Journal of the Korean Nuclear Society
Volume 23, Number 2, June 1991

A New Natural Convection Heat Transfer Correlation for Laminar and Turbulent Film Condensation Derived from a Statistical Analysis of Existing Models and Data

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(Received January 12, 1991)

기존모델과 실험자료의 통계적 분석에 의해 유도한 층류 및 난류 막응축에 대한 새로운 자연대류 열전달 관계식

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(1991. 1. 12 접수)

Abstract

A new semi-empirical average heat transfer correlation applicable for both laminar and turbulent film-wise condensation on a vertical surface has been presented. The functional form of the present correlation is based on the representative existing correlations for laminar and turbulent film flows, whereas the numerical coefficients of the present correlation have been determined by the least squares method using experimental data obtained from the open literatures. In addition, the performance of the present as well as the seven existing correlations (four for laminar 'and three for turbulent film flow regimes) were evaluated for their accuracy and the range of application. The result shows that for laminar film filow regimes Zazuli's and the present correlations give the samllest values of mean error, whereas for turbulent film flow regimes Kirkbride and Badger's and the present correlations produce the smallest values of mean error.

요 약

수직표면 위에서 일어나는 층류 및 난류응축 모두에 사용할 수 있는 새로운 반경험적 열전달 관계식을 제안하였다. 본 관계식의 함수 형태는 층류와 난류 막응축 유동에 대한 기존의 대표적 관계식에 근거를 두었고, 한편 본 관계식의 수치계수는 공개된 문헌에서 수집한 실험자료를 사용하여 최소자승법에 의해 결정하였다. 또한, 본 관계식과 기존 7개의 관계식 (즉 층류에 대한 관계식 4개와 난류에 대한 관계식 3개)의 성능을 정확도와 적용 범위에 대해서 평가하였다. 그 결과 층류 막응축에 대하여는 Zazuli의 관계식과 본 관계식이 가장 작은 평균 오차를 가져오고, 난류 영역에서는 Kirkbride와 Badger의 관계식과 본 관계식이 가장 작은 평균 오차를 가져오는 것을 보여 준다.

1. Introduction

Since Nusselt [1] first presented a solution for laminar condensation of a saturated vapor on an isothermal vertical surface, neglecting the effects of interfacial waves and heat capacity of the condensate and the drag of the vapor, a number of authors have extended the original analysis: (1) Bromley [2] considered the effects of subcooling the condensate, (2) Rohsenow [3] allowed for the non-linear distribution of temperature through the film due to energy convection, (3) Sparrow and Gregg [4] considered momentum changes in the film, (4) Chen [5] Koh, Sparrow, and Hartnett [6] and others have considered the influence of the drag exerted by the vapor on the liquid film, (5) Drew [7] and Minkowycz and Sparrow [8] have considered the influence of variations in physical properties across the condensate film.

The results of most studies [4,5] on the laminar film condensation show that assumptions made by Nusselt (i.e., neglect of momentum changes through the film and no drag exerted by the vapor on the liquid film) appear justified at Prandtl numbers around unity.

The influence of turbulece, on the other hand, has been studied by Kirkbride [9], Colburn [10], Chun and Seban [11] and by many others: Modeling of turbulent liquid films has been also the target of extensive research spanning the last six decades. An excellent summary of turbulent-film models of freely-falling films is given in a recent paper by Mudawwar and El-Masri [12].

For long vertical surfaces it is possible to obtain condensation rates such that the film Reynods number exceeds the critical value at which turbulence begins. Under such circumstances, substantial discrepancies exist between Nusselt's theory and the experimental data when the condensate flow becomes turbulent or when the vapor velocity is high. Therefore, it is desirable to develop a single correlation applicable for both flow regimes. A correlation that gives the average Nusselt number for both regimes of laminar or turbulent film flow without any discontinuity will be very useful for computer codes application, in particular.

A survey of the literature shows that although a number of models have been proposed for film condensation, applicable for either laminar or turbulent film flow regimes, still there is no general correlation that correctly predicts the average Nusselt number for both regimes without a discontinuity at the transition film flow region; and none are in forms convenient for direct application to the computer codes of nuclear safety analysis.

