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Heat transfer in horizontal mechanically formed thin film heat exchangers—application of penetration theory model

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Abstract—A heat transfer correlation involving dimensionless groups is developed and the role of surface tension *vis-à-vis* viscosity and other process variables like mass flow rate, rotor speed and number of blades, etc. on scraped film heat transfer coefficients is delineated. Also the application of the penetration theory model is examined. The scraped film heat transfer coefficients calculated from the penetration theory model are far higher than experimental values. A correction factor based on film Reynolds number greatly improved the applicability of this model.

INTRODUCTION

IN ANY heat exchanger, even a very thin film of working fluid on the heat transfer surface adversely affects the rate of heat transfer. This film can be removed very effectively by rotating blades or scrapers and this is the principle on which scraped surface heat exchangers (SSHE) operate. The blade action produces a complex liquid flow pattern when compared to 'Standard' heat exchangers. Due to the presence of two velocity components, one axial and the other circumferential, the basic heat transfer theories may fail to predict the performance of thin film scraped surface heat exchangers. These units have been in use in the food and chemical industries and are available in vertical and horizontal configurations. An exhaustive review regarding hydrodynamics and heat transfer in thin film SSHE has been published [1]. However, this essentially pertains to fluid flow and heat transfer in vertical thin film SSHE. The literature on horizontal thin film SSHE is scanty. Authors have published some information on heat transfer and power requirement aspects in horizontal thin film SSHE [2].

In thin film SSHE, a new fluid surface is generated with every revolution of the scraper and as such, apart from viscous forces, surface tension forces should also play a role. The objective of this paper is to examine the role of surface tension *vis-à-vis* viscosity and other process variables on the scraped film heat transfer coefficient in the heat transfer correlation developed for horizontal thin film SSHE and also to study the validity of the penetration theory, a simplified theory advanced in the literature to predict the heat transfer coefficient in SSHE. This study should provide a better insight in the understanding of the mechanism of heat transfer in thin film SSHE.

EXPERIMENTAL PROCEDURE

Materials and methods are detailed elsewhere [2] and for convenience are given only briefly below. The experimental conditions are delineated in Table 1.

Procedure

A line diagram of the experimental set-up is shown in Fig. 1. The working fluid was filled in the feed tank (1) at room temperature (26°C) and then pumped through a lobe-type positive displacement pump (2) into the heat exchanger (5) (0.34 m diameter; 0.007 m wall thickness and 0.55 m heated length; material of construction 304 stainless steel). The regulating valves (3) were adjusted to achieve the desired flow rate as indicated by rotameter (4). The variable speed drive (8) was energized and the scraper's (6) speed was adjusted by means of a manual speed controller. As hinged type blades were provided on the scraper, centrifugal action resulted in fluid being spread over the heat transfer surface as a thin film. Steam at atmospheric pressure was allowed to condense in the heat exchanger jacket to maintain the heating surface at 100°C. The excess steam was vented through an air vent (AV2). Temperatures at the inlet and outlet were measured by copper–constantan thermocouple sensors inserted in thermowells T_1 and T_2. In all 128 experiments were conducted at different levels of processing variables.

The heat transfer process in thin film SSHE is influenced by a large number of factors such as physical, thermal, kinematic and geometrical. Therefore, a dimensional analysis approach was adopted. The data were arranged in various dimensionless groups and correlated as follows:

$$Nu = C\, Re_f^a\, We^b\, Pr^c\, B_F^d.$$

NOMENCLATURE

B	number of blades
C_p	specific heat [kJ kg^{-1} K^{-1}]
D	inside diameter of heat exchanger [m]
h_s	scraped film heat transfer coefficient [W m^{-2} K^{-1}]
K	thermal conductivity of fluid [W m^{-1} K^{-1}]
L	length of heat exchanger/rotor [m]
$\dot{M}$	mass flow rate [kg s^{-1}]
N	rotor speed [rev s^{-1}]
W_B	weight of one blade [N].

Greek symbols

μ	coefficient of viscosity [Pa s]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]

Dimensionless groups

B_F	blade factor, $BW_B/\mu ND^2$
Nu	Nusselt number, $h_s D/K$
Pr	Prandtl number, $\mu C_p/K$
Re_f	film Reynolds number, $\dot{M}/\pi D\mu$
Re_R	rotational Reynolds number, $D^2 N\rho/\mu$
We	Weber number (rotational), $N^2D^3\rho/\sigma$.

