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BRIEF COMMUNICATION

CLASSIFICATION OF CONFIGURATIONS OF TWO-PHASE VAPOR/LIQUID BUBBLES IN AN IMMISCIBLE LIQUID IN RELATION TO DIRECT-CONTACT EVAPORATION AND CONDENSATION PROCESSES

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INTRODUCTION

"Two-phase bubbles" each comprising a vapor or gas phase and a liquid phase in a medium of another immiscible liquid have an importance in various kinds of heat and mass transfer processes. A principal example is direct-contact heat transfer to evaporating "drops" in a hotter medium, or from condensing "bubbles" in a cooler medium, of an immiscible liquid. These "drops" or "bubbles" take the form of "two-phase bubbles" while they are undergoing the liquid-vapor phase change. The ultimate objective of such a process may either be the heat transfer between the two-phase bubbles and the medium liquid (Sideman & Moalem-Maron 1982; Sudhoff *et al.* 1982) or the heat transfer, enhanced by the two-phase bubbles serving as latent heat carriers, between the medium liquid and an enclosure wall holding the fluids (Shimada *et al.* 1977; Hijikata *et al.* 1984). Other examples are found in some mass transfer operations: an extraction of a solute from the liquid phase in each two-phase bubble to the medium liquid (Hayakawa & Shigeta 1974) and a diffusion of a gas from the gas-phase core in each two-phase bubble to the medium liquid (Li & Asher 1973; Ollis *et al.* 1972). The characteristics of these transport processes described above are strongly dependent on the configuration of the two-phase bubbles which is in turn primarily controlled by the surface-tension relations in each given system. This communication presents a revised version of the classification diagram, of surface-tension-dominated equilibrium configurations of two-phase bubbles, prepared previously (Mori 1978) and then suggests possible changes from equilibrium of the configurations when the two-phase bubbles undergo either evaporation or condensation.

EQUILIBRIUM CONFIGURATIONS

The previous paper (Mori 1978) classified the possible configurations of the two-phase bubbles into four types as shown in figure 1 assuming the bubbles are placed in a stationary liquid medium under a vanishing gravity effect. In such a case the two-phase bubble configuration is exclusively determined by the surface or interfacial tensions appropriate for vapor/dispersed-phase liquid, vapor/continuous-phase liquid and liquid/liquid interfaces: these tensions are denoted respectively by σ_d, σ_c and σ_{cd}. Conditions which permit those configuration types are represented as (Mori 1978):

$$\left.\begin{array}{llll} \mathrm{I}: & S_{d/c} > 0\,, & (S_{c/d} < 0), & (S_{v/cd} < 0) \\ \mathrm{II}: & S_{d/c} < 0\,, & S_{c/d} < 0\,, & S_{v/cd} < 0 \\ \mathrm{III}: & (S_{d/c} < 0), & S_{c/d} > 0\,, & (S_{v/cd} < 0) \\ \mathrm{IV}: & S_{d/c} < 0\,, & S_{c/d} < 0\,, & S_{v/cd} > 0 \end{array}\right\} \qquad [1]$$

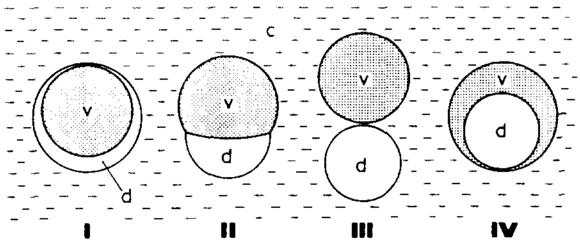

Figure 1. Configurations of two-phase bubbles in equilibrium as classified. c: continuous-phase liquid, d: dispersed-phase liquid, v: vapor.

where $S_{d/c}$, $S_{c/d}$, $S_{v/cd}$ are equilibrium spreading coefficients defined as

$$\left.\begin{aligned} S_{d/c} &= \sigma_c - (\sigma_d + \sigma_{cd}) \\ S_{c/d} &= \sigma_d - (\sigma_c + \sigma_{cd}) \\ S_{v/cd} &= \sigma_{cd} - (\sigma_d + \sigma_c) \end{aligned}\right\} \qquad [2]$$

Two inequalities in parentheses among the three specifying the condition appropriate for each of types I and III are automatically satisfied and thus can be eliminated from algebraical point of view. In figure 3 of the previous paper (Mori 1978) the above conditions for the respective configurations are presented in a simple diagram with coordinates ($S_{c/d}$, $S_{d/c}$) following Torza & Mason's work (1970) on interactions of three immiscible liquids. However, this diagram may give an erroneous impression that the whole area of each of the second, third or fourth quadrant yields respectively the possible conditions for type I, II or III. Another defect of the diagram is that we cannot indicate appropriately on the diagram a variation in configuration in the type II category.

