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Direct contact evaporation of a single two-phase bubble in a flowing immiscible liquid medium. Part I: two-phase bubble size

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Abstract

The evaporation of a single n-pentane drop in another warm flowing liquid (water) medium has been studied experimentally. A Perspex column with an internal diameter of 10 cm and height of 150 cm was used throughout the experiments. N-pentane liquid at its saturation temperature and warm flowing water with flow rate of 10, 20, 30 and 40 L/h were employed as the dispersed and continuous phases, respectively. The active height of the continuous phase in the column (i.e. the level of the continuous phase in the column) covered only 100 cm of the column's height. A Photron FASTCAM high-speed camera (~ 65,000 f/s) was used to film the evaporation of the drop, while AutoCAD was used to analyse the images from the camera. The diameter ratio (diameter of growing two-phase bubble to initial drop diameter) of the two-phase bubble formed because of the evaporation of the pentane drop in direct contact with the water was measured. Also, the vaporisation ratio (x), the open angle of vapour (β), the total height for complete evaporation and the total evaporation time were measured. The effects of the continuous phase flow rate and the temperature difference between the contacting phases, in terms of Jakob number (Ja), on the measured parameters were investigated. Furthermore, a statistical model to fit the experimental data was developed. The experimental results showed that the diameter of the two-phase bubble is strongly influenced by varying the continuous phase flow rate. The final size of the evaporated vapour bubble was unaffected by the flow rate of the continuous phase, while both the total height required for complete evaporation and hence the time required was significantly influenced. A similar impact was observed for the vaporisation ratio and the open angle of vapour.

Nomenclature

a	Radius of two-phase bubble (m)	m	Ratio of liquid to vapour density in the two-phase bubble (kg/m^3)
D	Diameter of two-phase bubble (m)	N	Constant appears in Eq. (2)
D_o	Initial diameter of drop (m)	$P1$	Constant appears in Eq. (2)
d_c	Diameter of column (m)	Q_c	Volumetric flow rate of continuous phase (m^3/s)
C_p	Spesific heat of continuous phase (kJ/kg. K.)	Re	Reynolds number
Ja	System Jakob number ($\rho_c C_p (T_c - T_d)/\rho_{dv} h_{fg}$)	T_c	Temperature of continuous phase ($^\circ C$)
H_v	Total height required for complete evaporation (m)	T_d	Saturation temperature of dispersed phase ($^\circ C$)
h_{fg}	Latent heat of evaporation of dispersed phase (kJ/kg)	U	Velocity of continuous phase (m/s)
		VR	Ratio of vapour volume to total volume of tow-phase bubble
		V_r	Radial velocity component (m/s)
		V_θ	Tangential velocity component (m/s)
		x	Vaporization ratio

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Greek symbols

β	Half opening angle (rad)
μ_c	Dynamic viscosity of continuous phase ($N. s/m^2$)
ρ_c	Density of continuous phase (kg/m^3)
ρ_{dL}	Density of liquid dispersed phase (kg/m^3)
ρ_{dv}	Density of vapour dispersed phase (kg/m^3)
τ	Dimensionless time

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1 Introduction

Developing a greater understanding of the heat transfer characteristics during evaporation of one fluid in contact with a second immiscible one is vital for the development of the three-phase direct contact heat exchanger. Such an exchanger has many advantages over traditional exchangers, and therefore has begun to receive significant research interest. The absence of a physical barrier, such as the tube wall in traditional shell-and-tube or plate heat exchangers, between the contacting hot and cold fluids can significantly reduce the heat transfer resistance and therefore increase the overall heat transfer coefficient and the contact area over which heat transfer can occur. Furthermore, problems such as corrosion and fouling are virtually eliminated. These factors mean that the total capital and operational costs of direct contact exchangers is significantly lower than traditional surface type exchangers. Beyond this, the ability to work with a very low temperature driving force makes these exchangers ideal for use in systems with low-grade heat, such as industrial waste heat or solar thermal collectors. Accordingly, direct contact heat exchange can be found in many different fields, such as water desalination by freezing, power generation from geothermal brine, and ocean thermal energy conversion [1]. However, the direct contact heat exchanger still has some disadvantages. For example, the two working fluids must be completely immiscible; otherwise an additional separation process is necessary, which increases the cost of the process.