Here a new dimensionless group blade factor, B_F, essentially signifies the inertia effects of the rotor by accounting for the weight of the blades and could be varied by varying the number of blades or the weight of the blades.

RESULTS AND DISCUSSION

About 684 data sets were generated and processed on a HCL-4 computer [3]. The regression analysis was carried out using the method of least squares to determine constant C and exponents a, b, c and d. The model obtained was:

$$Nu = 0.215(Re_f)^{0.962}(We)^{0.201}(Pr)^{0.791}(B_F)^{-0.059} \quad (1)$$

$$0.15 \leqslant Re_f \leqslant 631$$

$$400 \leqslant We \leqslant 28\,800$$

$$3 \leqslant Pr \leqslant 1270$$

$$0.42 \leqslant B_F \leqslant 6000.$$

The correlation coefficient was 87%.

Error analysis was carried out to evaluate efficacy of the model. Figure 2 shows the plot of $(Nu)_{\text{observed}}$ vs $(Nu)_{\text{expected}}$ for selected data sets. The 45°-line corresponds to $(Nu)_{\text{observed}} = (Nu)_{\text{expected}}$. It is observed that most of the data points lie near to the 45°-line. Therefore, equation (1) can be conveniently adopted to predict the scraped film heat transfer coefficient. The effect of various process parameters namely flow Reynolds number, Weber number (rotational), number of blades and weight of blades on Nusselt number, in the case of paraffin liquid for a particular data set, is shown graphically in Figs. 3–5. A similar trend was observed for other working fluids, i.e. water, ethandiol and glycerol. The functional dependence of the scraped film heat transfer coefficient on the parameters of the correlation is as follows:

$$h_s \propto (\dot{M})^{0.962}(N)^{0.461}(BW_B)^{-0.055} \quad (2)$$

$$h_s \propto (K)^{0.209}(C_p)^{0.791} \quad (3)$$

$$h_s \propto (\mu)^{-0.112}(\sigma)^{-0.201}(\rho)^{0.201}. \quad (4)$$

Equation (2) shows the dependence of h_s on process variables namely mass flow rate, scraper speed and total weight of blades. It can be seen that these parameters greatly influence the film coefficient. The mass

Table 1. Experimental conditions

Serial No.	Working fluids	Range of flow rates (kg s^{-1})	Flow Reynolds number range	Rotor speed range (rev s^{-1})	Range of Weber number (rotational)	Average Prandtl number
1	Water	0.025–0.078	170–631	0.83–5	400–14 400	3.5
2	Ethandiol	0.025–0.072	9.0–38	0.83–5	652–23 490	71.5
3	Paraffin liquid	0.02–0.067	11–50	0.83–5	800–28 800	92.0
4	Glycerol	0.0078–0.035	0.15–1.35	0.83–5	750–27 000	1270

Details of blades:

	Set 1	Set 2
Number of blades	2, 4, 6 and 8	2, 4, 6 and 8
Weight	1.14 N blade^{-1}	2.28 N blade^{-1}
Thickness	0.00175 m	0.0035 m
Length	0.69 m	0.69 m
Width	0.0135 m	0.0135 m
Material	304 stainless steel	304 stainless steel