The purposes of this paper is (1) first, to propose a new semi-empirical average heat transfer correlation applicable for both laminar and turbulent film condensations on a vertical surface obtained partly on the basis of functional forms of typical existing correlations and using existing experimental data for statistical analysis, and (2) secondly, to present the results of an assessment of existing film condensation models to identify the best performing correlation for each flow regime.

2. Summary of Existing Correlations Selected for Assessment

The models for film-wise condensation heat transfer can be broadly classified into those based on the assumption that the film flow is laminar and those which assume turbulent mixing exists. Among the various models that have been developed for condensation on a vertical surface, only seven representative average Nusselt number correlations (i.e., four correlations for laminar region and three correlations for turbulent region, respectively) were selected for present assessment of their accuracy and their range of applications; Those models that required extensive numerical analyses to compare with experimental data were

Table 1. Summary of Existing and Present Correlations

Authors	Average Nusselt Number Correlation	Applicalble Film Reynolds Number Range
Nusselt	$\overline{Nu}=1.47\cdot Re_{\Gamma}^{-\frac{1}{3}}$	$Re_{\Gamma}1800$
McAdams	$\overline{Nu}=1.88\cdot Re_{\Gamma}^{-\frac{1}{3}}$	$Re_{\Gamma}<1800$
Zazuli	$\overline{Nu}=1.01\cdot Re_{\Gamma}^{-0.22}$	$Re_{\Gamma}<1800$
Labuntsov	$\overline{Nu}=1.39\cdot Re_{\Gamma}^{-\frac{22}{75}}$	$Re_{\Gamma}<400$
Kirkbride & Badger	$\overline{Nu}=0.0077\cdot Re_{\Gamma}^{-0.4}$	$Re_{\Gamma}>1800$
Chun & Seban(1)	$\overline{Nu}=\frac{2.297\times10^{-3}Re_{\Gamma}^{0.4}Pr^{0.65}}{1-Re_{\Gamma_{tr}}^{0.6}Re_{\Gamma}^{-0.6}+2.269\times10^{-3}Pr^{0.65}Re_{\Gamma_{tr}}^{1.22}Re_{\Gamma}^{-0.6}}$ where $Re_{\Gamma_{tr}}=5800Pr^{-1.065}$	$Re_{\Gamma}>1800$
Chun & Seban(2)	$\overline{Nu}=\frac{2.297\times10^{-3}Re_{\Gamma}^{0.4}Pr^{0.65}}{1-Re_{\Gamma_{tr}}^{0.6}Re_{\Gamma}^{-0.6}+2.269\times10^{-3}Pr^{0.65}Re_{\Gamma_{tr}}^{1.22}Re_{\Gamma}^{0.6}}$ wher $Re_{\Gamma_{tr}}=2460Pr^{-0.65}$	$Re_{\Gamma}>1800$
Present	$\overline{Nu}=1.33\cdot Re_{\Gamma}^{-\frac{1}{3}}+9.56\times10^{-6}Re_{\Gamma}^{0.89}Pr^{0.94}+8.22\times10^{-2}$	$10<Re_{\Gamma}<3.1.\times10^{4}$

excluded. They are summarized and given in Table 1. A brief description of those models that are of particular interest for the present work is given here for convenience in discussion.

2-1. Laminar Regime

(1) Nusselt Equation : The original Nusselt equation [1] for a laminar film condensation on a vertical plane can be reduced to the following form

$$\overline{Nu}=1.47Re_{\Gamma}^{-\frac{1}{3}} \tag{1}$$

Equation (1) gives the average heat transfer coefficient when the condensate flows from the top of the plane surface ($z=0$) to a distance $z=z_0$. However, the Nusselt formula (Eq. (1)) has a very limited region of applicability, since the condensate film fall in a purely laminar flow is realized at very small film Reynolds numbers. Substantial discrepancies exist between Nusselt's theory and the experimental data when the condensate flow becomes turbulent or when the vapor velocity is very high.