Simply, the direct contact heat transfer is achieved by injecting drops or bubbles of one fluid, as a dispersed phase, directly into another immiscible liquid as a continuous phase. The temperature of the continuous phase is higher or lower than the saturation temperature of the dispersed phase depending on whether evaporation or condensation of the dispersed phase is desired. The mechanism of heat transfer in both systems is nearly identical [2–4], where a two-phase bubble/drop is formed immediately when the dispersed phase first contacts the continuous phase as it leaves the injection device. Two distinctive regions within the unique structure of the mother drop (in case of evaporation) are produced as the heat transfer process proceeds. These regions are in thermal equilibrium, and are made up of the vapour and liquid components. Due to the effect of gravity, the growing vapour phase is concentrated at the top of the two-phase bubble, while the liquid phase, which is being depleted, is found at the bottom.

It has been extensively reported [5–11] that the heat transfer during the evaporation of a drop in direct contact with an immiscible liquid is complex. This is because of the wide range of interdependent parameters such as phase temperatures, velocities, the physical and thermodynamic properties of the two phases and the system holdup. In addition, the immobility of the two-phase bubble wall, the changing shape as the bubble evolves due to the evaporation and the presence of impurities, regardless of which phase they are in, make this process complicated.

Despite this complexity, reasonable effort has been directed to the investigation of the evaporation of a drop in an immiscible liquid medium. The majority of these studies were theoretical, with only a few experimental studies having been performed. A complete understanding of this complex heat transfer process remains elusive. As direct contact heat exchangers have shown a dramatic increase in utility in recent years, this necessitates the construction of a more thorough body of precise experimental data to help in the development of empirical correlations for use in the design process. Due to the difficulty of deriving analytical solutions, simulations or numerical models are also crucial.

Despite the large body of work alluded to above, which has focussed on the direct contact evaporation of a drop in an immiscible liquid, very little attention has been paid to the instantaneous change of the two phase bubble's size. Such a parameter is crucial in understanding the fluid mechanical interaction of the drop with the immiscible medium, and of course to the mechanisms controlling heat transfer to the bubble. Sideman and Taitel [12] developed an experimental technique and a theoretical model to study the direct contact evaporation of single drops of pentane and butane in warm seawater and distilled water. Their analytical model was limited to producing an expression for Nusselt number. Their experimental data were correlated with a wide range of parameters including the velocity, heat transfer coefficient, total drop evaporation time and drop size. When considering the growth of two-phase bubbles, they observed that nucleation and evaporation are slower when the drops are smaller. These processes are also faster in seawater rather than in distilled water. Sideman and Isenberg [13] studied the basic mechanism of drop evaporation or bubble collapse (i.e. condensation) in immiscible liquid media. They developed an analytical expression for the change in the size of the drop due to evaporation or condensation. Both the heat transfer coefficient and the evaporation time were also modelled. Mukhtarzahah and Al-Shirbini [14] developed a numerical model to investigate the evaporation of a drop in immiscible liquid media. Their model involved the numerical solution of momentum, continuity and energy equations for a spherical drop as it moves and evaporates simultaneously in a cylindrical column of, warm, quiescent water. The importance of the initial (i) velocity, (ii) temperature and (iii) size of the drop on the evolution of the drop, as well as its motion and heat transfer characteristics were tested by the model. Thereafter, Battya et al. [1] solved

numerically the energy and momentum equations for single volatile drop evaporation while rising in an immiscible liquid. Their parametric study involved the diameter ratio of the drop and the dimensionless velocity. Different operational conditions, such as the initial Reynolds number, Froude number, Peclet number and Jacob number were tested and good agreement with the experimental data was achieved. Similarly a numerical study for the diameter ratio of an evaporating drop has been developed by Wanchoo et al. [15]. The same parameters that Battya et al. [1] considered were tested and the results showed a good agreement with the available experimental data. Mahood [16] modelled analytically the diameter ratio and the heat transfer coefficient of single drop evaporating in another immiscible liquid. The model, based on the solution of the energy equation with a concentric spheres configuration, included heat transfer by both convection and conduction from the continuous phase to the drop. The same effective parameters found by Battya et al. [1] were tested to assess the accuracy of the model, which showed a good agreement with literature values. Recently, Kulkarni and Ranade [17] conducted an experimental investigation in to the problem of a drop evaporating in an immiscible liquid. The experiments were carried out using a two-dimensional transparent experimental rig. They estimated the dimensions of the two-phase bubbles, their rise velocity, the distance travelled and the vapour fraction in the drop. A simple model was developed to simulate their experimental data.