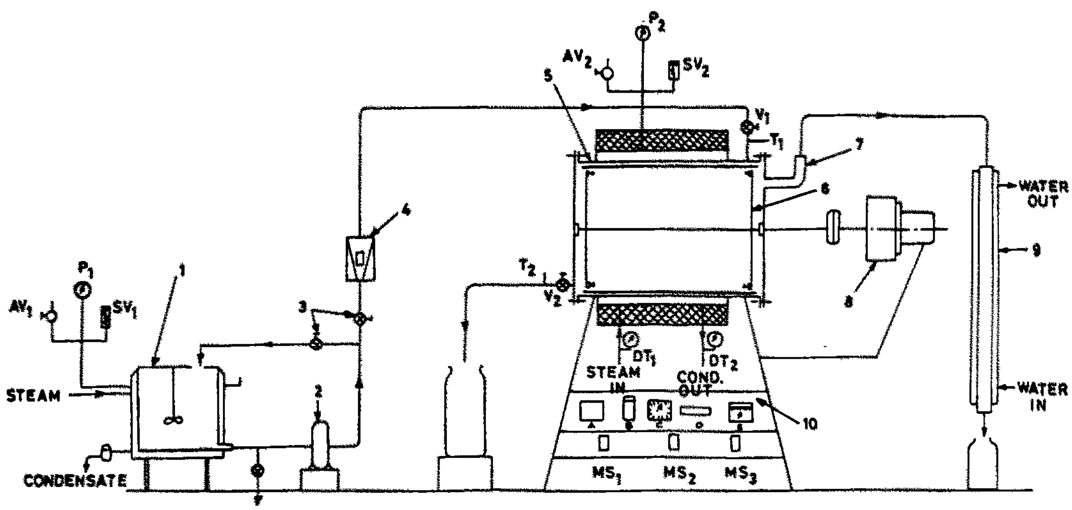

FIG. 1. Schematic diagram of experimental set-up: 1, feed tank; 2, feed pump; 3, flow regulating valves; 4, rotameter; 5, heat exchanger; 6, scraper; 7, vapour outlet; 8, variable speed drive; 9, condenser; 10, instrument panel; A, electronic regulator; B, manual speed controllers; C, selector switch; D, millivoltmeter; E, wattmeter; V_1 and V_2, inlet and outlet valves; T_1 and T_2, inlet and outlet thermowells; MS_1, MS_2 and MS_3, motor starters; AV_1 and AV_2, air vents; P_1 and P_2, pressure gauges; SV_1 and SV_2, safety valves; DT_1 and DT_2, dial thermometers.

flow rate seems to have the maximum effect on h_s. At any given instant, the fluid picked up by the blade is partly in the form of a film behind the blade and partly in the form of a fillet in front of the blade. The increase in mass flow rate causes the fillet volume to increase after the film had attained its final thickness (when hydrodynamic forces developed in film balance centrifugal force). Consequently the amount of fluid com-

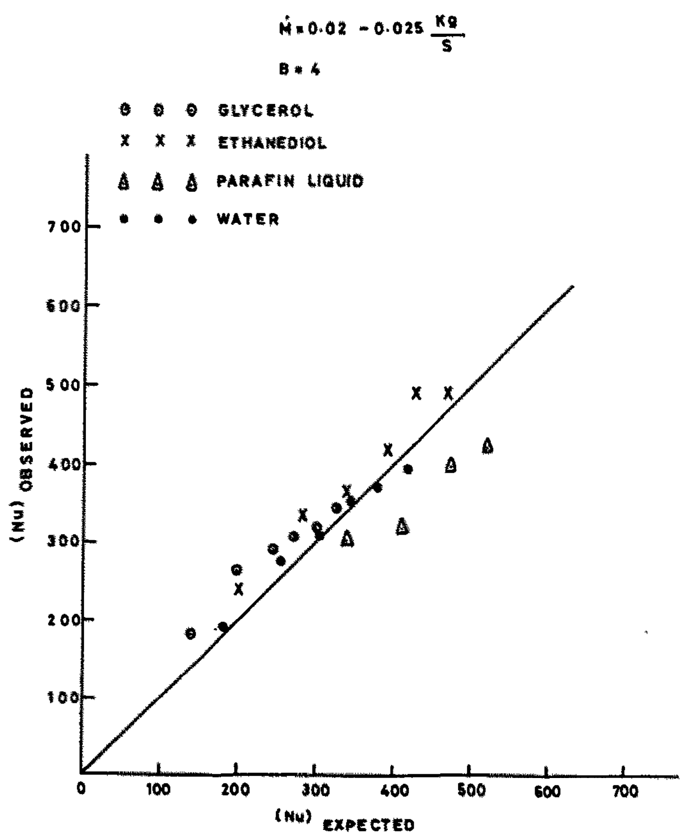

FIG. 2. Observed Nusselt number vs expected Nusselt number.

