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Effects of Condensate Inundation and Vapor Shear on Shell-Side Condensation

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<Abstract>

The present work describes various models with respect to the manner of allowing for the combined influence of condensate inundation and vapor shear on shell-side condensation. These models have been evaluated by simulating extensive data on condensation in a shell and tube condenser of industrial scale and design. The study includes condensation of vapors forming two-phase condensate, in which the method of predicting condensate film coefficient is more uncertain than that available for single phase condensates. It has been concluded for the data of the present work that condensate inundation and vapor shear affect the theoretical predictions of condensation significantly, and the best prediction was obtained when the combined coefficient obtained by the modified Shekriladze method for vapor shear is corrected for inundation by the method of Nusselt. Nusselt's correction may reduce the condensate film coefficient by 40%, while vapor shear enhances the coefficient by up to 25% for the systems considered here.

응축액의 Inundation과 증기의 전단이 shell측 응축에 미치는 영향

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<요 약>

본 연구에서는 shell측 응축에 미치는 응축액의 inundation과 증기 전단의 영향을 복합적으로

상관시키는 여러 가지 모델을 다루었다. 공업적 규모의 다관형 응축기에서 얻은 탄화수소 혼합물의 응축 실험데이터에 대한 수치모사를 수행하여 이러한 모델들을 평가하였다. 단일상의 응축액에 비해 응축액막의 열전달계수를 추산하는 것이 어려운 2상의 응축액을 형성하는 경우도 검토하였다. 응축액의 inundation과 증기의 전단이 응축현상에 대한 이론적 예측에 중요한 영향을 주는 것을 알 수 있었고, 증기의 전단에 대한 수정된 Shekriladze 방법에 Nusselt의 inundation 모델을 결합한 경우에 가장 좋은 예측을 얻을 수 있었다. 본 연구에서는 Nusselt의 inundation 모델이 응축액막의 열전달계수를 약 40% 정도 감소시키고, 증기의 전단은 25%까지 열전달계수를 증가시키는 것으로 나타났다.

1. Introduction

In horizontal tube bundles the condensate drips vertically from the uppermost tubes leading to thicker films and higher heat transfer resistance of the lower tube rows, known as condensate inundation. Where condensation occurs outside of a single horizontal tube, vapor shear will cause condensate film thinning and will enhance the heat transfer coefficient of the condensate film. At low vapor flowrate, gravity effects are dominant while vapor shear effects are dominant at higher vapor flowrate. Therefore, the average heat transfer coefficient of the condensate film is, in general, effected by both condensate inundation and vapor shear.

One of the most crucial problems in heat transfer calculations of shell-side condensation is to incorporate the effects of condensate inundation and vapor shear on the condensate film resistance. It is particularly important where the condensate film resistance is controlling and vapor shear is appreciable.

There are many correlations available for predicting the effects of inundation and vapor shear separately[1-10]. But no generalized methods on how to incorporate both effects have yet been available because of its complexity. And also studies of large tube bundles are rarely found in the open literature so that there is a clear requirement for further studies on this subject.

The present work describes various models with respect to the manner of allowing for the combined influence of condensate inundation and vapor shear. These models have been evaluated by extensive data on condensation of hydrocarbon mixtures in a shell and tube condenser of industrial scale and design. The study includes condensation of vapors forming immiscible liquids, in which the method of predicting condensate film coefficient is more uncertain than that available for single phase condensates.

2. Theory

Considerably less is known about forced convective condensation outside tube bundles.

The general approach is to correct the Nusselt equation[1] separately for the effects of condensate inundation and vapor shear. Neglecting vapor shear effects, the Nusselt equation for laminar filmwise condensation has long been used to estimate the heat transfer coefficient of the condensate outside a single horizontal tube.

