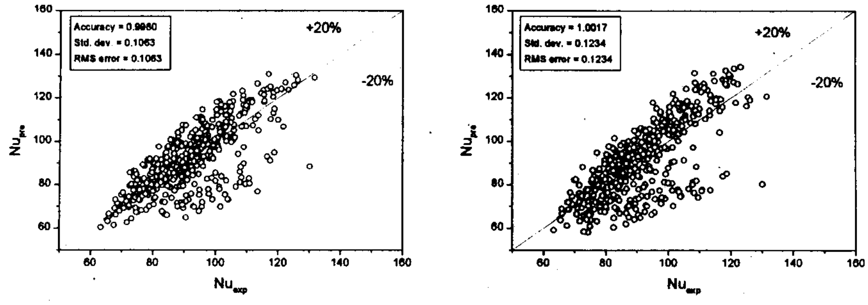
Fig. 3.1 Prediction results for saturated single-phase flow



(a) This study

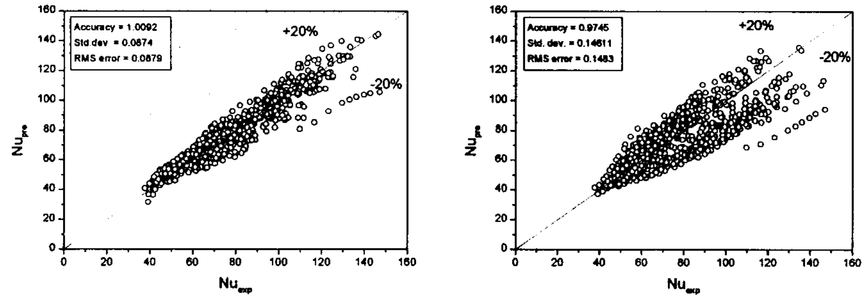
(b) Liu and Theofanous (1994)

Fig. 3.2 Prediction results for subcooled single-phase flow



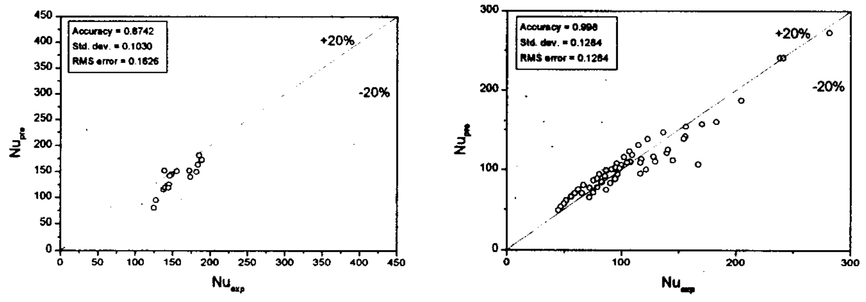
(a) This study (b) Liu and Theofanous (1994)

Fig. 3.3 Prediction results for upward two-phase flow



(a) This study (b) Liu and Theofanous (1994)

Fig. 3.4 Prediction result for downward two-phase flow



(a) Subcooled water (b) Saturated liquid nitrogen

Fig. 3.5 Prediction result for the natural convection data