Direct Contact Heat Transfer with Change of Phase: Experimental Technique

G. K. Raina
Department of Chemical Engineering
Regional Engineering College
Hazratbal, Srinagar, Kashmir, India
190006

P. D. Grover
Department of Chemical Engineering
Indian Institute of Technology
New Delhi, 110016, India

Direct contact heat transfer between liquids has the advantage of eliminating metallic heat transfer surfaces, which are prone to corrosion and fouling. In addition, if phase change occurs a large heat capacity for heat absorption is available. The mechanism of heat transfer and the dynamics of a vaporizing two-phase bubble are highly complex (Raina and Wanchoo, 1984, 1986). Klipstein (1963) found that the dispersed liquid droplet did not evaporate even when the temperature of the continuous-phase medium in which it formed was much higher than the boiling point of the liquid. While investigating the evaporation of droplets Moore (1959) reported that liquid droplets had to be greatly superheated in order to initiate vaporization. The effect of superheat was manifested in the form of explosive vaporization. The amount of superheat required depends on the initial diameter of the dispersed liquid droplet. During their experimental investigations Sideman and Taitel (1964) found that a single drop of dispersed liquid of large initial diameter nucleated easily while a smaller one resisted it very much. It was felt that the presence of a gas or vapor nucleus in the drop was *essential to induce* evaporation. Such nucleation was achieved by giving an electric power pulse through nichrome wire (Klipstein, 1963) or by injecting a tiny air bubble inside each drop (Prakash and Pinder, 1967; Tochitani et al., 1977a,b). A technique of Sambi (1981) was used during the present study. The main part of this technique is a Teflon tip with a surface tension higher than the dispersed phase and lower than the continuous-phase medium. However, this technique has been found to be ineffective for small drops.

During the course of evaporation the nucleated drop forms a two-phase bubble in which vapor occupies the upper portion covering the unevaporated dispersed liquid settled at its bottom; such a bubble is shown in Figure 3b. As the dispersed liquid is transparent in the liquid state and colored in the vapor state, a photographic technique fails to provide information about the instantaneous amount of residual dispersed liquid beyond 5% evaporation. A dilatometric method was considered to be the best technique for such a complicated study.

In the present work a new dilatometric technique has been developed. The set-up comprises a simple and a U-shaped dilatometer, a recorder unit, and a new mechanism for releasing the vapor bubble at total evaporation. The dilatometers and a high-speed camera were calibrated by allowing single drops of a mixture of dispersed-phase liquid *n*-pentane in *n*-heptane to evaporate. Liquid *n*-heptane is miscible only in the dispersed phase (*n*-pentane) with its boiling point three times more than the dispersed liquid. In such drops evaporation of the main dispersed liquid alone takes place to form a two-phase bubble. The evaporation of the drops of known initial diameter and composition, obtained by mixing *n*-pentane in *n*-heptane in various proportions, provides accurate information about the percentage evaporated during the growth of a two-phase bubble. Both dilatometric and photographic (calibrated) techniques represent a significant improvement over the earlier work.

Experimental Method

Equipment

The equipment, arranged as shown in Figure 1, consists of the main column, the dilatometric assembly, a bubble-releasing assembly, a thermostat, and a drop injection nozzle.

The main column consists of two concentric columns, the

Correspondence concerning this paper should be addressed to G. K. Raina.

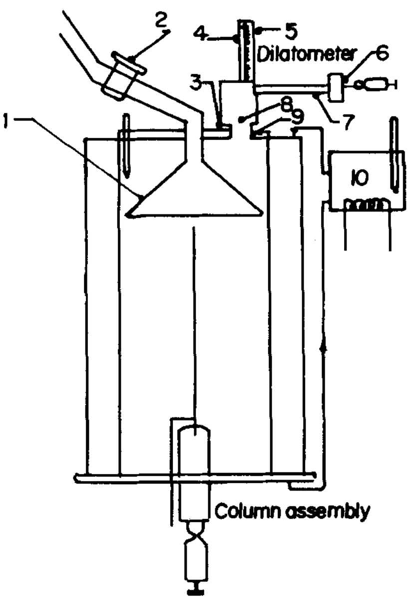


Figure 1. Experimental set-up

1. Conical funnel
2. Exit valve
3. Cover disk on main glass column
4. Dilatometer (tube)
5. Scale
6. Brass adaptor for drop-forming syringe
7. 3 mm ID glass tube
8. Brass adaptor for dilatometer assembly
9. Hole in cover disk
10. Thermostat

