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EFFECT OF NATURE AND COMPOSITION OF INERT GAS ON BINARY VAPOUR CONDENSATION

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ABSTRACT

We consider the problem of binary vapour condensation in the presence of an inert gas and analyse the effect of the nature of the inert gas and its composition on the condensation process. The analysis of the simultaneous heat and mass transfer process is carried out with the aid of two basically different models for vapour phase transfer: (i) an *interacting* model in which the diffusional interactions in the vapour phase are properly taken into account and (ii) a *non-interacting* model in which the diffusion process in the vapour phase is modelled using effective pseudo-binary diffusivities. These two models are applied to specific cases involving the condensation of methanol-water vapour mixtures in the presence of air and also in the presence of helium. Two cases involving rich and lean vapour mixtures are considered. The results of the computations show that interaction effects in the vapour phase are significant for rich vapour mixtures (small concentrations of inert gas). Also, the interactions in the system methanol-water vapour-helium are much larger than in the corresponding system with air as inert gas. The enhanced effect of diffusional interactions in the helium system is attributable to larger differences in the constituent binary pair diffusivities.

Introduction

The analysis of mixed vapour condensation, with or without the presence of an inert gas, has been considered by many authors [1-17], the pioneering work being that of Ackermann [1] and Colburn and Drew [4]. Established design procedures for condensation equipment follow the Ackermann-Colburn-Drew

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treatment, which was developed for binary systems; the extension of the binary analysis to multicomponent systems usually employ the use of effective diffusivities for the species in the vapour phase (see for example the papers of Schrodt [13] and Maa [8]). It has been recognised for some time that the transfer characteristics of systems with three or more components (i.e. multicomponent systems) are completely different from simple two-component systems [9,14,16,17]. General procedures for solving multicomponent diffusion problems were developed independently by Stewart and Prober [14] and Toor [16]. The Toor-Stewart-Prober theory involves assuming that the matrix of diffusion coefficients in a multicomponent system remains constant along the diffusion path. More recently Krishna [6,7] developed an alternative to the Toor-Stewart-Prober analysis using an exact matrix method of solution to the Maxwell-Stefan equations. Both procedures attempt to properly account for the diffusional interactions in the vapour phase, and in this paper they are jointly referred to as the interacting model to distinguish these from the non-interacting (or pseudo-binary) approaches of Maa and Schrodt.

Design procedures for multicomponent condensers taking account of diffusional interactions have been put forward [2,6,7,12]. Available experimental data on ternary systems have confirmed the superiority of the interacting models over simpler models using effective diffusivities (see the papers of Bandrowski and Kubaczka [2] and Krishna [5]). These tests of interacting models with experimental data are only preliminary and there is a crying need for further experimental work with ternary vapour-gas systems.

In the present communication, which is essentially an extension of earlier work [6,7], we present computational results showing the effect of the nature of the inert gas, and its composition, on the condensation phenomena. The object of the study is to point out the instances in which diffusional interaction phenomena are significant and must be taken into account. The computations have been carried out for condensation of methanol-water vapour-air and methanol-water vapour-helium systems for both rich and lean vapour mixtures. The calculations were performed for the interacting (using both the Toor-Stewart-Prober and Krishna et al., approaches) and non-interacting models, as has already been described earlier [6,7]. The details of the system studied are listed in Table 1. We discuss below the results of the computational studies.

Table 1

Condenser Tube Data:

geometry: single vertical tube with condensation taking place inside the tube, cooling water in annular section

inside diameter of tube: 0.0254 m

length of tube: 2.12 m

Flow Directions:

binary vapour + inert gas mixture flowing down the tube, co-current to condensate flow

cooling water flowing up the tube, counter-current to condensate flow

Summary of Operating Conditions:

	Case 1	Case 2	Case 3	Case 4
system:	methanol(1)-water(2)-air(3)		methanol(1)-water(2)-helium(3)	
inert gas flow, kmol/s	1.197×10^{-4}	1.841×10^{-5}	1.197×10^{-4}	1.841×10^{-5}
total gas flow, kmol/s	1.841×10^{-4}	1.841×10^{-4}	1.841×10^{-4}	1.841×10^{-4}
composition:				
y_1	0.2129	0.7000	0.2129	0.7000
y_2	0.1369	0.2000	0.1369	0.2000
y_3	0.6502	0.1000	0.6502	0.1000
entering gas temperature, K	344.2	360.0	344.2	360.0
pressure, bar	1.0135	1.0135	1.0135	1.0135
coolant flow rate, kg/s	0.04376	0.04376	0.04376	0.04376
coolant outlet temperature, K	308.15	308.15	308.15	308.15