(2) McAdams Correlation : Noting that the experimental data of average heat transfer coefficients for film type condensation of steam on vertical tubes obtained by a number of different investigators are roughly 50 per cent higher than the theoretical values given by Eq. (1), McAdams [13] recommended that the values given by Eq. (1) should be multiplied by a correction factor of 1.28 for $Re_{\Gamma}<1800$.

$$\overline{Nu}=1.28\times(\text{Eq. (1)})$$
$$=1.88Re_{\Gamma}^{-\frac{1}{3}} \tag{2}$$

(3) Zazuli Correlation : Zazuli [11] examined condensation data and formulated an empirical correction factor in terms of average heat transfer coefficients

$$\overline{Nu}=0.687Re_{\Gamma}^{-0.11}\times(\text{Eq. (1)})$$
$$=1.01Re_{\Gamma}^{-0.22} \tag{3}$$

(4) Labuntsov Correlation : According to Kutateladze and Gogonin [14], Isachenko and Labuntsov recommend adding an empirical correction term in the Nusselt formula, Eq. (1), to allow for the effect of the waves on enhancement of heat transfer

$$\overline{Nu}=\left[\frac{Re_{\Gamma}}{4}\right]^{0.04}\times(\text{Eq. (1)})$$
$$=1.39Re_{\Gamma}^{-\frac{22}{75}} \tag{4}$$

Experimental results agree very closely with Eq. (4) up to $Re_{\Gamma}=400$ [14].

2-2. Transition and Turbulent Regimes

With film condensation of vapor on a tall vertical tube, the Reynolds number $4\Gamma/\mu$ exceeds the critical value (~1800) at which turbulence begins [13]. Film Reynolds numbers ranging from 240 to 2100 have been proposed for the laminar to turbulent flow transition. In the transition regime, where waves exist, the effective film thickness for conduction becomes smaller than without waves for a given Re_{Γ} number, whereas the heat transfer area becomes larger. These lead to the increase in heat transfer rate. The disagreement between the existing correlations and data in the transition regime may be largely attributable to these factors. Also, the transition of flow characteristic is extremely difficult to analyze. In the developed turbulent regime of condensate film flow ($Re_{\Gamma}>4000$), the heat transfer rate increases [14] ; Numerous experimental studies have been made in the turbulent regime of condensate film flow, but these have led mainly to empirical correlations of more or less limited applicability.

(1) Kutateladze Formula for the Local Heat Transfer Coefficient in the Turbulent Flow : Over a wide range of the film Reynolds number, $400<Re_{\Gamma}<4000$, the heat transfer rate is practically constant [14] : At $Re_{\Gamma}>400$, the closest agreement with experiment is obtained by calculation according to Eq.(3) of Ref. [14] for a mixed regime of the condensate film flow, i.e., when the local heat transfer coefficient in the turbulent flow was calculated by the Eq. (3) of Ref. [14]. However, Kutateladze formula [14] is not included in the present assessment since it gives the local Nusselt number and cannot be transformed into an average Nusselt number correlation without having an explicit relationship between film thickness and axial distance z for turbulent flow regime.

(2) Kirkbride and Badger Correlation : When the film Reynolds number exceeds the critical value at which turbulent begins, Kirkbride and Badger [13] found that heat transfer coefficients are much greater than given by Eq. (1), and they correlated experimental data on vertical tubes for Re_{Γ} exceeding 1800 by

$$\overline{Nu}=0.0077Re_{\Gamma}^{0.4} \tag{5}$$

(3) Chun and Seban Correlation : Chun and Seban [11] presented results for the heat transfer coefficient for evaporation from the surface of water films flowing along the outside surface of a vertical tube for the cases of laminar and turbulent flows. The average heat transfer correlation for condensation given by Chun and Seban [11] can be expressed as

$$\overline{Nu}=\frac{2.297\times10^{-3}Re_{\Gamma}^{0.4}Pr^{0.65}}{1-Re_{\Gamma_{tr}}^{0.6}Re_{\Gamma}^{-0.6}+2.269\times10^{-3}Pr^{0.65}Re_{\Gamma_{tr}}^{1.22}Re_{\Gamma}^{-0.6}} \tag{6}$$

where the transition Renolds number is given by

$$Re_{\Gamma_{tr}}=5800Pr^{-1.06} \quad (7)$$

or

$$Re_{\Gamma_{tr}}=2460Pr^{-0.65} \quad (8)$$

For Reynolds numbers reasonably higher than the transition Reynolds number, the denominator of Eq. (6) is essentially unity.