inner one being thin-walled Pyrex glass of 50 mm ID and 850 mm length, and the outer one of Perspex, square in cross section, having dimensions 120 mm x 120 mm x 800 mm. The square shape of the outer column was necessary to minimize distortion during photography. The details of photographic equipment, lighting arrangement, and the nucleation site assembly are available in the literature (Sambi, 1981).

The dilatometric assembly was developed during the present study for measuring percentage evaporation, initial diameter of the dispersed liquid droplet, and the total time of evaporation. It consisted of a simple and a U-shaped dilatometer, a bubble-releasing device, and a resistance measuring circuit. Three glass dilatometric tubes (simple dilatometer) of 2.20, 4.85, and 10 mm ID were used to carry out the experiments in order to cover the range of drop sizes studied. For accurate measurement of the volume change using a dilatometer, a technique was devised for removing the vapor from the column after each run so that the vapor bubble did not enter the dilatometric section. To achieve this three holes of different diameters were drilled in a thick Perspex disk that was used to cover the upper end of the inner glass column. The tube (6 mm ID) portion of a conical glass funnel whose outside diameter was slightly less than the inside diameter of the glass column, passed through the central hole in the thick disk, as shown in Figure 1. An exit valve was fixed to the funnel tube 4 cm from the tube bend just above the disk. The portion of the tube beyond the exit valve was given an upward bend so that the liquid would not come out during the release of the vapor bubble. A thermometer (0–100°C) passed through the smallest hole in the Perspex disk. A threaded brass adaptor to hold the dilatometer assembly was screwed into internal threads cut into the third hole in the disk. The upper opening end of the main glass column was covered with this disk, with the funnel (to trap the bubble) inside and a valve (to release the trapped bubble at will) outside it, using araldite. A glass tube of 3 mm ID and 20 cm length was fixed to the dilatometric assembly at the bulging portion (7 mm ID, as shown in Figure 1 and 2), for calibration and for zeroing of the liquid level in it. Liquid feed to the dilatometer was done by passing the needle of the feed system through a septum fixed to the end of the tube, with the help of a brass adaptor. A scale attached to the dilatometer tube facilitated noting the volume change.

The U-shaped dilatometer, Figure 2, was developed to measure the instantaneous volume and total time of evaporation. It is similar to the simple dilatometer except that the simple tube was replaced by a U-shaped tube. The components of the circuit diagram are shown in Figure 2 along with transistor Tr_1 of type BC 107B. A 0.121 mm dia. constantan wire was used throughout and the change in resistance was recorded by an Omiscribe recorder with a chart speed to 10 in./min.

A high-speed camera was used at 100 frames per second to photograph the evaporating drop, Figure 3a; drop/bubble configuration is shown in Figure 3b. Satisfactory photographs were obtained using a backlighting arrangement, that is, with the light source behind the drop, directed toward the camera lens.

An Ultra thermostat was used for circulating water at constant temperature through the annulus between the two concentric columns. This thermostat has been designed to give constant temperature between −6 and +300 °C with an accuracy of ±0.02°.

Procedure

The preliminary settings and experimental procedure are the same as reported by Prakash and Pinder (1967). After making all the preliminary settings, saturated dispersed liquid was forced out of the syringe needle to form a drop on the tip of nozzle. The drop size was controlled either by changing the capillary bore or by varying the distance between the nucleation and nozzle tips. To control the drop size the nucleation tip was positioned with the help of a traveling microscope just above the nozzle tip.