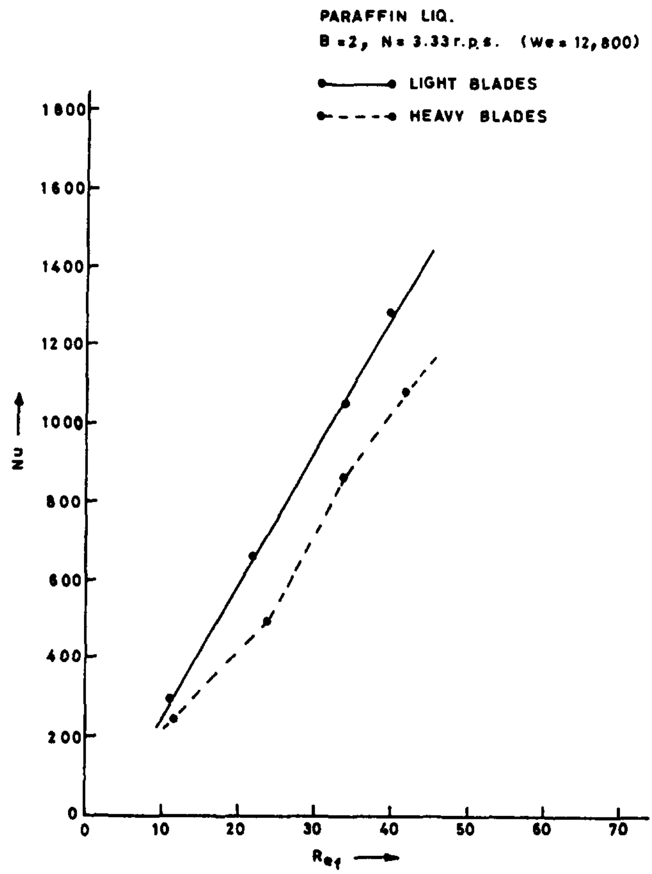

FIG. 3. Effect of flow Reynolds number on Nusselt number.

ing in contact with the heat exchanger surface or with the fluid film increases. This results in enhanced heat transfer rate and consequently higher values of h_s. The increase of h_s with rotor speed could be attributed to greater turbulence in fillet and higher frequency of its radial mixing. It is evident that as the weight of blades is increased h_s decreases. This could be due to the larger centrifugal force exerted by the blades causing much less fluid to squeeze past its tip. In other words, for heavy blades a larger amount of fluid is present in the form of fillet and its intermixing with the fluid film by blade action was relatively less. This resulted in lower heat transfer rates. Therefore, heavy blades offer no advantage and also use of heavy blades resulted in increased power consumption.

The effect of thermal properties such as thermal conductivity and specific heat is indicated in equation (3). The specific heat of fluid has a more pronounced effect on h_s as compared to thermal conductivity.

Equation (4) shows the influence of physical properties namely viscosity, surface tension and density of fluid on h_s. Surface tension seems to have a more profound effect as compared to viscosity on h_s. Therefore, in thin film SSHE the role of surface tension cannot be just ignored. Gudheim and Donovan [4] studied the effect of viscosity on the overall heat transfer coefficient in thin-film centrifugal processing units. It was observed that the bulk-temperature viscosity on the blade tip had little effect on the heat transfer rate up to a 10 000 fold gain in viscosity and further up to 40 000 fold, the effect was not too pronounced.

From equations (3) and (4), it is evident that within the confines of experimentation, the dependence of h_s on viscosity is relatively small. The greater dependence of h_s on thermal conductivity might indicate that the heat transfer mechanism is more dependent on heat conduction through the film in the liquid fillet adjacent to the wall.

Penetration theory

It is a simplified theory for predicting the heat transfer coefficient and explaining the heat transfer mechanism in scraped surface heat exchangers. This theory states that the heat transfer between the wall and the liquid takes place by a mechanism resembling unsteady state heat conduction between successive blade passes. When the blade passes a point on the surface, complete mixing is obtained so that at that instant the temperature from wall to vessel is equalized [5–7]. Hence, the temperature difference between the scraped plane and the bulk fluid occurs almost completely across a thin layer of material near the plane. This film is scraped from the wall and mixed with the bulk of the material and a clean heat transfer surface is exposed to fresh material, resulting in an enhanced rate of heat transfer.