Shekriladze and Gomelauri[2] have analyzed the case of downwards vapor flow over an isolated tube. They obtained an expression which fitted both the gravity-dominated and the vapor shear-dominated conditions:

$$h_{\ell 1} = 0.64 k_\ell [\rho_\ell u_g/(\mu_\ell d_o)]^{\frac{1}{2}}[1+(1+1.69\ F)^{\frac{1}{2}}]^{\frac{1}{2}} \qquad (1)$$

where $h_{\ell 1}$ = condensate film coefficient for a single tube, accounting for both the gravity and shear effects, (W/m^2K),

k_ℓ = condensate thermal conductivity, (W/mK),

ρ_ℓ = condensate density, (kg/m^3),

u_g = mean vapor velocity, (m/s),

μ_ℓ = condensate viscosity, (kg/ms).

d_o = tube outside diameter, (m),

$$F = g d_o \mu_\ell \frac{\Delta h_v}{u_g^2 k_\ell (T_I - T_W)} \qquad (2)$$

g = gravitational acceleration, (9.81 m/s^2),

Δh_v = latent heat of vaporization, (J/kg),

T_I = vapor-liquid interfacial temperature, (K),

T_W = tube wall temperature, (K).

Equation (1) is rewritten in a more compact form.

$$h_{\ell 1} = \left[\frac{1}{2}h_{\ell s}^2 + \left(\frac{1}{4}h_{\ell s}^4 + h_{\ell g}^4\right)^{\frac{1}{2}}\right]^{\frac{1}{2}} \qquad (3)$$

where $h_{\ell s}$ = condensate film coefficient where vapor shear effects are fully dominant,

$$= 0.90\ k_\ell \sqrt{\frac{\rho_\ell u_g}{\mu_\ell d_o}} \qquad (4)$$

and $h_{\ell g}$ is the condensate film coefficient where gravity effects are fully dominant, and can be predicted by the Nusselt equation with the assumption of $\rho_\ell - \rho_g = \rho_\ell$.

Equations (1) to (4) have been derived assuming that there is no separation of the boundary layer as the vapor flows across the tube. By considering the most forward position at which the boundary layer could separate, Shekriladze and Gomelauri introduced a multiplicative factor of 0.65 to the right-hand side of equations (1) and (3). However, this treatment gives a condensate film coefficient lower than Nusselt's prediction at low vapor velocity, which is not considered to be reasonable. Butterworth[3] suggested that the factor should be applied to equation (4) only, so that the Nusselt equation is obtained when vapor shear is negligible. Hence equation (4) becomes

$$h_{\ell s} = 0.59\, k_\ell \sqrt{\frac{\rho_\ell u_g}{\mu_\ell d_o}} \tag{5}$$

Combining equations (3) and (5) gives

$$h_{\ell 1} = 0.42\, k_\ell [\rho_\ell u_g/(\mu_\ell d_o)]^{\frac{1}{2}} [1+(1+0.47\ F)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{6}$$

The same author explained that boundary layer separation is inhibited to some degree by condensation and hence experimental data should lie between the results predicted from using equations (1) and (6).

Fujii et al[4] solved the governing equations by numerical methods. An empirical fit to the numerical solutions yields the equations;

$$h_{\ell 1} = 0.64\, k_\ell [\rho_\ell u_g/(\mu_\ell d_o)]^{\frac{1}{2}}\ [3.91(1+1/H)^{\frac{4}{3}} + 1.65\ F]^{\frac{1}{4}} \tag{7}$$

where

$$H = \frac{(T_I - T_W) k_\ell [\rho_\ell \mu_\ell / (\rho_g \mu_g)]^{\frac{1}{2}}}{\mu_\ell \Delta h_v} \tag{8}$$

Lee and Rose[5] have examined various theoretical studies of vapor shear effects using experimental data, available at that time. They concluded that most experimental data fall between the predictions of equation (6) and a very slightly modified form of equation (7).

While the works of Shekriladze and Gomelauri[2] and of Fujii et al[4] were carried out for downward vapor flow, Honda and Fujii[6] have shown that the results for horizontal vapor flow are almost identical to those for downward vapor flow.

Where vapor shear effects are negligible, therefore, the average coefficient for a vertical row of tubes is generally less than that given by Nusselt equations because of condensate inundation.

If there are Nr tubes in a vertical column and the condensate is assumed to flow smoothly from row to row, and if the condensate flow remains laminar, the average coefficient predicted by the Nusselt model, h_ℓ, is related to that for the top tube by;

$$h_\ell = h_{\ell,\mathrm{top}} \, Nr^{-\frac{1}{4}} \tag{9}$$

where $h_{\ell,\mathrm{top}}$ is condensate film coefficient for the top tube, and is equal to Nusselt film coefficient if vapor shear effects are ignored.