3. Derivation of a New Semi-Empirical Correlation

3-1. The Basis of the Functional Form of the Present Correlation

An insight into the most promising functional form for a new semi-empirical average Nusselt number correlation that is applicable for both regimes of laminar and turbulent film condensation on a vertical surface can be gained from the existing theoretical and empirical correlations just briefly outlined above.

In the laminar regimes of the condensate film flow, the experimental data are fairly well described by the Nusselt formula (i.e., Eq. (1)) woth correction factors ; The heat transfer for the laminar film condensation can be described practically by one relation of the following form [14]

$$\overline{Nu}=C_1Re_{\Gamma}^{-\frac{1}{3}} \quad (9)$$

The dominant mechanism controlling the heat transfer rate for laminar film condensation is conduction across the film thickness. In the transition and turbulent regimes, however, the importance of convective transport relative to conduction should be properly taken into account. Since the Prandtl number provides a measure of the relative effectiveness of momentum and energy transport by diffusion in the velocity and thermal boundary layers it may be inferred that Eq. (6) has the appropriate functional form for these regimes. For Reynolds numbers reasonably higher than the transition Reynolds number, in particular, Eq. (6) can be represented by

$$\overline{Nu}=C_2Re_{\Gamma}^{C_4}Pr^{C_5} \quad (10)$$

where C_4 and C_5 are positive values.

The combination of Eqs. (9) and (10), with a number of unknown constants to be determined by the least squares method, has been used here as the basic equation for the present correlation :

$$\overline{Nu}=C_1Re_{\Gamma}^{-\frac{1}{3}}+C_2Re_{\Gamma}^{C_4}Pr^{C_5}+C_3 \quad (11)$$

Equation (11) implies that as Re_{Γ} approaches its turbulent region, the first term on the right hand side tends to become zero whereas the contribution of second term becomes greater.

3.2. The Final Form of the Present Correlation

To determine the parameters C_1 through C_5 in Eq. (11) the method of least squares has been used. For obtaining the least square estimates of the parameters of nonlinear models Y=F(X), it is more usual to find log Y, for given X, rather than Y, that has constant variance [15]. Hence, we look for an average Nusselt number correlation that minimizes

$$SSE=\sum_{i=1}^{N}\left[\ln\left((\overline{Nu_i})_{exp}\right)-\ln\left((\overline{Nu_i})_{corr}\right)\right]^2 \quad (12)$$

where

$(\overline{Nu_i})_{exp}$ = average Nusselt number obtained from experimental data,

and

$(\overline{Nu_i})_{corr}$ = average Nusselt number predicted by Eq. (11)

The sum of square error (SSE) depends on C_k's, and a necessary condition for SSE to be a minimum is

$$\frac{\partial(SSE)}{\partial C_k}=0 \text{ for } k=1,\cdots,5.$$

This system of five non-linear equations can be solved by a variation of Newton's method which uses a finite difference approximation to the Jacobian matrix.

A total of 458 experimental data (summarized in Table 2) collected from open literatures has been used to determine the parameters C_k's (i.e., $C_1,\cdots,C_5$ in Eq. (11)). The resulting equation that minimizes the SSE for the data is

$$\overline{Nu}=1.33Re_{\Gamma}^{-\frac{1}{3}}+9.56\times10^{-6}Re_{\Gamma}^{0.89}Pr^{0.94}+8.22\times10^{-2} \quad (13)$$

4. Assessment of the New and Existing Correlations

4-1. Methods Used to Evaluate Correlations

The most important parameter used to judge the relative superiority of a model, in the present work, is the fractional error defined by

$$\varepsilon_i=\frac{(\overline{Nu_i})_{exp}-(\overline{Nu_i})_{corr}}{(\overline{Nu_i})_{exp}} \quad (14)$$

where ε_i is the fractional error of the predicted value of the correlation.

In order to compare the accuracy of predicted values of correlations for groups of data, the mean error $\bar{\varepsilon}$, the root-mean-square (RMS) error ε_{RMS}, and the standard deviation of error σ_ε are also computed as follows :

$$\bar{\varepsilon}=\sum_{i=1}^{N}\frac{\varepsilon i}{N} \quad (15)$$

$$\varepsilon_{RMS}=\left[\sum_{i=1}^{N}\frac{\varepsilon_i^2}{N}\right]^{\frac{1}{2}} \quad (16)$$

$$\sigma_\varepsilon=\left[\frac{1}{N-1}\sum_{i=1}^{N}(\varepsilon_i-\bar{\varepsilon})^2\right]^{\frac{1}{2}} \quad (17)$$

The correlation that produces the smallest values of $\bar{\varepsilon}$, ε_{RMS}, and σ_ε is considered as the best correlation.