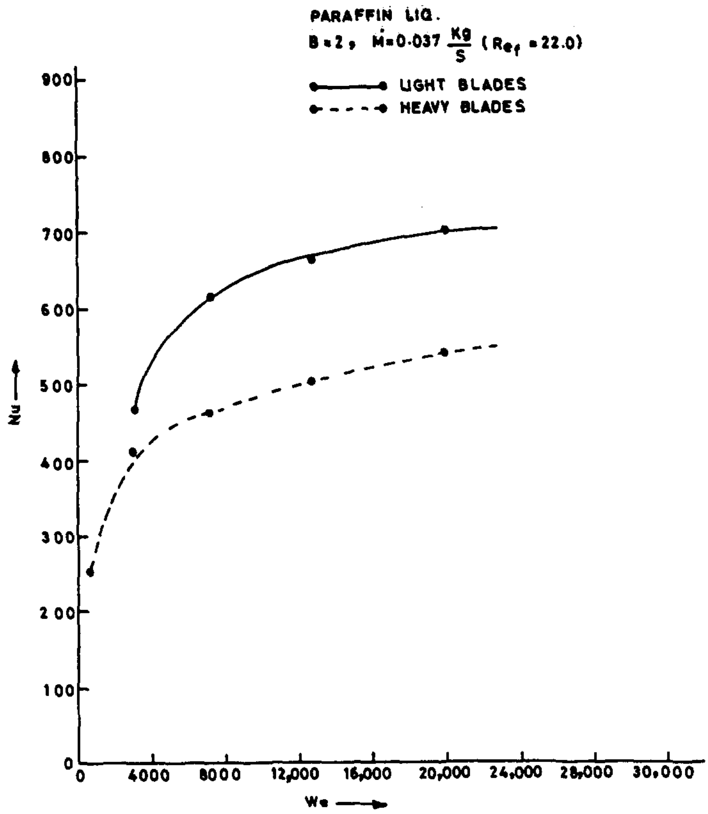

FIG. 4. Effect of Weber number (rotational) on Nusselt number.

For transient conduction into a semi-infinite solid, the solution of Fourier's equation averaged over the contact time, t, gives for the time average coefficient:

$$h_s = \sqrt{\left(\frac{KC_p\rho}{\pi t}\right)}. \tag{5}$$

In the SSHE, contact time is

$$t = 1/NB. \tag{6}$$

Hence

$$h_s = 1.13\sqrt{(KC_p\rho NB)}. \tag{7}$$

In terms of dimensionless groups this expression becomes

$$(Nu)_{\text{penetration}} = 1.13(Pr\ Re_R\ B)^{0.5}. \tag{8}$$

The ratio $(Nu)_{\text{observed}}/(Nu)_{\text{penetration}}$ was computed for different fluids and the ranges obtained were:

for glycerol

$$\frac{(Nu)_{\text{observed}}}{(Nu)_{\text{penetration}}} = 0.0124\text{–}0.0837$$

for ethandiol and paraffin liquid

$$\frac{(Nu)_{\text{observed}}}{(Nu)_{\text{penetration}}} = 0.0509\text{–}0.4766$$

for water

$$\frac{(Nu)_{\text{observed}}}{(Nu)_{\text{penetration}}} = 0.0905\text{–}0.8209.$$

It can be observed that scraped film coefficients calculated from the penetration theory model are far higher than actual experimental values or even those obtained from the prediction model, equation (1). Thus the use of the penetration model leads to erroneous results especially in the case of highly viscous fluids, because it assumes that heat transfer is independent of viscosity, which is known to be incorrect, especially in the turbulent regime. It postulates complete mixing when the blade passes a point on the surface so that at that instant the temperature from the heat transfer wall to the processor axis is equalized. Also, the limitation of this theory is that it assumes the need for good mixing for heat transfer to viscous liquids and hence predicts higher coefficients than those obtained in practice. This also conforms to the observations of Kool [5] and Harriot [6]. Moreover, the penetration model does not account for the effect of mass flow rate on scraped film heat transfer coefficient. The experiments have shown that in horizontal thin film SSHE, the mass flow rate has a very significant effect on heat transfer, as is also evident from equation (2). While penetration theory predicts that h_s will increase as long as N and B are increased, our results showed that after a certain value of N and B have been reached, h_s will not increase cor-