Results and Discussion

The composition and temperature profiles for the four cases listed in Table 1 are given, respectively, in Figs. 1-4. On the scale of the figures given, the results for the Toor-Stewart-Prober interacting model and the Krishna et al., model could not be distinguished and the term interacting model is used in the figures for the common result of these models. The non-interacting model is one in which effective pseudo-binary diffusivities are used for each of the transferring species in the vapour-gas mixture [6,7].

Consider the results for Case 1 (Figs. 1a and 1b) corresponding to the condensation of a lean methanol-water vapour mixture in the presence of air. Since the mixture is dilute in the transferring species, the cross mass transfer coefficients k_{y12} and k_{y21} in the matrix of vapour phase mass transfer coefficients will be small relative to the main coefficients. For example at the top of the condenser (entrance) the values of the matrix of mass transfer coefficients are calculated to be (units: mmol/s/m^2/mole fraction)

$$k_{y11} = 1.830; \qquad k_{y12} = -0.024$$
$$k_{y21} = 0.079; \qquad k_{y22} = 2.835 \tag{1}$$

Due to the small magnitude of the cross coefficients the differences between the interacting model and the non-interacting model for temperature and composition profiles are negligibly small. The effective diffusivity model is adequate for describing the condensation process.

The results for a rich vapour mixture of methanol-water vapour condensing in the presence of air are given in Figs. 2a and 2b. The differences between the interacting and non-interacting models is now quite significant. The reason for much larger interactions for this case can be understood if we consider the values of the matrix of mass transfer coefficients. At the top of the condenser we calculate the coefficients as:

$$k_{y11} = 2.187; \qquad k_{y12} = -0.0827$$
$$k_{y21} = 0.12\ ; \qquad k_{y22} = 2.461 \tag{2}$$

which shows, on comparing with (1) above, that the cross coefficients are now much larger than before. This is because the coefficient k_{y12} is proportional to the mole fraction y_1 and the coefficient k_{y21} is proportional to the mole fraction y_2:

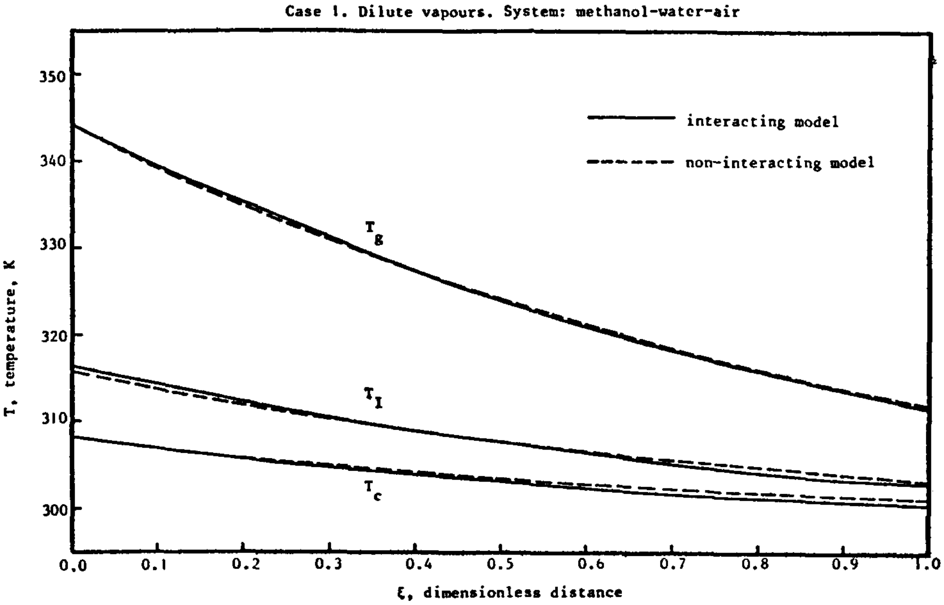

FIG. 1a
Temperature variations along condenser tube length

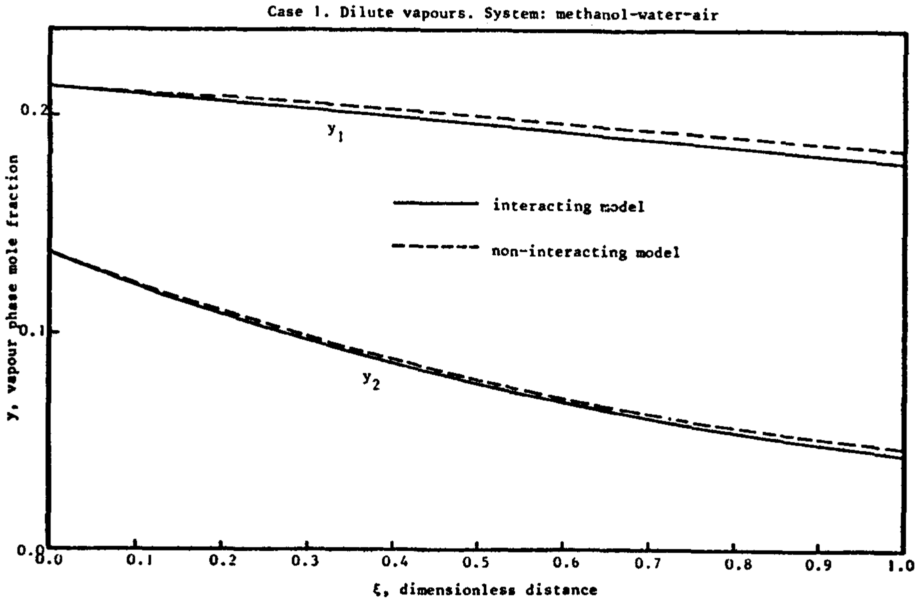

FIG. 1b
Variations of vapour phase mole fractions along condenser tube length

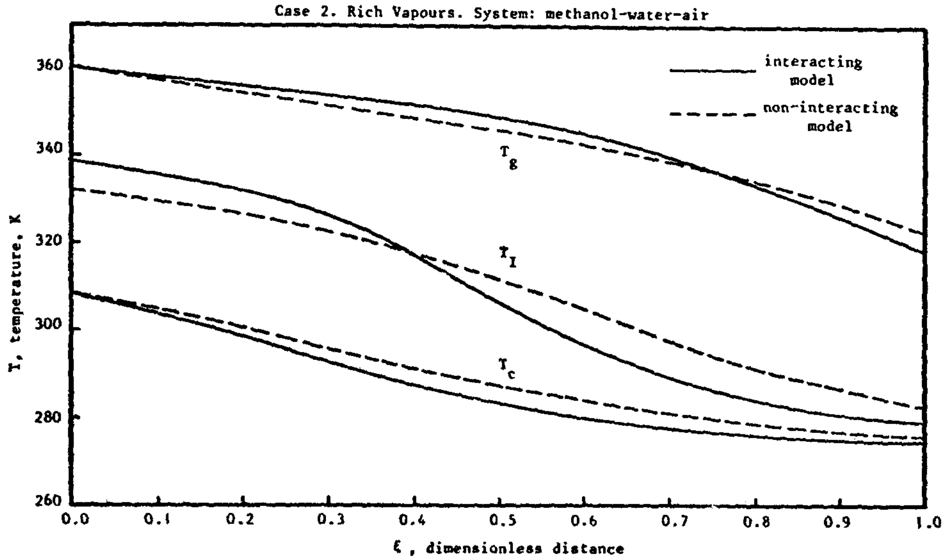

FIG. 2a
Temperature variations along condenser tube length

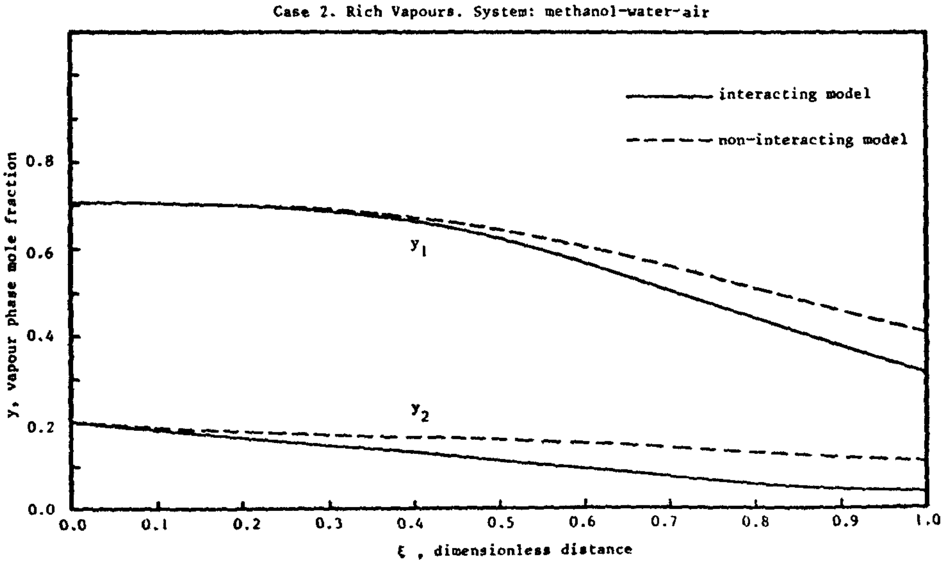

FIG. 2b
Variations of vapour phase mole fractions along condenser tube length

$$k_{y12} = y_1 k_{23}(k_{13} - k_{12})/(y_1 k_{23} + y_2 k_{13} + y_3 k_{12}) \tag{3}$$

$$k_{y21} = y_2 k_{13}(k_{23} - k_{12})/(y_1 k_{23} + y_2 k_{13} + y_3 k_{12}) \tag{4}$$

where k_{ij} are the binary mass transfer coefficients of the pair i-j, calculated from an appropriate j-factor mass transfer correlation. Equations (3) and (4) show that when the condensing species 1 and 2 are rich then the cross coefficients are proportionately large and for this case interaction effects can be expected to be significant.

Another factor which determines the magnitude of k_{y12} and k_{y21} is the differences in the constituent binary mass transfer coefficients k_{ij}. If the species 3 (inert) is largely different in molecular weight and molecular volume from the condensing species 1 and 2, then the differences $(k_{13} - k_{12})$ and $(k_{23} - k_{12})$ will be large giving rise to larger cross coefficients. Thus if instead of air, the inert gas is chosen to be helium, whose molecular weight is much lower than the molecular weights of methanol and water vapour, then the cross coefficients will be much larger giving rise to much larger interactions as compared to the methanol-water vapour-air example. Figures 3a and 3b give the results for condensation of a lean mixture of methanol and water vapour in the presence of helium. We notice, as anticipated, now that the interactions are much more significant than the corresponding Case 1 for air.

The calculations for rich vapour mixture condensing in the presence of helium gives the highest interactions among the four cases studied (see Figs. 4a and 4b). For this case both factors influencing the cross mass transfer coefficients: large values of y_1 and y_2 and large differences in the constituent binary pair mass transfer coefficients lead to much larger values for the cross coefficients. For example at the top of the condenser the values of the matrix of mass transfer coefficients are calculated to be (units: mmol/s/m^2/mole fraction)

$$\begin{aligned} k_{y11} &= 4.510; \quad & k_{y12} &= 2.185 \\ k_{y21} &= 0.749; \quad & k_{y22} &= 3.136 \end{aligned} \tag{5}$$

The large values of the cross coefficients k_{y12} and k_{y21} give rise to largely enhanced interaction phenomena and the use of the effective diffusivity approach will lead to large errors in the calculations of the temperature and composition profiles, and consequently to large errors in design.