4-2. Experimental Data Used

The average heat transfer data for film-wise condensation were obtained from McAams [13], Kutateladze and Gogonin [14], and Ratiani and Shekriladze [16]. The major criterion used to select the experimental data is the test condition : All the data summarized in Table 2 were selected from the studies of film condensation of quiescent vapor on vertical surfaces at atmospheric pressure.

5. Results and Discussions

To examine the accuracy and the applicable range of the existing and the new correlations a series of analyses was performed using Eqs. (15) through (17). A total of 458 experimental data has been used in the present assessment. The results of the statistical analysis are summarized and shown in Tables 3 and 4 for laminar ($Re_\Gamma<1800$) and turbulent ($Re_\Gamma>1800$) regimes, respectively. These tables give the $\bar{\varepsilon}$, ε_{RMS}, and σ_ε values obtained for each model along with the number of data points used for each region of Reynolds numbers.

Table 3 shows that out of four existing models for laminar film flow regimes Zazuli's correlation (Eq. (3)) gives the smallest values of $\bar{\varepsilon}$, ε_{RMS}. For a limited range of $Re_\Gamma<400$, however, Labuntsov's correlatin gives the smallest ε_{RMS}. Also, it should be noted that the mean error ($\bar{\varepsilon}$) of the present correlation in the laminar region is smaller than that of Zazuli's whereas the ε_{RMS} and σ_ε values of the present correlation and that of Zazuli's are about the same.

As can be seen in Table 4, when existing correlations are compared for turbulent film flow regimes Kirkbride and Badger's correlaton (Eq. (5)) produces the smallest value of $\bar{\varepsilon}$, ε_{RMS}, and σ_ε of the present correlation for these regimes are about the same as those of Kirkbride and Badger's. The major drawback of the Kirkbride and Badger's correlation is that this model does not take the effect of Prandtl number into consideration. The Kirkbride and Badger's correlation is based on the data obtained by Ullok [13], and Monrad and Diamond [13]. Prandtl numbers were 5.0 for both cases as can be seen in Table 2.

Table 2. Test Conditions of Experimental Data

Investigators	Fluid	T_s-T_w ($^{\circ}K$)	Test Section		Prandtl Number	Range of Re_{Γ}	No. of Data
			Length (m)	Dia. (mm)			
Shea & Krase [13]†	water	2.8~21.7	0.119	plate	1.75	80~ 250	14
Fragen13]	water	1.1~12.8	0.244	22.2	1.75	140~ 2200	24
Stroebe [13]	water	1.7~18.9	6.096	50.8	1.75	290~ 4200	28
Hebbard [13]	water	2.8~21.7	3.658	25.4	1.75	480~ 3400	19
Ullock [13]	Diphenyl mixture	19.4~40.0	3.566	22.2	5.0	2500~23000	67
Monrad & Diamond [13]	Diphenyl oxide	12.8~72.2	3.658	19.1	5.0	1200~31000	72
Callender & Nicolson [13]‡	water	–	–	–	1.75	1700~ 2400	3
Jordan [13]‡	water	–	–	–	1.75	830~ 4400	12
Ratiani & Shekriladze16]†	water	0.3~12.4	0.217	21.5	1.75	10~ 150	25
Kutateladze & Gogonin [14]‡	water	–	–	–	1.75	90~ 5100	60
Kutateladze & Gogonin [14]‡	Freon-21	–	–	–	3.5	40~17000	13

Note : †Test section material is copper.
‡Test conditions are not clear.

To further evaluate the applicability and accuracy of the present correlation, the predictions made by Eq. (13) are compared with experimental data and predictions of other correlations in Fig. 1. This figure shows that over a wide range of film Reynolds numbers (from 10 to 31000) and over a range of Prandtl number from 1.75 to 5.0 the agreement between the present correlation and experimental data is fairly good and consistent; Present model is, in general, superior or equal to the existing correlations examined here.