In practice, the condensate will not flow smoothly from tube to tube. Actual condensate flow patterns may be affected by the vapor flow, and a factor of $Nr^{1/6}$ has been applied in equation (9) by Kern[7]:

$$h_\ell = h_{\ell,\mathrm{top}} \, Nr^{-\frac{1}{6}} \tag{10}$$

Butterworth[8] has derived the following correlation from the work of Short and Brown[9].

$$h_{\ell N} = h_{\ell,\mathrm{top}} \, (\Gamma_N/\gamma_N)^{-\frac{1}{4}} \tag{11}$$

where $h_{\ell N}$ = condensate film coefficient for the Nth tube from the top of the bundle.

Γ_N = condensate drainage from the Nth tube, (kg/ms),

γ_N = condensate generated on the Nth tube, (kg/ms).

This result is equivalent to,

$$h_\ell = 1.24 \, h_{\ell,\mathrm{top}} \, Nr^{-\frac{1}{4}} \tag{12}$$

Equation (12) is valid only for large values of Nr (say greater than 10) but it is possible to derive numerical values for low Nr.

Grant and Osment[10] obtained a similar empirical correlation based on their experimental data with steam condensation:

$$h_{\ell N} = h_{\ell,\mathrm{top}} \, (\Gamma_N/\gamma_N)^{-0.223} \tag{13}$$

Butterworth[8] has shown numerically that the empirical equations of both Grant and Osment[10] and Kern[7] are in close agreement with that obtained from Short and

Brown[9].

No general guidance on how to incorporate the effects of inundation and vapor shear to estimate an average condensate film coefficient for a tube bundle has yet been published. Owen and Lee[11] recommend the following equation, in which the coefficient for the top tube with the vapor shear effect of Shekriladze and Gomelauri, (as modified by Butterworth[3]), is corrected for inundation by the method of Kern.

$$h_{\ell} = \left[\frac{1}{2} h_{\ell s}^{2} + \left(\frac{1}{4} h_{\ell s}^{4} + h_{\ell,Nu}^{4} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} Nr^{-\frac{1}{6}} \tag{14}$$

where $h_{\ell s}$ and $h_{\ell,Nu}$ are calculated by equation (5) and Nusselt equation respectively.

In the recent work of Rashtchian and Webb[12], the Nusselt's coefficient alone has been corrected for inundation by the method of Short and Brown as suggested by Butterworth. The shear and modified gravity coefficients have been combined to produce an average condensate coefficient, as recommended both by Shekriladze and Gomelauri and Butterworth. This method can be expressed as

$$h_{\ell} = \left[\frac{1}{2} h_{\ell s}^{2} + \left\{ \frac{1}{4} h_{\ell s}^{4} + \left(1.24\, h_{\ell,Nu}\, Nr^{-\frac{1}{4}} \right)^{4} \right\}^{\frac{1}{2}} \right]^{\frac{1}{2}} \tag{15}$$

where $h_{\ell s}$ is obtained by either equation (4) or (5). Rashtchian and Webb showed that the modification of the Shekriladze approach to account for boundary layer breakaway has little effect for the conditions of their experimental data in which the condensate coefficient is not controlling.

3. Analytical Methods

To simulate thermal performance and pressure drop of the condenser the film theory method has been applied in the manner described by Webb and Panagoulias[13]. It is based on the use of an effective diffusivity and assumes the local condensate is unmixed.

The application of the film model relies on calculation of local heat and mass transfer coefficients and these have been evaluated as follows. Heat transfer coefficients have been estimated by standard methods, for most part as proposed by Owen and Lee[11]. The shared surface model of Bernhardt et al[14] has been applied for the estimation of heat transfer coefficients of two-phase condensate. In a study of condensation of steam-air mixtures in the same condenser, Rashtchian and Webb[12], it was apparent that a significant dirt resistance was present and this was estimated to have a value of 0.000143

m^2K/W. This resistance has been assumed in the present analysis.

The gas-vapor side has been treated by the methods developed by Bell[15] as reported by Taborek[16]. Mass transfer coefficients have been obtained by the Chilton-Colburn analogy[17] from the predicted heat transfer coefficients.

Pressure drop calculations have been based on the approach of Bell[15], modified for two-phase flow as proposed by Ishihara et al[18]. The effect of high mass flux and decelerational pressure recovery have been included.