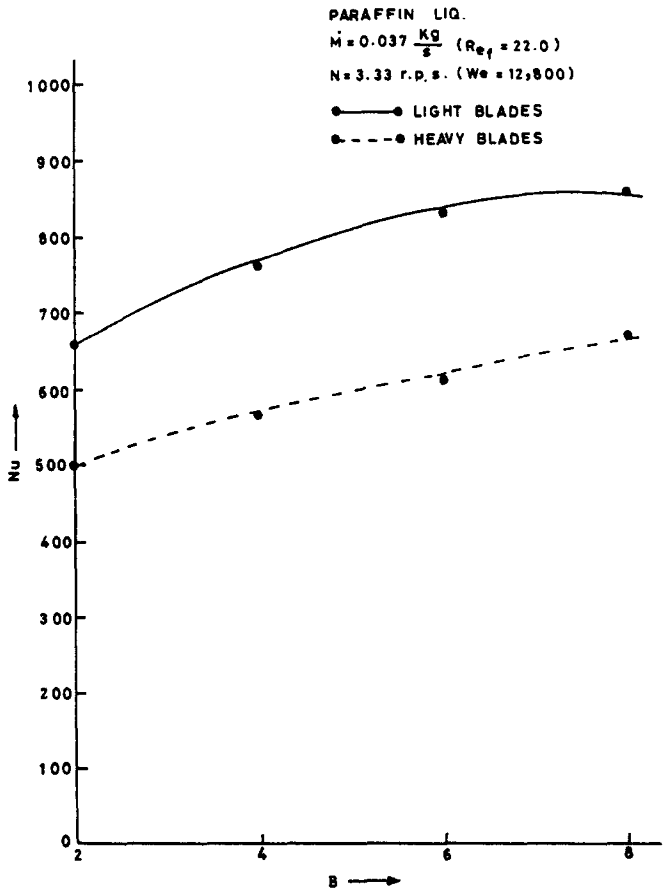

FIG. 5. Effect of number of blades on Nusselt number.

respondingly [2]. This further indicates the existence of interactions between axial and rotational forces which affect the heat transfer phenomenon.

In the case of liquid full SSHE units such as Votator, modifications to the penetration theory have been proposed to include the effects of physical properties. The most important one being of Trommelen *et al.* [8], which introduces a correction factor based on Prandtl number. However, the scatter of the points as well as the behaviour which results from blade speed–mass flow rate interactions remain essentially the same as was found for the uncorrected penetration equation. The failure of a factor based on Prandtl number to correct the theoretical predictions for the heat transfer coefficients might indicate that the phenomenon responsible for the discrepancy is not dependent on the physical properties only. Cuevas and Cheryan [9], concluded that any theoretical approach for describing the heat transfer phenomenon in SSHE should explicitly include both the axial and rotational components of the velocity field. Similar conclusions were arrived at by Ramdas *et al.* [10] for liquid-full SSHE and by Miyashita and Hoffman [11] for vertical film-type SSHE units. In both cases, the axial velocity effects accounted for in the axial or film Reynolds number, were found to be important.

An attempt is made to improve the penetration theory model as applied to horizontal thin film SSHE, by introducing a correction factor based on film Reynolds number expressed as

$$(Nu)_{\text{mod.pen.}} = 1.13(Pr\, Re_R\, B)^{0.5} f$$

where $f = C_1(Re_f)^{a_1}$ is a correction factor.

The data were programmed for methods of least squares to determine the intercept constant C_1 and exponent a_1. The values obtained were:

$C_1 = 0.057$ and $a_1 = 0.636$ (for glycerol)

$C_1 = 0.0057$ and $a_1 = 1.069$ (for ethandiol and paraffin liquid)

$C_1 = 0.00012$ and $a_1 = 1.289$ (for water).

Figure 6 shows the plot of observed Nusselt number vs Nusselt number obtained from the modified penetration theory model for particular data sets. As most of the points lie on or near to the 45°-line, it is evident that within the confines of experiments, the modified penetration theory model can also be used for determining the scraped film heat transfer coefficient in horizontal thin film SSHE.

CONCLUSIONS

In thin film SSHE where a new fluid surface is generated with every revolution of the rotor, the role