The initial diameter of the drop and the percentage evapora-

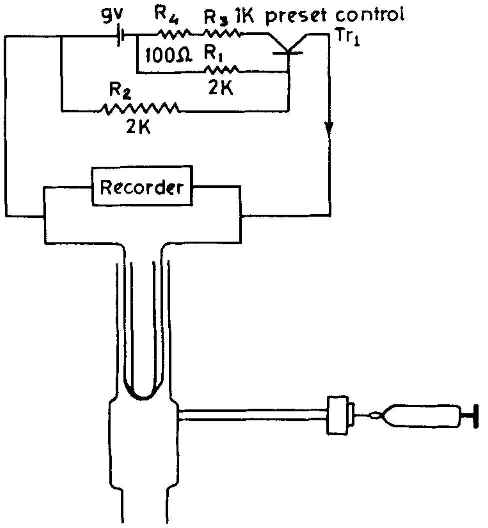


Figure 2. Set-up of U-shaped dilatometer.

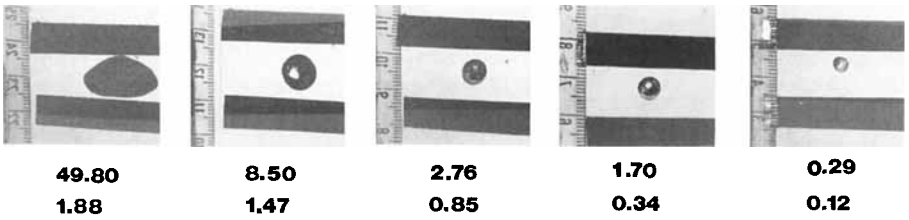


Figure 3a. Sequence photographs of evaporation of 3.12 mm furan drop in 98% aqueous glycerol.
top row: x, %; bottom row: t, s

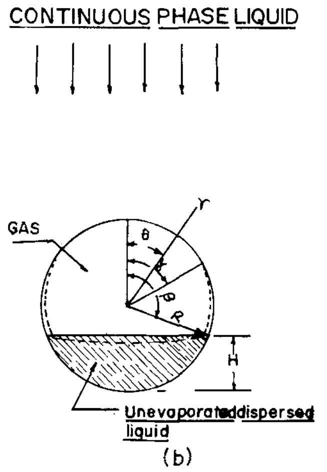


Figure 3b. Configuration of two-phase bubble.

tion of a growing two-phase bubble were found by a simple dilatometer, while the total time of evaporation and instantaneous volume measurements were made with the help of the U-shaped dilatometer.

A microscope calibrated by viewing spherical glass beads of known diameter in a duplicate column, was used to determine the initial diameter of the evaporating dispersed liquid drop. The initial diameter of the drop obtained from the volume measured by the dilatometer was found to match that found by the microscope. The camera—also calibrated with glass beads of known diameter—recorded the upward movement of the nucleated drop.

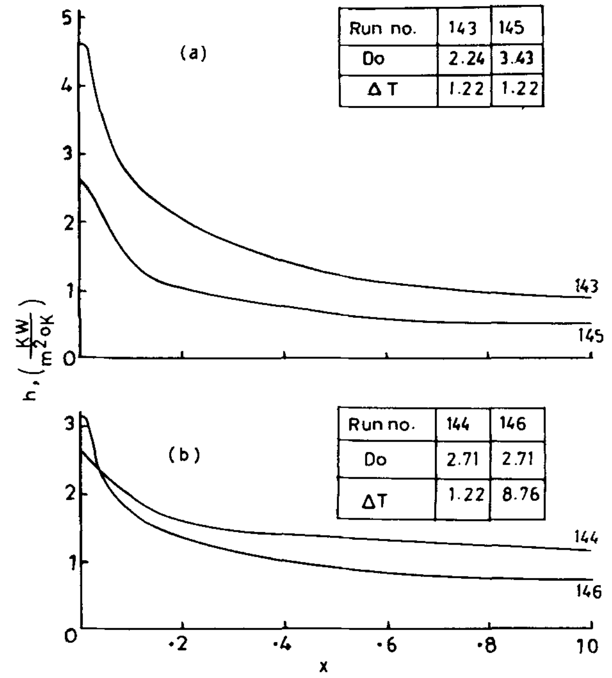
The vapor bubble formed during the experiment entered the conical funnel. Since the exit valve was in a closed position during the experiment, the liquid level rose in the calibrated dilatometer tube, which was kept open to atmospheric pressure. When photography of the evaporating drop was complete, the volume recorded by the dilatometer was noted from the scale attached to the simple dilatometer using a microscope.