6. Conclusions

Noting that there is no existing general formula that correctly predicts the average Nusselt number for both regimes of laminar and turbulent film condensations without a discontinuity at the transition region, a new semi-empirical average heat transfer correlation applicable for both laminar and turbulent film condensations on a vertical surface has been proposed here.

Table 3. The Error Analysis of the New and Existing Film-Wise Condensation Heat Transfer Correlations for Laminar Regimes($Re_\Gamma \le 1800$)

Correlation	Range of Re_Γ	$\bar{\varepsilon}$	ε_{RMS}	σ_ε	No.of Data
Nusselt	$0<Re_\Gamma\le 400$	0.1622	0.2019	0.1208	90
	$400<Re_\Gamma\le 1800$	0.3313	0.3642	0.1519	138
	$0<Re_\Gamma\le 1800$	0.2646	0.3105	0.1628	228
McAdams	$0<Re_\Gamma\le 400$	-0.0724	0.1700	0.1546	90
	$400<Re_\Gamma\le 1800$	0.1441	0.2414	0.1944	138
	$0<Re_\Gamma\le 1800$	0.0586	0.2161	0.2084	228
Zazuli	$0<Re_\Gamma\le 400$	0.0254	0.1380	0.1364	90
	$400<Re_\Gamma\le 1800$	0.0307	0.2065	0.2049	138
	$0<Re_\Gamma\le 1800$	0.0286	0.1825	0.1807	228
Labuntsov†	$0<Re_\Gamma\le 400$	0.0410	0.1338	0.1281	90
Present	$0<Re_\Gamma\le 400$	-0.0050	0.1346	0.1353	90
	$400<Re_\Gamma\le 1800$	-0.0129	0.2134	0.2138	138
	$0<Re_\Gamma\le 1800$	-0.0097	0.1863	0.1865	228

Note : †applicable for $Re_\Gamma \le 400$ only

Table 4. The Error Analysis of the New and Existing Film-Wise Condensation Heat Transfer Correalations for Turbulent Regimes($Re_\Gamma > 1800$)

Correlation	Range of Re_Γ	$\bar{\varepsilon}$	ε_{RMS}	σ_ε	No.of Data
Kirkbride & Badger	$1800<Re_\Gamma\le 4000$	0.0666	0.2180	0.2091	68
	$4000<Re_\Gamma<3.1\times10^4$	-0.0243	0.1688	0.1675	162
	$1800<Re_\Gamma<3.1\times10^4$	0.0026	0.1847	0.1851	230
Chun & Seban(1)	$1800<Re_\Gamma\le 4000$	-0.0057	0.2272	0.2289	68
	$4000<Re_\Gamma<3.1\times10^4$	0.0307	0.1515	0.1488	162
	$1800<Re_\Gamma<3.1\times10^4$	0.0199	0.1773	0.1765	230
Chun & Seban(2)	$1800<Re_\Gamma\le 4000$	0.0644	0.2232	0.2153	68
	$4000<Re_\Gamma<3.1\times10^4$	0.0359	0.1531	0.1493	162
	$1800<Re_\Gamma<3.1\times10^4$	0.0443	0.1768	0.1715	230
Present	$1800<Re_\Gamma\le 4000$	-0.0635	0.2289	0.2216	68
	$4000<Re_\Gamma<3.1\times10^4$	-0.0008	0.1453	0.1458	162
	$1800<Re_\Gamma<3.1\times10^4$	-0.0193	0.1743	0.1736	230