The methods of Nusselt and Kern were considered for the condensate inundation effect. Two methods have also been considered for the vapor shear effect, the work proposed by Shekriladze and Gomelauri[2] and its modification to allow for boundary layer breakaway, recommended by Butterworth[3]. It is also considered that the effect of inundation can be applied either to the gravity coefficient of Nusselt only or to the combined gravity and shear coefficients.

4. Data Analysis

Three sets of experimental data have been analyzed for the purposes of the present study. System 1, having 13 runs, is the condensation of a four-component mixture of hexanes, carried out at atmospheric pressure, and System 2 having 14 runs is the condensation of a mixture of methyl cyclohexane and toluene carried out under reduced pressure. These two sets of data were taken from the work of Kim[19]. One further set of data is available from the work of Rashtchian[20]. He has carried out 20 experimental runs with the same mixture as System 2. All the sets of data were obtained with a standard shell and tube condenser of industrial scale and design.

In Figures 1 to 6, with various combinations of inundation and vapor shear effects, the ratios of predicted to experimental values of overall heat load are plotted against superficial vapor velocity predicted at the center of the first baffle space of the test condenser.

Firstly, two methods of inundation correction, Nusselt and Kern, were applied without taking into account the vapor shear effect. The predictions of these two cases are shown in Figures 1 and 2. It is clear from Figure 1 that Nusselt's correction for inundation gives underprediction of heat load. In consequence the condensate heat transfer coefficient should be enhanced by taking into account the vapor shear effect.

It is interesting in Figure 2 that Kern's inundation correction gives good agreement of heat load although the vapor shear effect is neglected. It may be due to the fact that the effects of condensate inundation and vapor shear are at least to some extent compensatory. In this case Kern's correction underestimates the inundation effect and the vapor shear effect is offset by the underestimation of inundation. Comparing Figures 1 and 2, Kern's correction gives a higher heat load by 5% than Nusselt's correction for this particular experimental data.

Although Kern's correction without the vapor shear effect gives excellent predictions, it is not considered to be acceptable because it cannot explain physically the vapor shear effect which is appreciable in the present work. Therefore, only Nusselt's correction for inundation has been considered in combination with vapor shear effects.