In order to overcome the above mentioned defects, the diagram is revised as shown in figure 2. Two sets of coordinates are fixed on a common plane. Only the area on the plane confined by coordinates (σ_{cd}/σ_c, σ_d/σ_c) on their positive sides represents conditions which are physically possible and algebraically consistent. The contact angles θ_{dc}, θ_{dv} and θ_d measured through the dispersed-phase liquid at the three-phase contact line as shown in figure 2, are employed as indices of configuration in type II category, and the values of these angles are

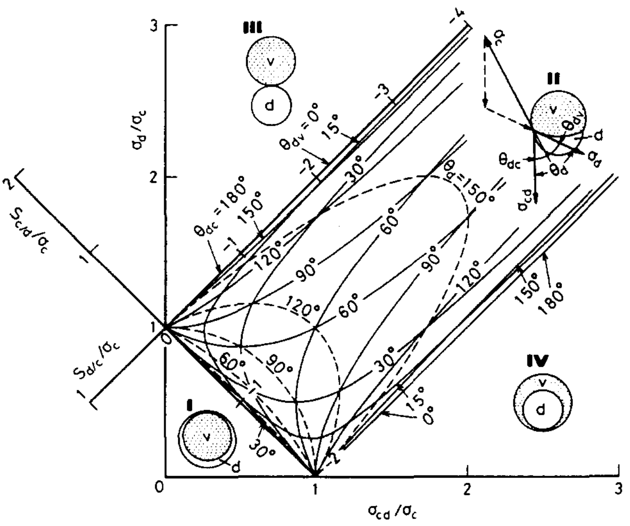

Figure 2. Classification diagram to identify appropriate conditions for respective configuration types.

indicated in the rectangular area assigned to type II. Those values are determined by Neumann's triangle condition and given as (Princen 1969):

$$\left.\begin{aligned} \theta_{dc} &= \cos^{-1}\left[\frac{1 + (\sigma_{cd}/\sigma_c)^2 - (\sigma_d/\sigma_c)^2}{2\sigma_{cd}/\sigma_c}\right] \\ \theta_{dv} &= \cos^{-1}\left[\frac{1 + (\sigma_d/\sigma_c)^2 - (\sigma_{cd}/\sigma_c)^2}{2\sigma_d/\sigma_c}\right] \\ \theta_d &= \cos^{-1}\left[\frac{1 - (\sigma_d/\sigma_c)^2 - (\sigma_{cd}/\sigma_c)^2}{2(\sigma_d/\sigma_c)(\sigma_{cd}/\sigma_c)}\right] \end{aligned}\right\} \qquad [3]$$

This new diagram assigns explicitly an area to type IV. It should be noted, however, that no real system has been found so far which yields a positive value of $S_{v/cd}$. This fact suggests that type IV is fictitious, or at least it is quite uncommon and bears little practical importance.

CONFIGURATIONS IN EVAPORATION AND CONDENSATION PROCESSES

The configuration classification shown in figure 1 and the above mentioned criteria for configurations related to that classification cannot be applied directly to the case of two-phase bubbles undergoing evaporation or condensation while moving in a medium, which is a case of practical importance in relation to direct-contact evaporators or condensers. Experimental results accumulated hitherto through fundamental studies on direct contact heat transfer permit us to have a broad outlook on possible relations between equilibrium configurations and configurations to be shown in actual evaporation and condensation processes. Figure 3 is a schematic diagram showing such relations based partly

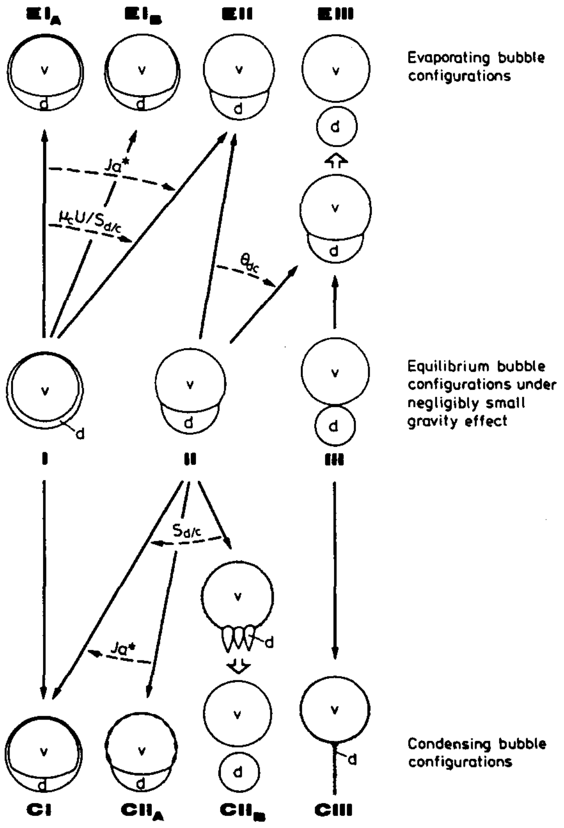

Figure 3. Scheme of possible configuration-relations between two-phase bubbles in equilibrium and those in phase-change processes.