This technique also helped in relating the volume of the two-phase bubble to percentage evaporation, shown in Figure 7, by evaporating drops of known initial diameter and composition obtained by mixing dispersed-phase liquid n-pentane in n-heptane in various known proportions.

The instantaneous volume and the total evaporation time were recorded in terms of the change in the resistance of a wire probe in the U-shaped portion. To prevent contact with the main column fluid and to increase the conductivity, myristic acid was kept in the bulging portion of the dilatometer assembly. Apart from being less dense and insoluble in water, the boiling point of the myristic acid is higher than the dispersed phases studied in the present work. In order to overcome time lag, the recorder circuit was kept on prior to the formation and release of drop. To avoid the possibility of inaccurate measurement by this technique owing to a change in the resistance of the wire probe, the wire was replaced after a few trials. The bulging portion of the dilatometer assembly was kept above 50°C to avoid any possibility of crystalization of myristic acid.

During the present study both photographic and dilatometric techniques were used to record the progress of evaporation of single drops of isopentane, n-pentane, and furan in distilled water and of furan in 98% aqueous glycerol.

As far as the photographic technique is concerned, the procedure of converting the experimental information into values of heat transfer coefficient—Figures 4, 5, and 6—is the same as that adopted by Sideman and Taitel (1964). The total time of evaporation, obtained by the U-shaped dilatometer, has been taken directly from the recorder response. Apart from these experimental runs, a total of 55 data points involving the evaporation of single drops consisting of a mixture of n-pentane and n-heptane were also taken during the present work with the help



Run no.	143	145
Do	2.24	3.43
ΔT	1.22	1.22

Run no.	144	146
Do	2.71	2.71
ΔT	1.22	8.76

Figure 4. Instantaneous heat transfer coefficient, furan-distilled water system.
Do, drop dia., mm; Δ T, temp. difference, °C

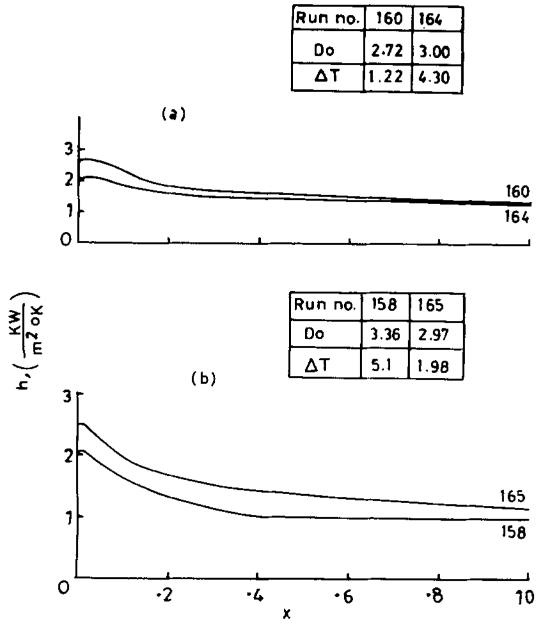


Figure 5. Instantaneous heat transfer coefficient, isopentane-distilled water system.
Do, drop dia., mm; Δ *T*, temp. difference, °C

of the simple dilatometer to relate the volume of a two-phase bubble to percentage evaporation, Figure 7.

Mechanism of Heat Transfer

The effects of temperature, initial diameter of the drop, and viscosity of the continuous-phase medium on the instantaneous heat transfer coefficient for furan, pentane, and isopentane in distilled water and for furan in a 98% glycerol-water system are shown by Figures 4–6. The instantaneous heat transfer coefficient increases sharply up to about 3.5% vaporization and then falls moderately over the remaining vaporization range. Its value seems to fall with an increase in temperature difference and/or the initial diameter of the vaporizing drop.