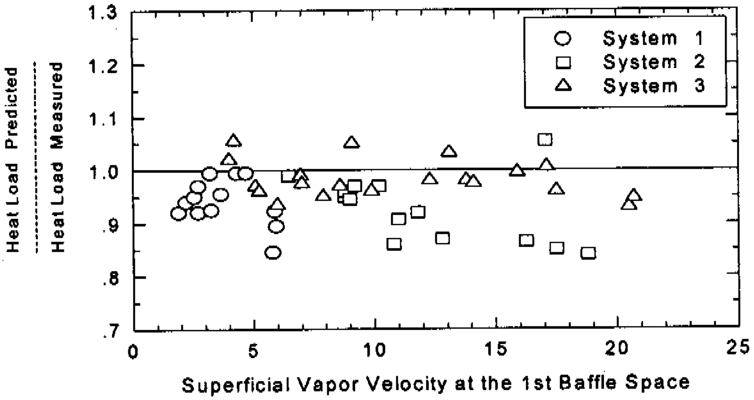

Figure 1 Predictions by Nusselt's Inundation Method without Vapor Shear

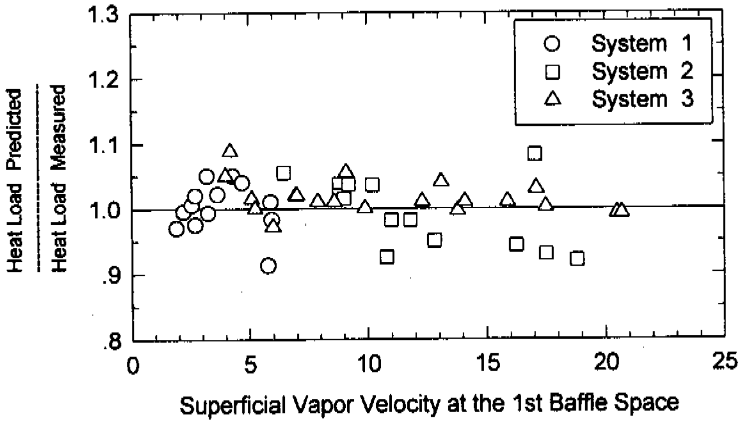

Figure 2 Predictions by Kern's Inundation Method without Vapor Shear

To estimate an average condensate film coefficient for a tube bundle, Nusselt's inundation correction was applied to the condensate coefficient suggested by Shekriladze and Gomelauri for a single tube, equation (1). The predictions by the film theory method under this condition are shown in Figure 3. Considering the vapor shear effect as a function of vapor velocity, it is clearly seen in Figure 3 that the vapor shear effect is overestimated by Shekiladze and Gomelauri so that overall heat load is overestimated especially for the experimental runs having high vapor velocity. This is consistent with their work. They explained the overestimation is due to boundary layer breakaway.

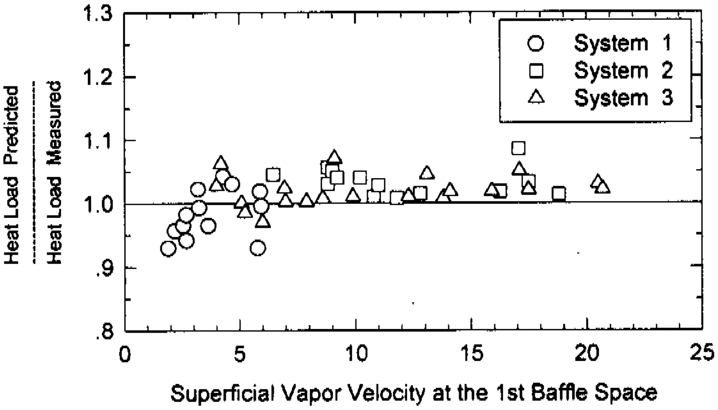

Figure 3 Predictions by Nusselt's Inundation Method Applied to a Combined Coefficient with Shekriladze's Methods for Vapor Shear

Attention is now turned to the modified method of Shekriladze and Gomelauri suggested by Butterworth, equation (6) in which boundary layer breakaway is taken into account. With application of Nusselt's inundation correction to the modified Shekriladze method it is seen, in Figure 4, that the film theory method gives excellent predictions. ± 10% agreement in overall heat load. There is no dependence of predictions of vapor velocity such as that which appeared in the previous case (Figure 3). This, of course, shows that the vapor shear effect is properly estimated by the modified method of Shekriladze and Gomelauri.

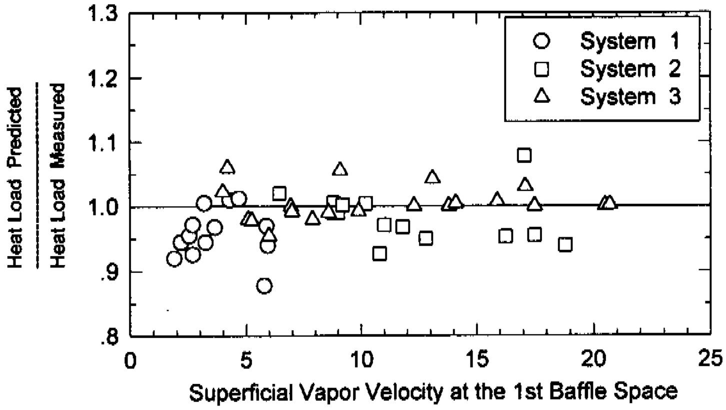

Figure 4 Predictions by Nusselt's Inundation Method Applied to a Combined Coefficient with the Modified Shekriladze Method for Vapor Shear

Figure 5 is obtained for the case in which the gravity coefficient alone has been corrected for inundation by Nusselt and this coefficient is combined with the shear controlled coefficient by the modified method of Shekriladze and Gomelauri. This case gives very similar predictions to the case shown in Figure 3 and gives much worse predictions than the previous case presented in Figure 4.

