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ON THE TEMPERATURE JUMP IN LIQUID–LIQUID DIRECT-CONTACT HEAT EXCHANGERS

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Abstract—Experimental results on the flow mechanism of the dispersed phase during drop formation and release in a liquid–liquid system are presented. The strong circulation patterns during the formation and release process, the possible turbulent flow conditions and the mixing in the rest drop encountered in the experiments provide a qualitative explanation for the high heat and mass transfer rates which have been consistently found in experimental investigations. On the other hand, the large variety of possible flow fields experienced during drop formation and release account for the difficulty in predicting transfer processes during this process.

INTRODUCTION

It is well established that heat transfer rates are very high during drop formation and release of the dispersed phase in liquid–liquid spray columns. This phenomenon was found by Loutaty (1968), Letan & Kehat (1965), Hupfauf (1973), Moresco & Marschall (1979) and more recently by Culbreth & Marschall (1983), all of whom measured the temperature variation of the dispersed phase in liquid–liquid direct-contact heat exchangers. Even though the experimental techniques employed by these authors varied greatly in sophistication and accuracy, the obtained results uniformly showed a dramatic temperature change in the dispersed phase during drop formation and release. This temperature change is now commonly referred to as "temperature jump." An analogous effect exists for mass transfer during drop formation and release. Marr & Moser (1976) discussed this effect and stated that mass transfer rates measured during drop formation and release may contribute 10–50% of the total mass transfer rate. Attempts have been made by Culbreth & Marschall (1983) to express the high heat transfer rates during drop formation and release in terms of a "heat transfer efficiency." Experiments yielded efficiencies which ranged from about 15% to over 40%. Analogous mass transfer studies carried out by Skelland & Minkas (1971) showed mass transfer efficiencies of 14–40% indicating the same range of results. Given this wide range of efficiency, it is not surprising that correlations of efficiencies in terms of nondimensional groups have not been too successful.

Internal drop "circulation" is obviously a major factor in the heat and mass transfer process. However, "circulation" is without a quantitative definition and has not been measured or has its effect on the transfer process been realistically studied. Humphrey *et al.* (1974) proposed that a "circulation number" could be used to quantify this process. Expanding on the work of Halligan & Burkhart (1968), an expression for a circulation number was developed as the product of a modified Weber number and a modified Reynolds number. The modifications were made by using an equivalent diameter for the characteristic length and an equivalent system viscosity. While no quantitative correlation with empirical heat or mass transfer measurements was made, a qualitative one was suggested with some limited data available from their own work and from several other investigators. Generally a high value of the proposed circulation number was noted with systems where high mass or heat transfer occurred. In addition to this qualitative correlation, a value of the circulation number was found for the transition point between "circulating" and "noncirculating" drops for 28 systems that the authors tested. Circulation was considered to be present if the average instantaneous tangential velocity on the drop interface was equal to or greater than 1% of the maximum nozzle velocity. A very significant variation in the transition number for the various systems was observed. While this general approach to the problem provides a better qualitative insight, it primarily supports the author's conclusion that additional research is required.

The difficulty in reliably and accurately predicting the high heat transfer rates during drop formation and release suggests that the fluid mechanics during drop formation and release may be too complicated to allow correlation of experimental data in forms of simple and straightforward equations. To support this suggestion, examples of various fluid flow phenomena which regularly occur during formation and release of drops in liquid–liquid systems are presented. These examples are partial results of flow visualization experiments conducted by the authors. They reveal the nature of the internal velocity field which exists during development and release of the drops. The visualization technique used in these experiments was a photochromic process which was originally developed by Popovich & Hummel (1967). It is essentially a nonintrusive technique that has the potential to provide accurate velocity information with a high degree of spatial resolution. The technique utilizes a soluble photochromic dye which, in the absence of short wavelength light, is colorless when in solution in many nonpolar liquids. The dye may be selectively activated by an ultraviolet light source to produce a bright blue color. When the light source is a sharply focused beam, as it was for the present investigations, very narrow and well-defined lines may be created in the solvent and dye solution. The lines, which are initially straight and through the axis of the nozzle perpendicular to the line of view, are distorted by the internal flow field, and their time-location histories are recorded photographically for subsequent analysis of velocities.