The system studied so far has been broadly classified into two categories (Raina and Wanchoo, 1984). As already pointed out, large drops of dispersed liquid nucleate easily while small drops resist it very much (i.e., need artificial nucleation). This suggests that the start of nucleation would be confined to a point in the case of a single dispersed liquid drop of less than 2 mm initial diameter while it involves a significant portion of a bigger drop. Almost all investigators in the field have observed oscillations in the two-phase bubble as it rises and evaporates through the continuous medium.

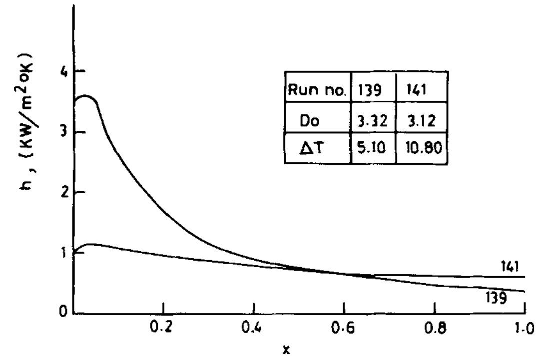


Figure 6. Instantaneous heat transfer coefficient, furan–98% glycerol-water system.
Do, drop dia., mm; *T*, temp. difference, °C

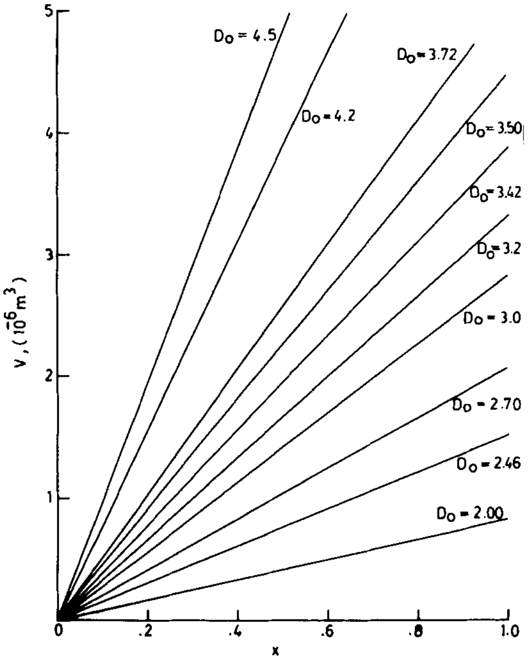


Figure 7. Volume of two-phase bubble of pentane-heptane mixture in water vs. vaporization ratio.

For a known system having a known temperature driving force, the frequency of such oscillations has been found to be higher, Figure 3a, in the case of drops greater than 2 mm initial diameter, and to decrease as the drop size decreases (Tochitani et al. 1977a,b). The area of the two-phase bubble coming under the sway of vapor (nucleation) depends upon the frequency of oscillations. It is therefore logical to believe that in comparison to small drops, the lower value of heat transfer coefficient for larger single drops would be due to vapor blanket formation, which in turn results in the reduction of liquid-liquid heat transfer area. The formation and extension of this blanket is fast as the temperature driving force increases. This effect is predominant during the early stages of evaporation owing to the larger quantities of unevaporated dispersed liquid present in the two-phase bubble. When the quantity of the unevaporated dispersed liquid decreases or the size of the two-phase bubble increases, the effect subsides and the vapor occupies the upper part toward the major portion of evaporation. The unevaporated disposed liquid then sloshes from one side to the other, resulting in the formation of a thin film along the upper inside surface of the two-phase bubble. This in turn results in an increase of liquid-liquid heat transfer area. The frequency of such sloshing being more in the case of bigger drops evaporating in a less viscous medium, it results in negligible or moderate fall in the values of heat transfer coefficient toward the major portion of evaporation. The narrowing of the bridge between the experimental values of heat transfer coefficient for smaller and larger drops, Figures 4 and 6, toward the major portion of evaporation can also be attributed to the above fact.