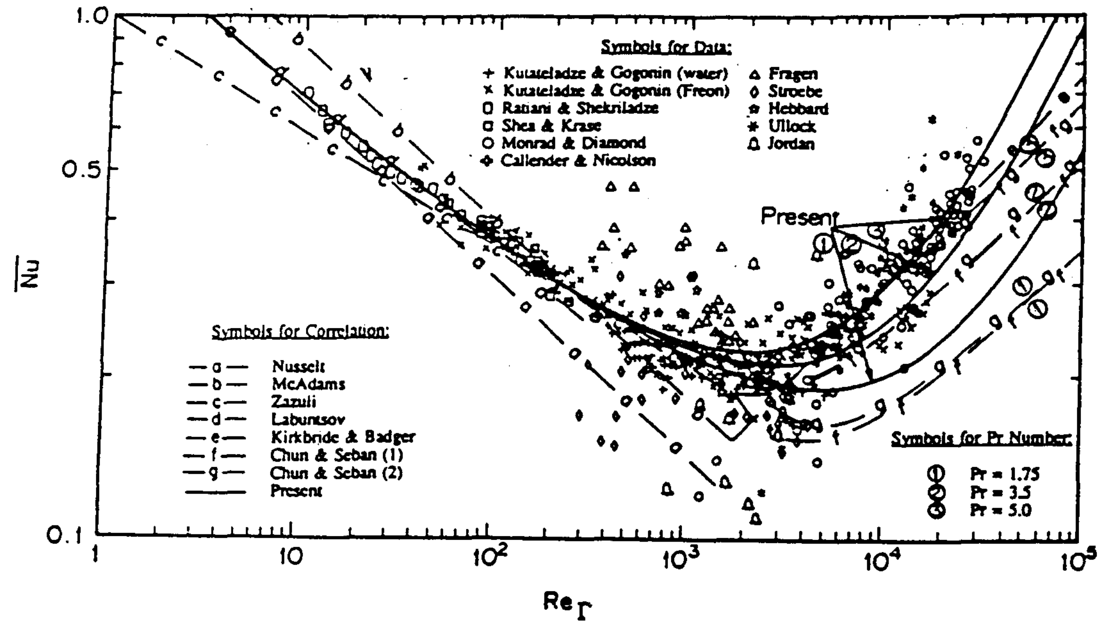

Fig. 1. Film-Wise Condensation Heat Transfer on Vertical Surface. (Pr = 1.75 for Water, Pr = 3.5 for Freon-21, Pr = 5.0 for Diphenyl Oxide and Diphenyl Mixture)

In addition, the performance of the present as well as seven existing Nusselt number correlations for filmwise condensation was evaluated for their accuracy and the range of application. The result can be summarized as follows:

(1) Out of the four existing correlations examined for laminar film flow regimes, Zazuli's correlation [11] gives the smallest values of the mean ($\bar{\epsilon}$) and RMS (ϵ_{RMS}) errors.

(2) For turbulent film flow regimes, Kirkbride and Badger's correlation [13] produces the smallest value of mean error ($\bar{\epsilon}$).

(3) The present correlation for laminar film flow regimes gives smaller value of $\bar{\epsilon}$ than that of Zazuli's, and the $\bar{\epsilon}$, ϵ_{RMS}, and σ_{ϵ} values of the present correlation in turbulent film flow regimes are about the same as those of Kirkbride and Badger's [13].

Present correlation agrees with experimental data over a wide range of film Reynolds mumbers (from 10 to 31000) and over a range of Prandtl numbers between 1.75 and 5.0. Also, present correlation is, in general, superior or equal to the best performing correlations among the existing correlations examined here. It should be noted here that the present correlation, Eq. (13), is applicable for Prandtl numbers between 1.75 and 5.0.

Nomenclature

C_1, C_2, C_3	coefficients of the present correlation
C_4, C_5	exponents of the present correlation
c_p	specific heat of condensate, J/kg·°K
g	gravitational acceleration, m/s^2
$\bar{h}$	average heat transfer coefficient, $W/m^2 \cdot °K$
k	thermal conductivity of condensate, W/m·°K
N	total number of data
Nu	average Nusselt number, $(\bar{h}/k)(\mu^2/\rho^2 g)^{1/3}$
Pr	Prandtl number, $c_p \mu / k$
Re_Γ	film Reynolds number, $4\Gamma / \mu$

$Re_{\Gamma tr}$	transition film Reynolds number
SSE	sum of squre error
T_s	saturation temperature, °K
T_w	wall temperature, °K
z	axial distance, m
Greek	
Γ	*mass flow rate per unit film width*, kg/s·m
ε_i	fractional error defined by Eq.(14)
$\bar{\varepsilon}$	mean fractional error
ε_{RMS}	root-mean-square fractional error
σ_ε	standard deviation from the mean fractional error
μ	dynamic viscosity of condensate, N·s/m^2
ρ	density of condensate, kg/m^3
subscript	
corr	predicted value by correlation
exp	experimental data

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