Test system and photographic results

For photographs shown in figures 1 through 9, the dispersed phase was a commercial petroleum solvent with a specific density of 0.75 at 23°C. The continuous phase was distilled water, and the interfacial tension measured by the Du Noüy ring method was 37 dynes/cm. The interfacial tension was also computed from pseudo-static drop size measurements at the beginning of each test run (except for figure 7) to ensure consistency and an absence of effective surfactant contamination. The nozzle inside diameter was 4.88 mm except for figure 8 where the wetted diameter was about 6 mm and the inside nozzle diameter was 1.59 mm. The photographs were made with a motor driven, 35-mm SLR camera for illustrative purposes only, so that pictures which appear to be sequential views of a single drop are, in fact, views of different drops formed during a single test run. Actual test data

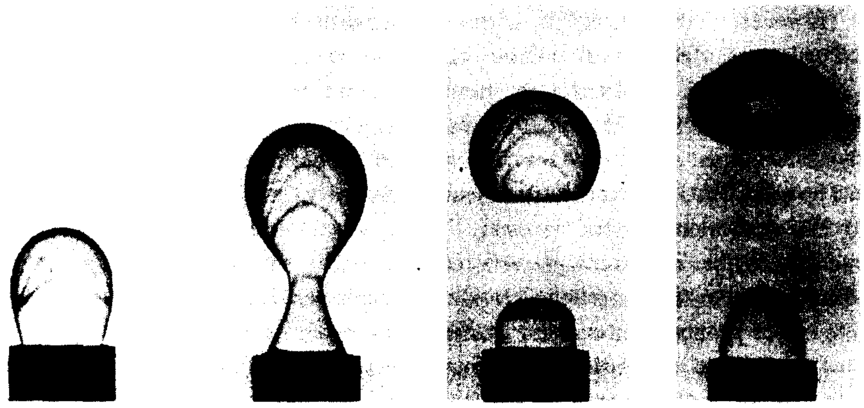

Figure 1. Slow drop formation rate.

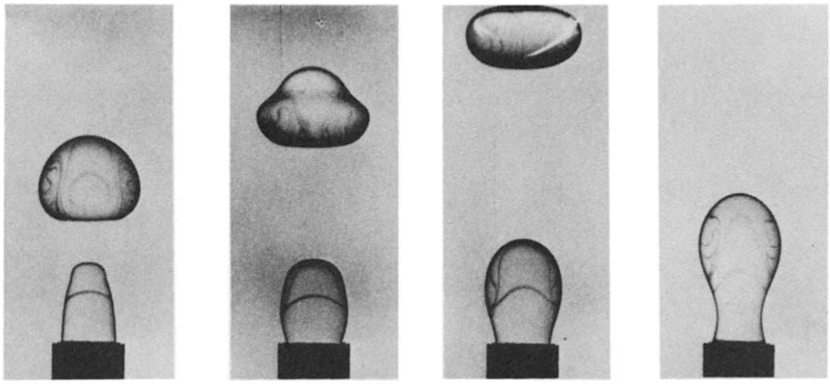

Figure 2. Fast drop formation rate.

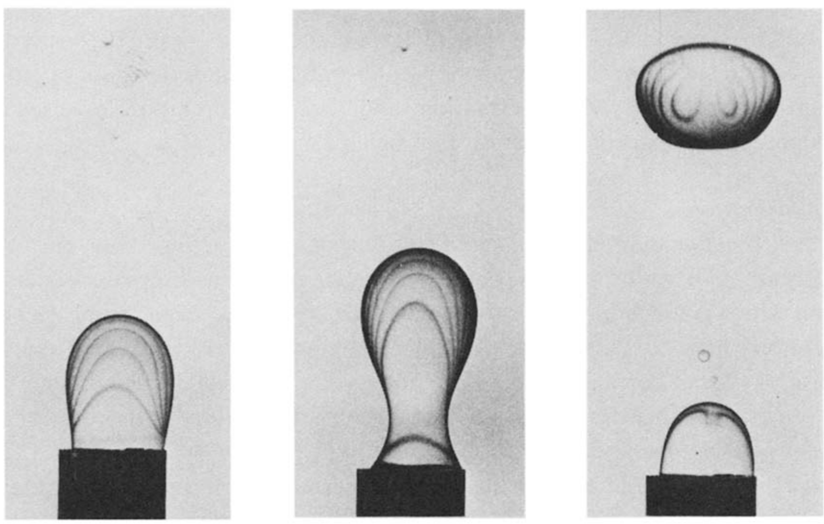

Figure 3. Asymmetric nozzle wetting.