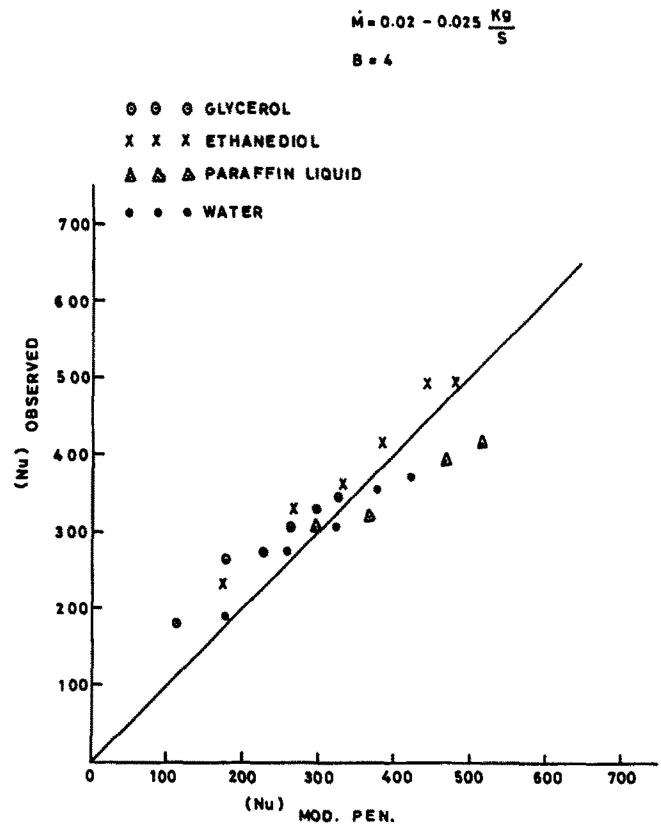

FIG. 6. Observed Nusselt number vs modified penetration theory model Nusselt number.

of surface tension on the scraped film heat transfer coefficient should also be considered.

The scraped film heat transfer coefficient increases with increase in mass flow rate, rotor speed and number of blades but decreases with increase in weight of the blades.

The penetration theory model as applied to the horizontal thin film situation yields highly erroneous results. The correction factor based on film Reynolds number greatly improved the applicability of this model.

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TRANSFERT THERMIQUE DANS DES ECHANGEURS A FILM MINCE FORME MECANIQUEMENT—APPLICATION DU MODELE DE LA THEORIE DE PENETRATION

Résumé—On développe une formule de transfert thermique avec des groupes adimensionnels et on dégage le rôle de la tension interfaciale vis-à-vis de la viscosité et d'autres variables telles que le débit-masse, la vitesse du rotor, le nombre de pales, ... sur les coefficients de transfert thermique de film raclé. On examine aussi l'application du modèle de la théorie de pénetration. Les coefficients de transfert thermique du film raclé, calculés par la théorie de la pénétration sont beaucoup plus élevés que les valeurs expérimentales. Un facteur de correction basé sur le nombre de Reynolds de film améliore fortement l'applicabilité du modèle.

WÄRMEÜBERGANG IN EINEM MECHANISCH GEFORMTEN DÜNNEN FILM AUF EINER HORIZONTALEN WÄRMETAUSCHERFLÄCHE

Zusammenfassung—Es wird eine Korrelationsgleichung für den Wärmeübergang mit Hilfe dimensionsloser Kennzahlen entwickelt. Dabei wird der Einfluß der Oberflächenspannung gegenüber den Einflüssen der Viskosität und anderer Prozeßvariabler wie Massenstrom, Rotorgeschwindigkeit und Blattzahl etc. auf den Wärmeübergangskoeffizienten abgegrenzt. Ebenso wird die Anwendbarkeit des Durchdringungsmodells untersucht. Wärmeübergangskoeffizienten, die mit Hilfe dieses Modells berechnet werden, sind weit größer als die experimentellen Werte. Ein Korrekturfaktor, der auf der Reynolds-Zahl der Filmströmung beruht, verbessert die Anwendbarkeit des Modells stark.

ТЕПЛОПЕРЕНОС В ГОРИЗОНТАЛЬНЫХ ТОНКОПЛЕНОЧНЫХ ТЕПЛООБМЕННИКАХ. ИСПОЛЬЗОВАНИЕ МОДЕЛИ ТЕОРИИ ПРОНИКНОВЕНИЯ

Аннотация—Выведено соотношение, включающее безразмерные группы, и установлена роль поверхностного натяжения по отношению к вязкости, а также влияние таких характеризующих процесс переменных, как массовый расход жидкости, скорость вращения и число лопастей, и т. д. на коэффициенты теплопереноса в пленке. Рассматривается также применение модели теории проникновения. Коэффициенты теплопереноса в пленке, рассчитанные при помощи этой модели, намного превосходят экспериментальные значения. Поправочный коэффициент, основанный на числе Рейнольдса для пленки, намного расширил область применимости данной модели.