

PHENOMENA AND PROBLEMS IN THE CONDENSATION OF BINARY VAPOURS OF IMMISCIBLE LIQUIDS

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Synopsis

The paper describes the phenomena of immiscible binary mixtures when condensed on a flat plate or a single tube and over a tube bank. It discusses the resistances of heat and mass transfers from the bulk vapour to the condenser outside wall and the condensate flow patterns. The paper finally addresses some of the problems associated with the condensation of the binary vapours of immiscible liquids through tube bundle as well as the effect of vapour shear on the condensation process.

Nomenclature

ΔT_f	condensing film temperature difference, K
F	degree of freedom
j	number of components
l	number of phases
T	Temperature °C
h	heat transfer coefficient, $\text{kJ/m}^2\text{K}$
x	condensate mole fraction
y	vapour mole fraction
Q	heat flux, kW/m^2
N	Molar flux, $\text{kmol/m}^2\text{s}$

Subscripts

A	azeotrope
B	bulk mean value
C	condensate
cw	cooling water
f	film
g	gas
I	interface
o	outside
w	wall
1,2	mixture components (1-water; 2-Organic)

Introduction

The condensation of binary vapours of immiscible liquids is an important industrial operation, frequently occurring in the oil and chemical industries. This type of condensation is also frequently encountered in association with the operation of steam distillation. The condensation of such vapours has been subjected to numerous and intensive studies. Most of these studies apply to condensers of simple geometry (condensation on a flat plate or inside and outside single tubes) and the condensation process was based on slow moving or gravity from vapour mixture. Many correlations for the condensate heat transfer coefficient have been produced but most results show that the Bernhardt and Westwater

- (1) volume weighted average of the Nusselt Coefficients
- (2) is the most accurate.

studies on condensation of these vapours over large tube banks are expensive because of the very high heat load involved and are difficult to interpret because of the complicated vapour and condensate flow patterns. The vapour mixture properties change as condensation progresses down the bundle and the liquid condensate flow pattern is irregular due to inundation effects.

Nature of the problem

Prior knowledge of some of the phenomena of immiscible binary mixtures is necessary for the understanding of their condensation heat transfer characteristics. The manner in which the vapours condense depends on the vapour composition and the vapour-liquid interface temperature. The vapour liquid equilibrium diagram for a completely immiscible system of two components 1 and 2 is shown in Figure 1.

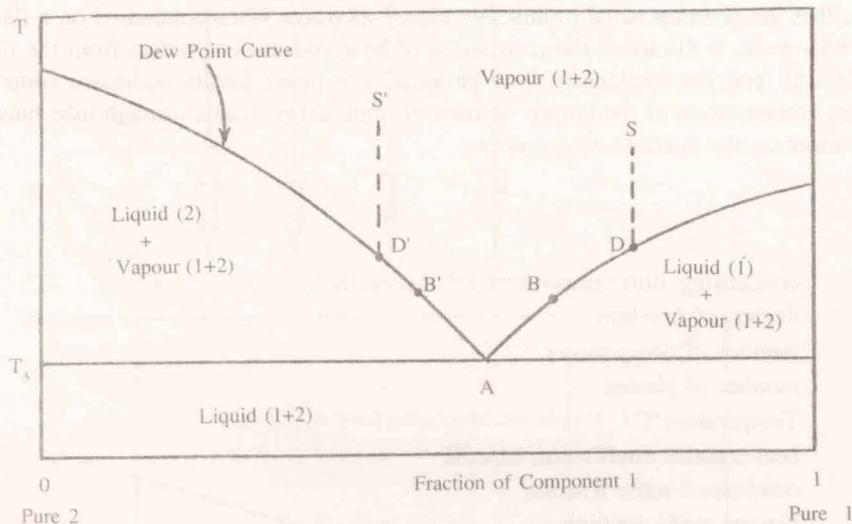


Figure 1 Immiscible Liquids Phase Diagram

If a superheated vapour at point $S(S')$ is cooled it will eventually reach its dewpoint temperature at D (or D'). At this point further cooling will result in condensation giving the pure component 1 (or 2). The remaining vapour will become richer in the non-condensing component and thus after subsequent cooling to its dewpoint the composition will change to that at point B (or B').

Eventually the vapour composition will be that at point A . From this point onwards the vapour will condense as a mixture giving a two phase liquid of the same composition as the vapour. This mixture and T_A is the azeotropic temperature. At the equilibrium point there is one vapour phase and two liquid phases. From Gibbs phase rule it follows that the number of degree of freedom is given by,

$$\begin{aligned} F &= j - \lambda + 2 \\ &= 2 - 3 + 2 \\ &= 1 \end{aligned} \quad \dots (1)$$

where j = number of components and
 λ = number of phases

Therefore if any one property such as the system pressure is selected, the azeotropic temperature and composition are fixed. For any point along the dewline there is only one vapour and one liquid phase, giving $F=2$. Hence two independent properties are needed to fix a dew point.