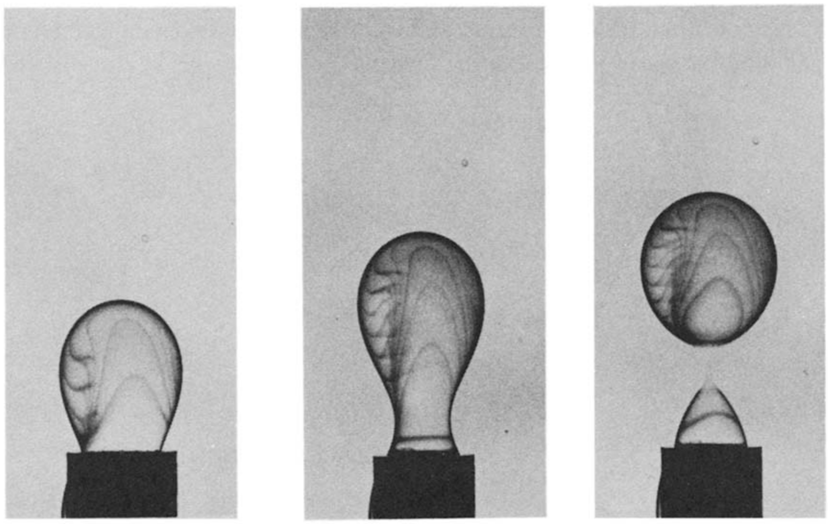

Figure 4. Asymmetric flow in the nozzle.

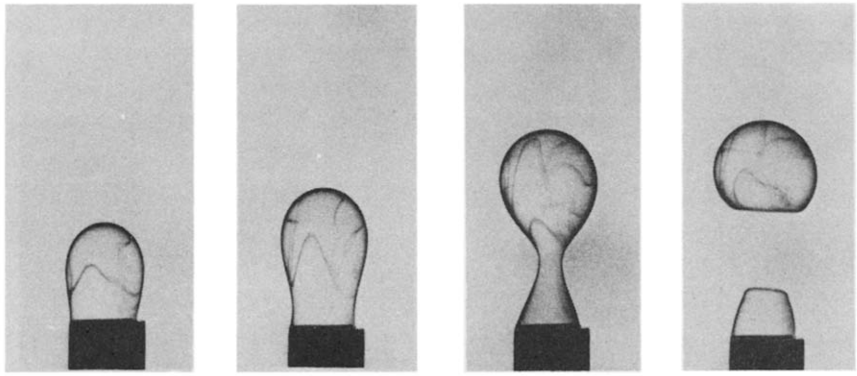

Figure 5. Obstruction at the nozzle outlet.

was extracted from sequential frames from pictures made with a 16-mm high-speed camera. Tests were conducted between the limits of pseudo-static flow and the onset of jetting flow. The qualitative terms of "slow drop formation" and "fast drop formation" are used simply to indicate which general part of the test range is being considered.

Slow drop formation

Line distortion due to internal velocity fields during slow drop formation and release are shown in figure 1. Slow drop formation is characterized by a drop rise velocity during detachment which is much larger than the mean velocity in the dispersed phase nozzle. As can be seen, very little "circulation" exists during the formation of the drop. However, after drop release, the lower portion of the drop is accelerated towards the drop center causing a strong "circulation." This effect must be viewed as one of the reasons for the observed high heat transfer rates.

It is worthwhile to note that in all of our experiments the internal drop circulation damped out over a distance of a few drop diameters even for drops with diameters up to 10 mm.

Fast drop formation

Examples of line distortion due to internal flow fields during fast drop formation and release are presented in figure 2. In this case the drop rise velocity during detachment is not much larger than the mean velocity in the dispersed phase nozzle. In contrast to the slow

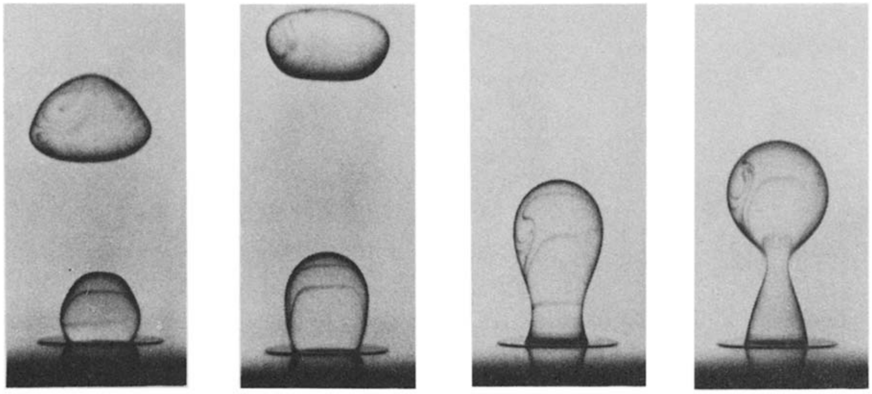

Figure 6. Short entry length nozzle with fast formation rate.