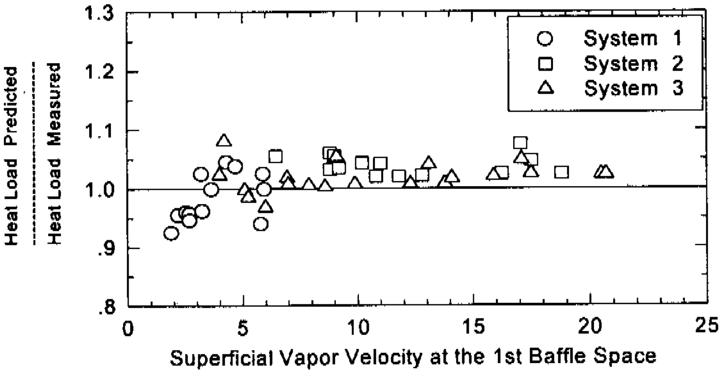

Figure 5 Predictions by Nusselt's Inundation Method Applied to the Gravity Coefficient Only, with the Modified Shekriladze Method for Vapor Shear

Finally, one more case is considered for comparison purposes. In this case the combined coefficient obtained by the modified Shekriladze method has been corrected for condensate inundation by the method proposed by Kern. The predictions are shown in Figure 6. As expected from the results shown in Figure 2, overall heat load has been overpredicted. The independence of the predictions to vapor velocity indicates that such disagreement is due to improper correction for the inundation effect rather than the vapor shear effect.

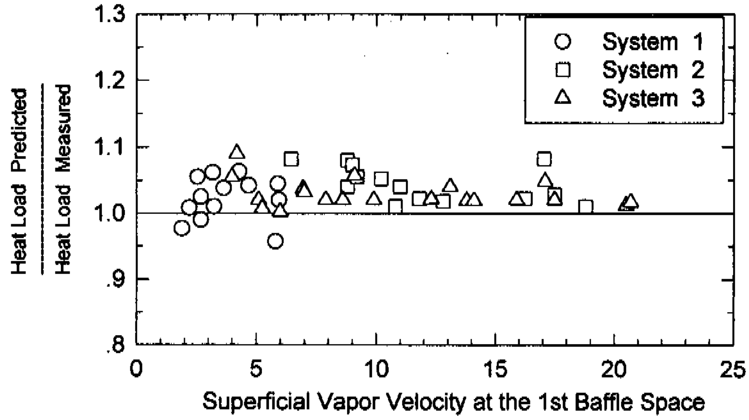

Figure 6 Predictions by Kern's Inundation Method Applied to a Combined Coefficient with the Modified Shekriladze Method for Vapor Shear

To investigate the possible effect of vapor shear in more detail the predictions shown in Figures 1 and 4 are compared. Figure 7 shows the ratio of predicted heat loads by the modified Shekriladze method and the Nusselt method including no shear effect.

The effect of vapor shear does not show strong dependence on vapor velocity. Moreover, the effect of vapor shear on overall heat load varies between the three systems considered here. This is at least in part due to the fact that the vapor shear effect is not a function of vapor velocity only. Considering that System 2 and Rashtchian's data are for the same mixture, except that the latter has a lower heat flux, the different trend of the shear effect between these systems shown in Figure 7 appears to be due mainly to the difference in heat flux.

It is clear from Figure 7 that vapor shear enhances overall heat transfer coefficient by up to 13% for the systems considered here. In the present work, about 50% of the overall heat transfer resistance is due to the condensate film resistance for all three systems. Therefore the condensate film coefficient may be increased by up to 25% by the effect of vapor shear. It is thought that the condensate film resistance for the systems studied here is controlled more by gravity than vapor shear, over the condenser as a whole. However, it should be emphasized that some experimental runs having high vapor velocity may be affected significantly by vapor shear, in the earlier part of the condenser.

The individual effect of inundation on the prediction of overall performance of the test condenser was not estimated in the present work. The prediction of overall heat load is not a good indicator to measure the effect of inundation for the systems considered, because total condensation would be predicted before the end of the test condenser area was reached if no inundation was assumed. However, the effect of inundation on the condensate film coefficient can be estimated from the correlation used. For the test condenser Nusselt's correction may reduce the condensate film coefficient by 40% approximately.