From the above statements it is apparent that if two liquids are condensing simultaneously the vapour temperature adjacent to the liquid film is the azeotropic temperature T_A . Therefore the film temperature difference is given by,

$$\Delta T_f = T_A - T_w \quad \dots (2)$$

Where T_w is the outside wall temperature.

Variation of Interface Condition along a Single Tube

Consider a condensation process of these binary vapours on a single tube. at a very low cooling water temperature both components may be condensing all along the tube. The vapour liquid interface condition is at the azeotrope and remains azeotropic along the tube length. Raising the cooling water temperature to a sufficiently

high value, there is a point along the tube where there is only one component condensing. This happens when the rising cooling water temperature gets high enough to cause the interface temperature T_I to be higher than the azeotropic temperature T_A . It is the richer component that condenses while the other component behaves like non-condensable gas.

Assuming that the inlet bulk vapour mixture is superheated and this condition is constant along the tube, the variation of the interface condition is as shown on phase diagram in Figure 2. The interface condition varies from point A to point O which is at the outlet end of the tube. Correspondingly the path of the process along which the bulk vapour goes towards the interface varies from S-D-A to S-D-O respectively.

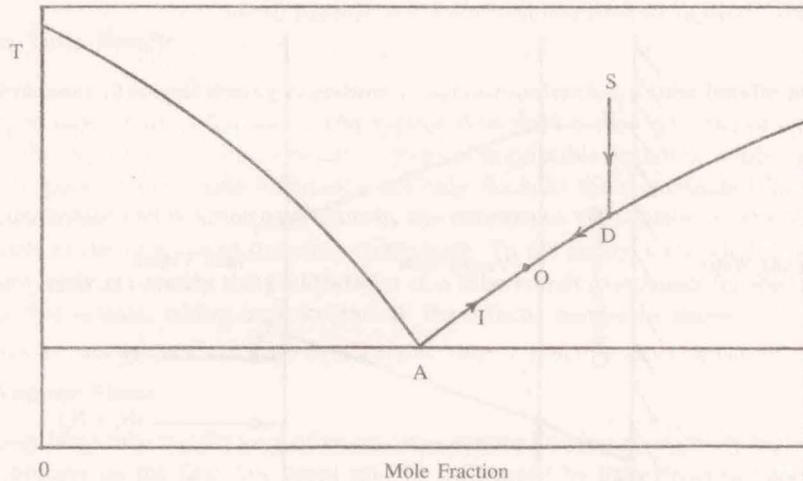


Figure 2 Variation of Interface Condition Along A Tube During Transformation From 2 To 1 - Component Condensation

Variations of Bulk Vapour and Interface Conditions Down a Tube Bundle

Consider next, a similar condensation process over a tube bundle. Figure 3 shows the variations of the bulk vapour and the average interface conditions down the bundle. It is assumed that the cooling water temperature is at a high value such that it causes a 1-component condensation on the first row only and a 2-component condensation on the lower rows. again, assuming that the bulk vapour is superheated at the inlet to the bundle, desuperheat and change of composition occur simultaneously as the mixture goes through the bundle. Due to condensation and subcooling, the change of the condition of the bulk vapour mixture may follow the path $S_1 - S_2 - S_N$ or right to point A along the dewline, if the bundle is large enough. On the first row the condition at the interface across which only the richer component passes through is represented by point I which can be anywhere along the dewline between D_1 and A. For the lower rows on which two components pass through the interface the condition of which is always at point A. On the first row the path of the process during which the change of condition of the vapour takes place as it travels from the bulk to the interface is represented by $S_1 - D_1 - I$. On the other rows the path of the same process is represented by path $S_2 - D_2 - A$ if the vapour is still superheated or path $S_N - A$ if the vapour is saturated or represented by a single point, A, if the vapour is both saturated and azeotropic.

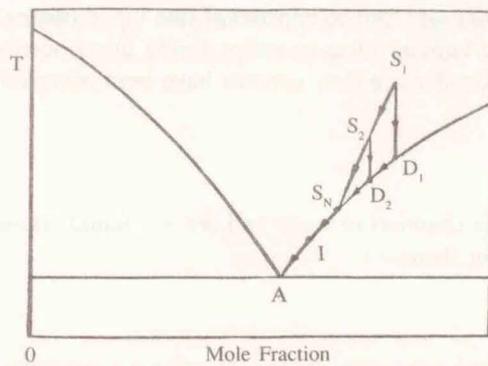


Figure 3 Variations of bulk vapour and interface conditions down the bundle

Resistances to Heat and Mass Transfer

In a condensation of binary vapours of immiscible liquids the vapour-side heat and mass transfer resistances exist depending on the conditions as well as the composition of the vapour mixture. For a mixture richer in one component the overall vapour-side resistance is made up of three factors as illustrated in Figure 4.

- (i) Diffusional resistance of the vapour phase boundary layer,
- (ii) Vapour-condensate interfacial resistance,
- (iii) Conductive resistance of the condensate layer.