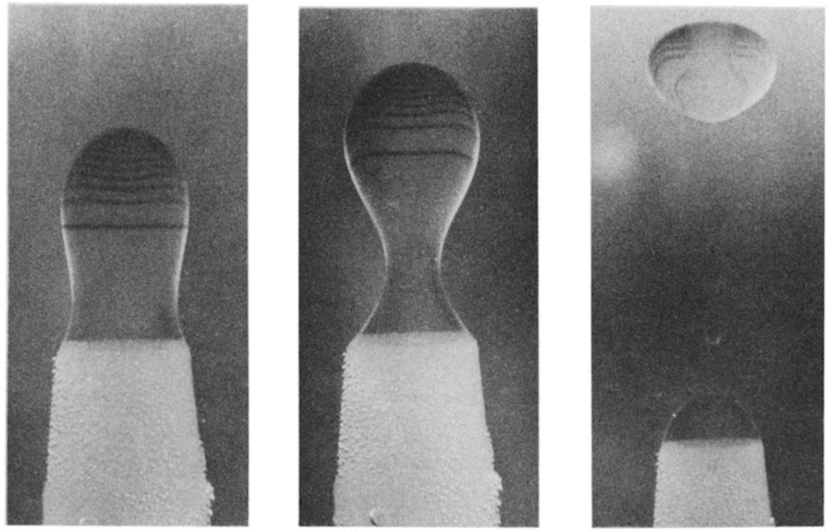

Figure 7. Teflon nozzle with slow drop formation rate. Water might have been contaminated.

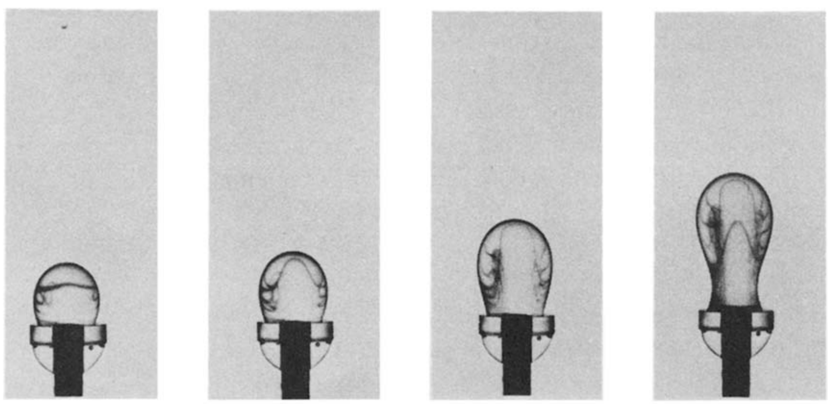

Figure 8. Nozzle with extended wetted area.

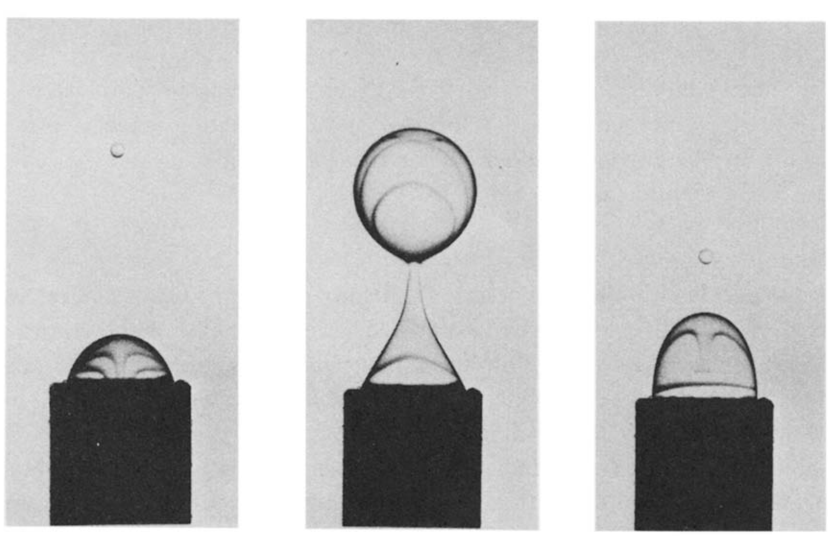

Figure 9. Mixing in the rest drop.

drop formation, strong circulation patterns are observed while drops form rapidly. The circulation is enhanced by the release process. However, this enhancement becomes weaker with decreasing difference between free rise velocity and mean velocity in the dispersed phase nozzle. As before, the circulation dampens out very rapidly after the release process has taken place. The strong circulation experienced during the formation of drops must be partly responsible for the high heat transfer rates during the formation and release process.