on assumption and partly on experimental results. Note that evaporating and condensing bubbles are illustrated there for the case that they are moving almost rectilinearly in a liquid medium with little shape oscillation. In each two-phase bubble most of the liquid phase accumulates at the bottom because of the density difference between the liquid and the vapor, while the rest of the liquid may occupy an upper position. Particular types of configuration are:

EI_A: A small fraction of the liquid spreads over the upper surface of bubble forming a thin film which completely envelops the vapor phase.

EI_B: The liquid film paritally envelops the vapor phase.

EII: This is essentially the same as type II.

EIII: As the vapor phase grows it separates from the liquid phase resulting in a configuration essentially the same as type III.

CI: A thin film of condensate envelops completely the vapor phase.

CII_A: The condensate forms discrete lenses over the bubble surface instead of a continuous film.

CII_B: The condensate forms several blunt drops at the bottom of the bubble, turns into a conical tail through coalescene, and then drops away from the bubble resulting in a configuration essentially the same as type III.

CIII: Tiny droplets of the condensate continuously detach from the bubble.

Solid arrows in figure 3 represent the possible relations between configurations in equilibrium and those in phase-change processes. Each broken arrow intersecting the solid arrows shows a possible tendency of transition from relation to relation with an increase of the parameter indicated on the arrow. Notations used in the parameters are as follows: $Ja^* = \rho_c c_{pc} \Delta T/(\rho_d \Delta h_{vd})$, ρ is density, c_p is specific heat, ΔT is temperature difference, Δh_v is specific latent heat of vaporization, μ is dynamic viscosity and U is rise velocity of the two-phase bubble, while subscripts c and d refer to the continuous- and dispersed-phase liquids respectively. Among the relations indicated by the solid arrows only those listed in table 1 have been confirmed experimentally. Others are presumptions about which I would like to briefly discuss below.

In the previous paper (Mori 1978) it was pointed out that configurations like EI_A and EI_B are possible, in the case with no phase change, depending on the value of $\mu_c U/S_{d/c}$ as long as $S_{d/c}$ has positive values. Even in the case with evaporation these configurations may be possible, if the evaporation from the liquid film is so slow that it could be made up by the liquid supply from the lower puddle by the capillary force. Recently Raina & Grover (1982) analyzed the heat transfer to a bubble of type EI_B based on the configuration model

Table 1. List of experimental confirmations of the configuration relations between two-phase bubbles in equilibrium and those in phase-change processes

Relation	Researchers	Dispersed phase/ continuous phase
II ⟶ EII	Sideman & Taitel (1964)	Butane/sea water Pentane/water Pentane/sea water
	Tochitani, Mori & Komotori (1977)	Pentane/glycerol Furan/glycerol
III ⟶ EIII	Mori & Komotori (1976)	Water/silicone oil
	Gradon & Selecki (1977)	Water/silicone oil
II ⟶ CII_B	Higeta, Mori & Komotori (1983)	Methanol/silicone oil
III ⟶ CIII	Higeta, Mori & Komotori (1979)	Water/silicone oil
	Higeta, Mori & Komotori (1983)	Water/silicone oil + 1.82 % wt. 1-decanol

presented by myself (1978). They applied their analysis to a pentane/water system to predict the variation of instantaneous heat transfer coefficient in the system. This is unconvincing, however, because recent studies on surface and interfacial tensions in two-component systems (Mori *et al.* 1984; Murase *et al.* 1985) show that in a pentane/water system $S_{d/c}$ is negative, at least around the saturation temperature of pentane under atmospheric pressure, and thus type EI_B is impossible.

Type CI has been widely accepted by researchers on the direct-contact condensation heat transfer since Isenberg & Sideman (1970). This type has not been actually confirmed so far, because a thin condensate film over the bubble surface cannot be recognized on photographs. However, this type seems possible, even if $S_{d/c}$ has a small negative value, as long as the condensation rate is so large as to surpass the film drainage rate. If the condensation rate is fairly low, and if $S_{d/c} < 0$, the condensate may form discrete lenses, instead of a continuous film, resulting in a configuration of type CII_A.