The interfacial resistance (ii) is usually negligible.

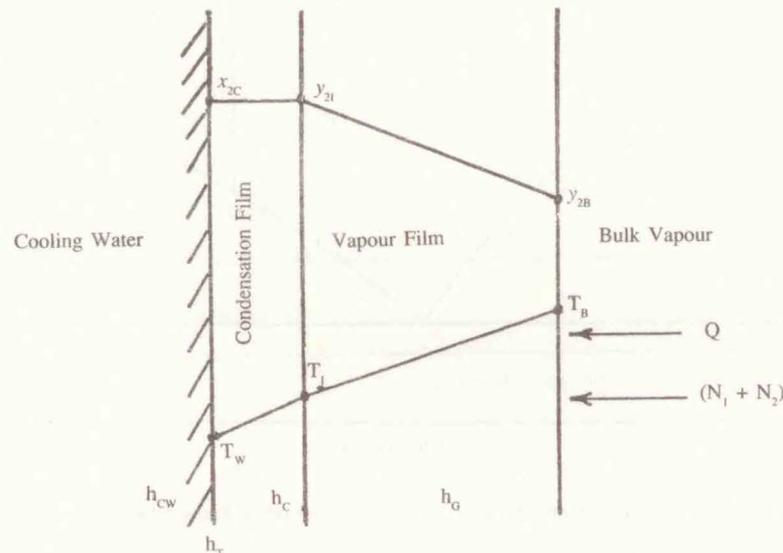


Figure 4 Heat and mass transfer resistances (water-rich vapour mixture)

The diffusional resistance of the vapour boundary layer is due to the concentration gradient in the vapour layer. For a vapour mixture of azeotropic composition this resistance does not exist. It only exists during the condensation of non-azeotropic vapour mixture and the presence of this resistance is not significant at ΔT_f greater than about 15K at which the bulk flow of both components towards the interface is relatively high. This resistance however becomes important as ΔT_f is reduced. At a certain low value of ΔT_f at which $T_1 \approx T_A$, this resistance across the boundary layer is relatively high enough to prevent the less-rich component from being dragged against its concentration gradient. At this condition the less-rich component behaves exactly like a non-condensable gas.

The conductive resistance of the condensate layer has now been very well understood. The explanation is available in many textbooks on heat transfer.

Condensate Flow Patterns

In the condensation of binary vapours of immiscible liquids, when the vapour-condensate interface temperature equals that of the azeotrope, the condensate formed consists of two liquid phases. This results in condensate flow patterns markedly different from the laminar films occurring during the condensation of pure vapours. On a flat plate or around a single tube these condensate flow patterns have been accepted to fall into three most common types.

(i) Channeling Flow

The condensates form into separate channels of water and organic liquid. These channels may contain droplets of the other component embedded in them.

(ii) Film Drop Flow

An organic film completely wets the condenser surface, forming a continuous film. Water forms drops on the surface of the organic film and flow from the surface as a series of drops.

(iii) Standing Drop Film

The organic forms a film over the condenser surface with small drops of water in it. At some points the surface is occupied by large standing drops of water, which grow by absorbing the small drops of water, direct condensation on their surfaces and by coalescence with other drops. When these drops are large enough they slide down the condensing surface detaching other drops in their path.

Polley (3) has speculated that a change from standing drop flow to channeling flow occurs as the temperature driving force across the film increases. Observations by Hoon (4) show that channeling occurs on oxidised surfaces even at very low temperature differences.

Condensation on Tube Bundle

The physical processes involved during crossflow condensation within a tube bundle are more complex than those for an isolated tube or for a flat plate. The vapour flow within the bundle is not uniform and condensate inundation occurs. Further, condensation of binary vapours of immiscible liquids on a tube bundle is more complex than that for pure vapours. Condensate inundation not only thickens the condensate film of the lower rows but also effects the condensate composition and disturbs the condensate flow patterns. Droplets of one component may hit the channels of the same or of the other component. To the author's knowledge nobody has established a method to predict fairly accurately the performance of a tube bundle condenser for the condensation of binary vapours of immiscible liquids, taking into account all the effects mentioned above.

The Effects of Vapour Shear

Condensation over large tube bundle very often involves vapour flowing at relatively high velocities. As a result, the condensation process on the first row tubes may be influenced by the effects of vapour shear. If there is a great variation of vapour flow area down the bundle, the effect of vapour shear may be more important than area is minimum. The effects of vapour shear on the condensation of pure fluids has been established to cause an increase of the condensate film heat transfer coefficient. The same effect is expected when condensing binary vapours of immiscible liquids under the influence of vapour shear. This effect is also found to have some bearings on the condensation rate of one component in relation to the other. Musa (5) have found that the effect of increasing the vapour Reynolds number on the vapour phase transport process together with the effect of vapour shear on the condensate channels is to increase the condensation rate of water more than that of trichloroethylene.

References

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