Asymmetric drop formation

The two previous flow fields appear to be symmetric with respect to the nozzle axis. However, even in the absence of any cross-flow, this symmetry cannot always be maintained. In fact, in any industrial equipment symmetric flow fields during drop formation and release should not be taken for granted. Figures 3, 4 and 5 show three cases of asymmetric flow during drop formation. In figure 3 the reason for the slight asymmetric flow is an asymmetric wetting of the nozzle rim. In figure 4 the asymmetry is caused by a nonsymmetric flow within the dispersed phase nozzle. An intentional obstruction which blocked about 25% of the nozzle diameter was placed 2 nozzle diameters from the nozzle outlet. Note that in this case the flow is laminar (no localized dispersion and blurring of the individual lines), but it is principally flow up one side of the forming drop and back down the other side. In figure 5, the obstruction (similar in size and shape to that used in figure 4) was placed immediately inside the nozzle outlet. In this case asymmetric wetting resulted and evidence of turbulence directly downstream of the obstruction may be observed. Clearly, other reasons may account for asymmetric flow, for instance, a slanted nozzle configuration, cross flow, or a poorly finished or worn nozzle. While it is not clear how heat transfer during asymmetric drop formation differs from that found under symmetric flow conditions, one should expect that it is not the same.

Slug flow

Figure 6 presents an example of slug flow within a drop developing at a "flat plate" nozzle. This situation is typical for flow at sieve trays in direct-contact equipment. Because of the short length of the nozzle the flow of the dispersed phase is undeveloped. As the drop grows, the flow obtains a more developed character and behaves more similarly to the flow discussed before. A entirely different situation is shown in figure 7. Here, the flow inside the developing drop maintains slug flow character right up to the release process. These pictures were made during early tests whose object was development of the flow visualization technique. The test system characteristics were neither carefully controlled nor measured as they were in subsequent testing. Even though the exact reason for this type of flow could not be established, it is speculated that a form of surface active agent was present. The occurrence of slug flow provides another explanation for the wide variation of heat transfer rates during drop formation and release.

Extended nozzle wetted area

Sieve trays and thick walled nozzles are frequently observed to have an area wetted by the dispersed phase that extends well beyond the inside diameter of the nozzle opening. Figure 8 shows a case of very slow drop formation but with a wetted diameter about four times greater than the nozzle diameter. The circulation is very strong with counter flow along the entire interface of the forming drop. There is also a turbulent layer between the region of influx through the nozzle and the region of counter flow along the interface. While the drop size in this case was about the same as that shown in figure 1, the actual formation rate, and hence the dispersed flow rate, was much lower. Clearly the heat or mass transfer with figure 1 and 8 are vastly different.

Turbulent flow

As a rule, transport processes within forming drops occur at laminar flow conditions. Even so, the flow may have regions of turbulence during formation and release of drops. This is shown in figure 5 and 8.

Mixing after drop detachment

An effect which has been apparently overlooked in the discussion of heat transfer during drop formation and release is the mixing in the rest drop after drop detachment. Immediately after drop release the upper part of the rest drop is accelerated downwards towards the nozzle causing some mixing in the rest drop. This is apparent from figure 9 in which a detaching drop and rest drops at various states are shown. Thus, newly forming drops contain some fluid which has already been in intense contact with the continuous phase. This effect is more pronounced in slower drop formation processes.

CONCLUSION

We have presented qualitative experimental results on the flow mechanism of the dispersed phase during drop formation and release. The large variety of possible flow fields experienced during this process must be viewed as one reason for the difficulty in predicting heat and mass transfer during drop formation and release with reliability and accuracy. On the other hand, the strong circulation patterns during the formation and release process, the possible turbulent flow condition, and the mixing in the rest drop help explain qualitatively the high transfer rates which have been consistently found in experimental studies.

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