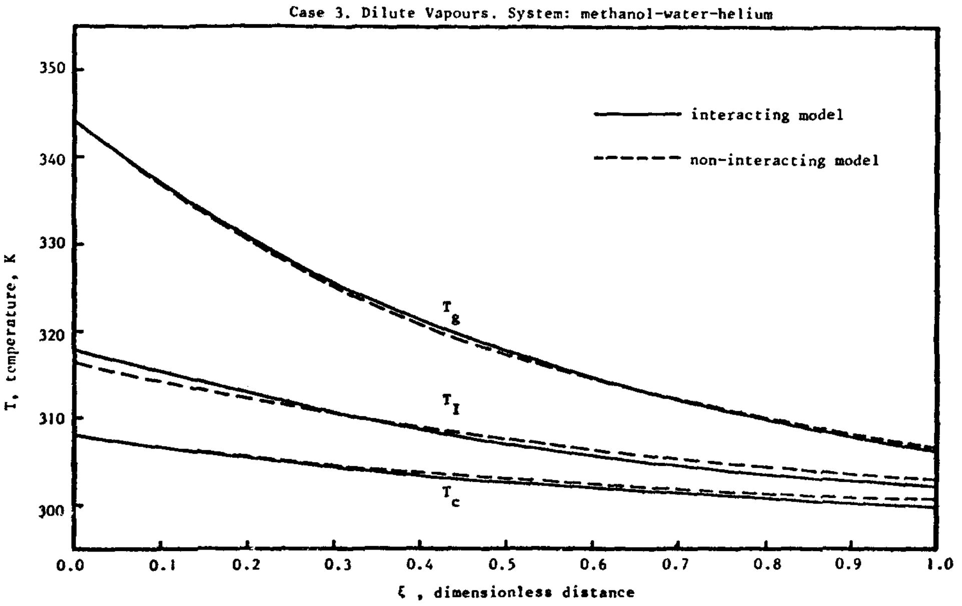

FIG. 3a
Temperature variations along condenser tube length

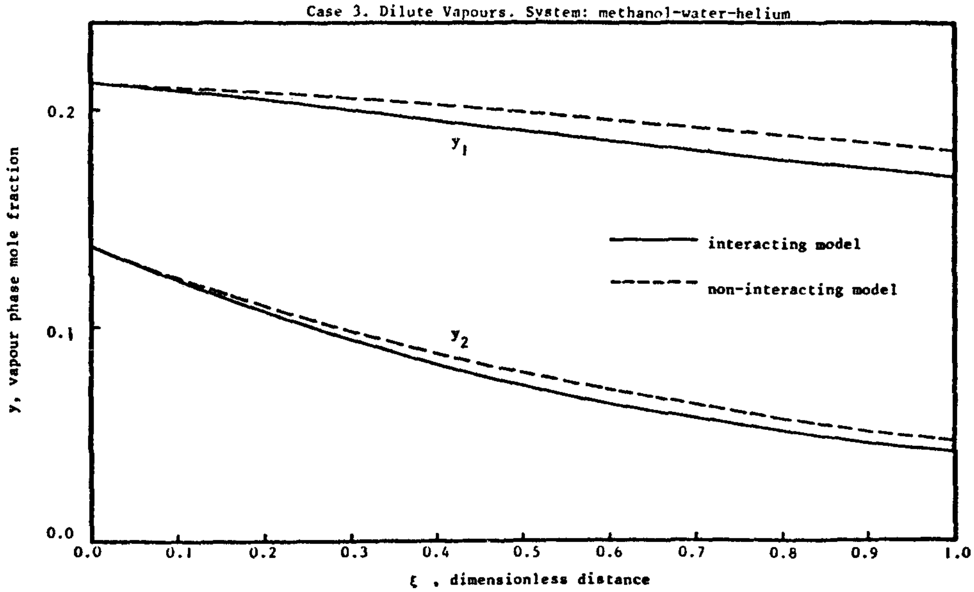

FIG. 3b
Variations of vapour phase mole fractions along condenser tube length

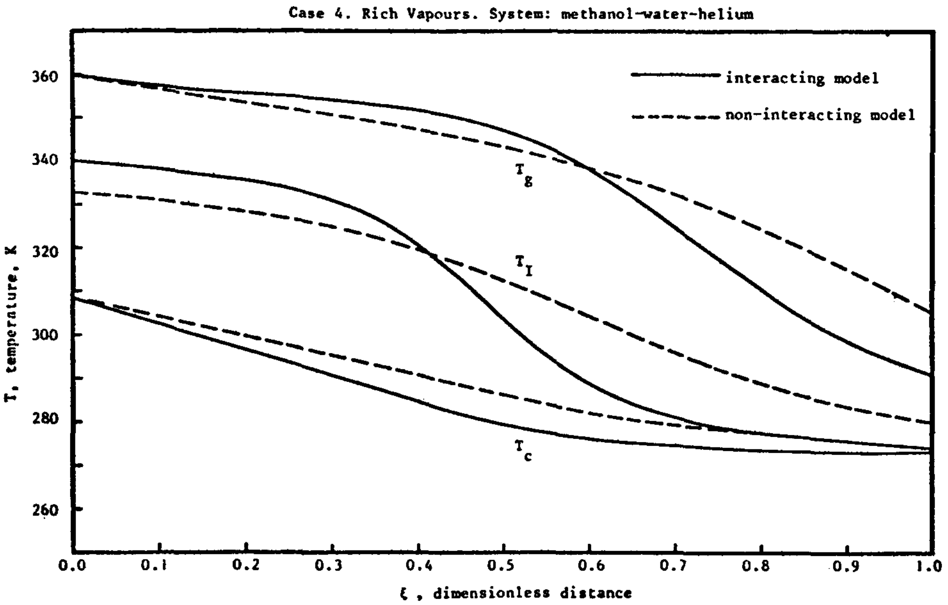

FIG. 4a
Temperature variations along condenser tube length

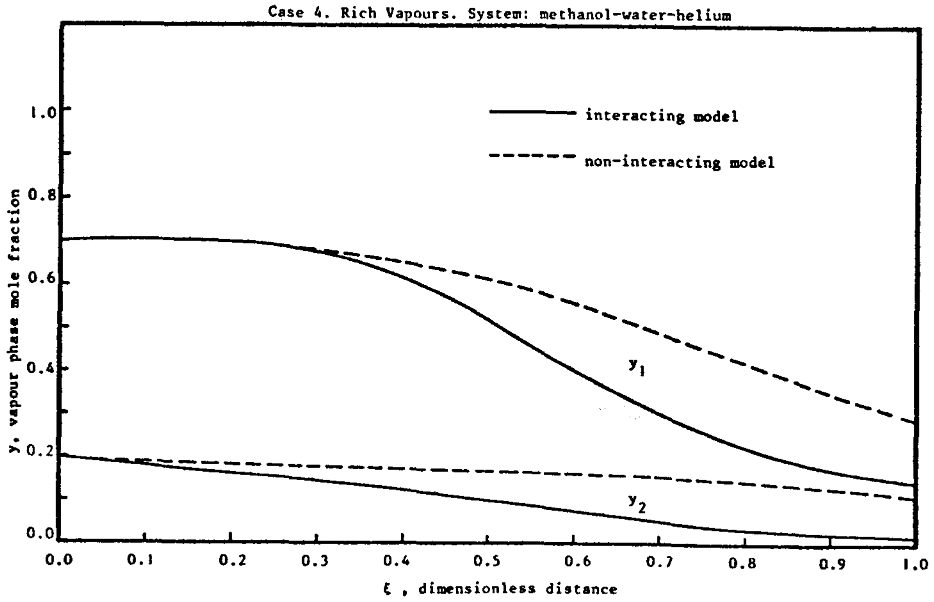

FIG. 4b
Variations of vapour phase mole fractions along condenser tube length

Concluding Remarks

Using computational results for condensation in the systems methanol-water vapour-air and mathanol-water vapour-helium, the influence of the nature of the inert gas and its composition on the condensation process has been determined. The following general conclusions can be drawn regarding the importance of diffusional interaction phenomena in condenser design:

i) for rich vapour mixtures condensing in the presence of an inert gas the interaction effects can be expected to be more significant than for the corresponding case of lean vapour condensation, and

ii) the larger the differences in the constituent pair mass transfer coefficients (arising from large differences in the constituent pair binary vapour diffusivities), the larger the interaction effects to be expected.

The results presented in this paper should prove useful to the design engineer involved in condensation because the cases in which interaction effects are expected to be significant are delineated. Another use of the results presented here is that they would help in the choice of the proper experimental system to test the models developed.

Finally it must be remarked that the theory of multicomponent condensation is now well understood and documented; there is, however, a great need for more experimental work *with the proper systems* in order to test the theories developed. Once the theories have been verified they can be incorporated into standard computer programs for their design. Available experimental data point to the validity of the multicomponent mass transfer theory taking account of diffusional interactions [2,5].

Nomenclature

k_{yij}	elements of vapour phase multicomponent mass transfer coefficients matrix
k_{ij}	mass transfer coefficient of binary pair i-j in multicomponent mixture (these coefficients are calculated from a mass transfer correlation using the appropriate binary vapour phase diffusivity D_{ij})
y_1	bulk vapour phase mole fraction of species 1
y_2	bulk vapour phase mole fraction of species 2
y_3	bulk vapour (gas) phase mole fraction of inert species 3
T_g	bulk gas temperature

T_I gas-liquid interface temperature

T_C coolant water temperature

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