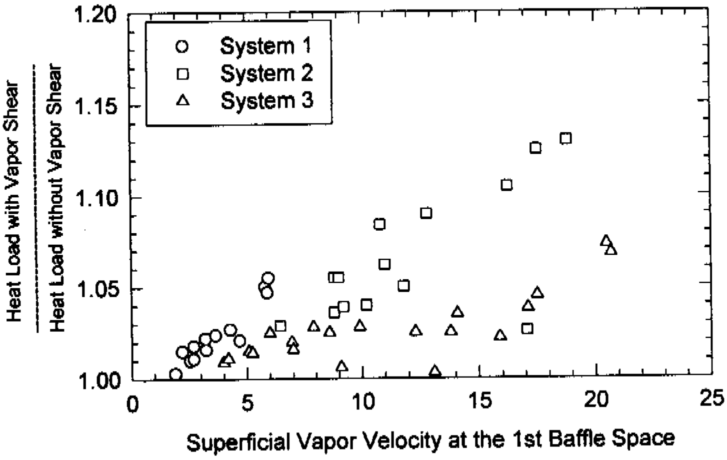

Figure 7 Vapor Shear Effect of the Modified Shekriladze vs Superficial Vapor Velocity

To make the evaluation of the best model, which is the application of Nusselt's inundation to the modified Shekriladze method, more reliable, this model is further assessed against the data on the condensation of mixed vapors of hydrocarbons and water, which form immiscible liquids. System 4, comprising 20 runs, is the condensation of a four-component mixtures of hexanes and steam, carried out at atmospheric pressure. System 5, having 35 runs, is the condensation of mixed vapors of methyl cyclohexane, toluene and steam, which is carried out at atmospheric and reduced pressures.

Figures 8 and 9 show the comparisons of predicted and experimental heat load for Systems 4 and 5 respectively. It is apparent that the model gives good agreement of overall heat load, within ± 15%. There is no clear dependence of predictions of overall heat load on feed composition. Comparing the predictions for Systems 4 and 5, the former has the tendency of under design while the latter gives conservative design. No clear explanation of this tendency is apparent.

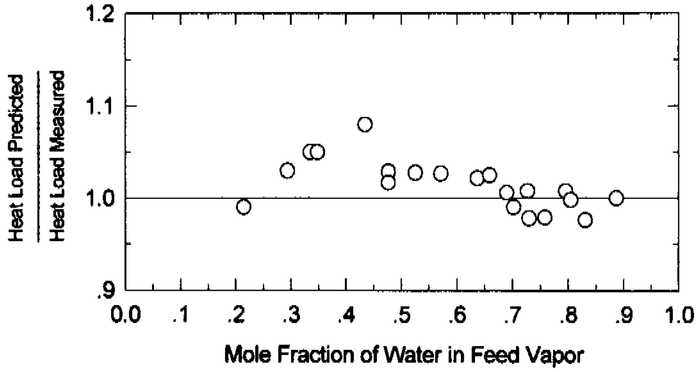

Figure 8 Comparasion of Predicted and Experimental Heat Load for System 4

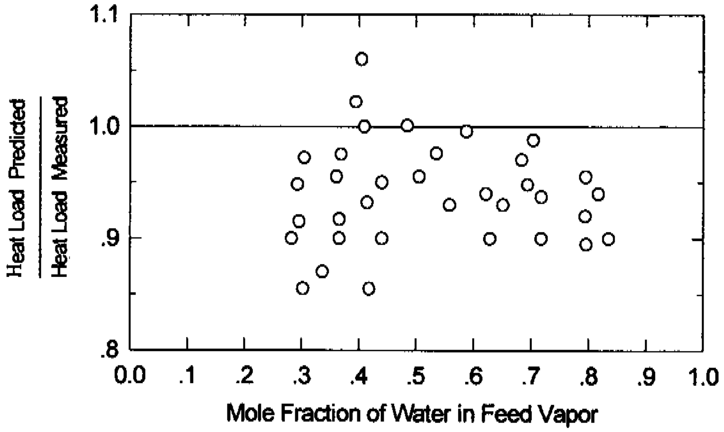

Figure 9 Comparison of Predicted and Experimental Heat Load for System 5

5. Conclusions

It has been concluded for the data of the present work that condensate inundation and vapor shear affect the theoretical predictions of condensation significantly. Of the various methods for describing the combined effect of condensate inundation and vapor shear considered in shell-side condensation of hydrocarbon mixtures, the combination of Nusselt's correlation of inundation and the modified Shekriladze correlation of vapor shear gave the best results.

The model also gave good predictions of overall heat load for the condensation processes involving two-phase condensate, within ± 15%.

For the test condenser Nusselt's correction may reduce the condensate film coefficient by 40%, while vapor shear enhances the coefficient by up to 25% for the systems considered here.

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