The oscillations observed during the evaporation period decrease as the initial diameter of the drop decreases and it tends to behave like a rigid sphere. The period of rigidity maintained by a drop of known initial diameter depends on the viscosity of the continuous phase and the temperature driving force. A drop of less than 2 mm initial diameter, evaporating through a high-viscosity continuous-phase medium under small temperature driving force, is expected to maintain rigidity throughout the evaporation period. The effect is reversed as the temperature driving force and initial diameter of the drop increase and the viscosity of the continuous phase medium decreases. As long as single drops of small initial diameter behave like rigid spheres, the effective liquid-liquid heat transfer area would be the portion subtended by the angle $\beta - \gamma$ in Figure 3b. The evaporation of such drops would be smooth, with vapor confined to the top leading edge only, owing to the absence of oscillations. The undue effect of the vapor blanket formation is overcome, resulting in higher values of heat transfer coefficient. The heat transfer coefficient is highest for a drop of smallest initial diameter during the early period of evaporation. The thickness of the liquid forming a very small drop would be insignificant as compared to bigger drops (greater than 2 mm initial diameter). Therefore, the whole of the liquid-liquid interface of such small drops would be responsible for the transfer of heat during the early period of evaporation as against the thin film (which is a part of the total liquid-liquid area) lying between the zenith angle β and γ, Figure 3b, for relatively bigger drops.

The effect of the decrease in the amount of unevaporated dispersed liquid, during progressive evaporation, enhanced by the corresponding increase in the size of the two-phase bubble, results in a decrease of liquid-liquid area and an increase in vapor-liquid area. In such a situation the decrease in the heat transfer coefficient is sharp toward the major portion of evaporation.

Figure 3a shows that even a bigger drop of 3.32 mm initial diameter, consisting of high-density dispersed liquid evaporating in a high-viscosity continuous-phase medium, behaves like a rigid drop; i.e., the path followed by the evaporating two-phase bubble through the continuous medium is straight, without or with negligible oscillations. When the temperature driving force is greater, oscillations occur—run 141, Figure 6—in such systems also. As far as oscillations are concerned, dominating parameters for such systems are the viscosity of the continuous phase, the density of the dispersed phase, and the temperature driving force.

Literature Cited

Klipstein, D. H. "Heat Transfer to a Vaporizing Immisable Drop," D.Sc. Thesis, MIT, Cambridge, MA (1963).

Moore, G. R., "Vaporization of Superheated Drops in Liquids," *AIChE J.*, **5**, 458 (1959).

Prakash, C. B., and K. L. Pinder, "Direct Contact Heat Transfer between Two Immiscible Liquids During Vaporization. I: Measurement of Heat Transfer Coefficient," *Can. J. Chem. Eng.*, **43**, 210, II: "Total Evaporation Time," ibid., 215 (1967).

Raina, G. K., and R. K. Wanchoo, "Direct Contact Heat Transfer with Change of Phase: Theoretical Expression for Instantaneous Velocity of a Two-Phase Bubble," *Int. Commun. Heat Mass Trans.*, 2(3), 227 (1984).

———, "Direct Contact Heat Transfer with Change of Phase, Bubble Growth, and Collapse," *Can. J. Chem. Eng.*, **64**, 393 (1986).

Sambi, S. S. "Direct Contact Heat Transfer to Vaporizing Drop in Immiscible Liquids," Ph.D Thesis, IIT, N. Delhi (1981).

Sideman, S., and Y. Taitel, "Direct Contact Heat Transfer with Change of Phase: Evaporation of Drops in an Immiscible Liquid Medium," *Int. J. Heat Mass Trans.*, **7**, 1273 (1964).

Tochitani, Y., T. Nakagawa, Y. H. Mori, and K. Komotori, "Vaporization of Single Liquid Drops in Immiscible Liquid. I, "*Warme und Stoffubertragung*, **10**, 51 (1977a), "II: Heat Transfer Characteristics," ibid., 71 (1977b).

Manuscript received July 31, 1985, revision received Jan. 6, 1988.