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REFERENCES

GRADOŃ, L. & SELECKI, A. 1977 Evaporation of a liquid drop immersed in another immiscible liquid. The case of $\sigma_c < \sigma_d$. *Int. J. Heat Mass Transfer* **20,** 459–466.

HAYAKAWA, T. & SHIGETA, M. 1974 Extraction from two-phase droplets with coalescence (in Japanese). *Kagaku Kōgaku* **38,** 60–69.

HIGETA, K., MORI, Y. H. & KOMOTORI, K. 1979 Condensation of a single vapor bubble rising in another immiscible liquid. *AIChE Symp. Ser.* **75** (189), 256–265.

HIGETA, K., MORI, Y. H. & KOMOTORI, K. 1983 A novel direct-contact condensation pattern of vapour bubbles in an immiscible liquid. *Can. J. Chem. Engng* **61,** 807–810.

HIJIKATA, K., MORI, Y. & ITO, H. 1984 Experimental study on convective boiling of immiscible two-component mixture (in Japanese). *Prep. Japan Soc. Mech. Engrs* No. 840–5, 73–80.

ISENBERG, J. & SIDEMAN, S. 1970 Direct contact heat transfer with change of phase: bubble condensation in immiscible liquids. *Int. J. Heat Mass Transfer* **13,** 997–1011.

LI, N. N. & ASHER, W. J. 1973 Blood oxygenation by liquid membrane permeation. In *Adv. Chem. Ser.,* Vol. 118, R. F. Gould (Ed.). Amer. Chem. Soc., Washington, D.C. pp. 1–14.

MORI, Y. H. 1978 Configurations of gas-liquid two-phase bubbles in immiscible liquid media. *Int. J. Multiphase Flow* **4,** 383–396.

MORI, Y. H. & KOMOTORI, K. 1976 Boiling of single superheated drops in an immiscible liquid. *Heat Transfer—Japanese Res.* **5,** 75–95.

MORI, Y. H., TSUI, N. & KIYOMIYA, M. 1984 Surface and interfacial tensions and their combined properties in seven binary, immiscible liquid-liquid-vapor systems. *J. Chem. Engng Data* **29,** 407–412.

MURASE, M., MATSUBARA, H., MORI, Y. H. & NAGASHIMA, A. 1985 Measurements of surface tensions of liquids in contact with other-component vapors and of liquid-liquid interfacial tensions by the pendant drop method (in Japanese). Submitted to *Trans. Japan Soc. Mech. Engrs.* **51** (468B) (In press).

OLLIS, D. F., THOMPSON, J. B. & WOLYNIC, E. T. 1972 Catalytic liquid membrane reactor: I. Concept and preliminary experiments in acetaldehyde synthesis. *AIChE J.* **18,** 457–458.

Princen, H. M. 1969 The equilibrium shape of interfaces, drops, and bubbles. Rigid and deformable particles at interfaces. In *Surface and Colloid Science,* Vol. 2, E. Matijević (Ed.). Wiley-Interscience, New York. pp. 1–84.

RAINA, G. K. & GROVER, P. D. 1982 Direct contact heat transfer with change of phase: theoretical model. *AIChE J.* **28,** 515–517.

SHIMADA, Y., MORI, Y. H. & KOMOTORI, K. 1977 Heat transfer from a horizontal plate facing upward to superposed liquid-layers with change of phase. *Trans. ASME, J. Heat Transfer* **99,** 568–573.

SIDEMAN, S. & MOALEM-MARON, D. 1982 Direct contact condensation. In *Adv. Heat Transfer* Vol. 15, J. P. Hartnett and T. F. Irvine, Jr. (Eds.). Academic Press, New York. pp. 227–281.

SIDEMAN, S. & TAITEL, Y. 1964 Direct-contact heat transfer with change of phase: evaporation of drops in an immiscible liquid medium. *Int. J. Heat Mass Transfer* **7,** 1273–1289.

SUDHOFF, B., PLISCHKE, M. & WEINSPACH, P.-M. 1982 Direct contact heat transfer with change of phase—condensation or evaporation of a drobble. *Ger. Chem. Engng* **5,** 24–43.

TOCHITANI, Y., MORI, Y. H. & KOMOTORI, K. 1977 Vaporization of single liquid drops in an immiscible liquid. Part I: Forms and motions of vaporizing drops. *Wärme- und Stoffübertrag.* **10,** 51–59.

TORZA, S. & MASON, S. G. 1970 Three-phase interactions in shear and electrical fields. *J. Colloid Interface Sci.* **33,** 67–83.