Further studies have been carried out regarding the direct contact evaporation of a drop in an immiscible liquid, but these studies excluded the drop growth due to evaporation. For instance, [18–21] theoretically studied the instantaneous velocity and heat transfer coefficient of a drop evaporating while rising in a stagnant water column Wanchoo and Raina [22] developed an analytical model to investigate the instantaneous two-phase bubble velocity and the drag coefficient of drop evaporating in a less viscous continuous phase. The drag coefficient was found to increase with increasing two-phase bubble velocity.

It is obvious that all previous studies have considered evaporation of a drop in a quiescent warm immiscible liquid column. Therefore, the effect of the continuous phase velocity on the development of the size history was not considered. A flowing continuous phase is the most likely situation found in a practical direct contact heat exchanger, in which there is a counter-current flow of the contacting phases. To close this gap, this paper describes the study of a single drop evaporating in another flowing immiscible liquid. The effect of the temperature driving force, expressed in terms of Jacob number, and the continuous phase flow rate on the two-phase bubble size were investigated experimentally using n-pentane and warm flowing water as the dispersed and continuous phases, respectively.

2 Experimental setup and procedure

2.1 Experimental apparatus

Figure 1 shows schematically the experimental rig used in the present research. It consists of three parts: the test section, the dispersed phase delivery system and the continuous phase delivery system. The test section is a cylindrical Perspex tube of 10 cm diameter and 150 cm height. Only 100 cm is used as the active height of the continuous phase in the column. The tube is connected to the injection nozzle at the bottom (for the injection of the dispersed phase) and with the continuous phase inlet tube at the top. The injection nozzle is made of copper tubing with 0.75 cm internal diameter and about 10 cm in height. The dispersed phase fluid, i.e. liquid n-pentane, is supplied to this nozzle from a 20 L plastic storage vessel via a peristaltic pump.

Four holes were made in the test section wall at heights of 20 cm, 40 cm, 60 cm and 80 cm to fix four K-type thermocouples. These measure temperature to an accuracy of $\pm 1\%$. A rectangular Perspex jacket of width 20 cm is used to maintain the temperature of the continuous phase in the test section at a constant level and to minimize distortion during photography. Hot water at a constant temperature is circulated through the jacket for this purpose. The continuous phase, distilled water, flows from a 500 L plastic storage water tank via a peristaltic pump, valves, rotameter and plastic connection tubes.

A Photron FASTCAM SA1 high-speed camera (about 65,000 frames per second) and 1/2000 per second shutter, with movable stand was used to record the evaporation of the n-pentane droplet. The vertical progress of the drop was calibrated using a vertical scale.

The experimental procedure started by circulating the continuous phase through the test section to achieve a uniform temperature. Simultaneously, hot water at the same temperature as the continuous phase was circulated throughout the jacket to maintain temperature control. The maximum temperature difference between the inlet and outlet of the continuous phase was measured as less than 0.1 °C. Upon stabilisation of the continuous phase level and temperature, the dispersed phase (liquid pentane) was pumped via a low flow rate peristaltic pump through a plastic tube to a pool type heat exchanger, where it was warmed to its saturation temperature (36 °C). It was then injected into the test section as a single droplet via a single copper nozzle. The growth and rise velocity of the two-phase drop formed was recorded by the high-speed camera from the moment of detachment from the nozzle tip to the end of evaporation.

2.2 Image analysis

The size and position of the two-phase bubble along the test section were captured from the moment of detachment from the nozzle until the drop had completely evaporated. These

Fig. 1 Schematic diagram of the experimental test rig
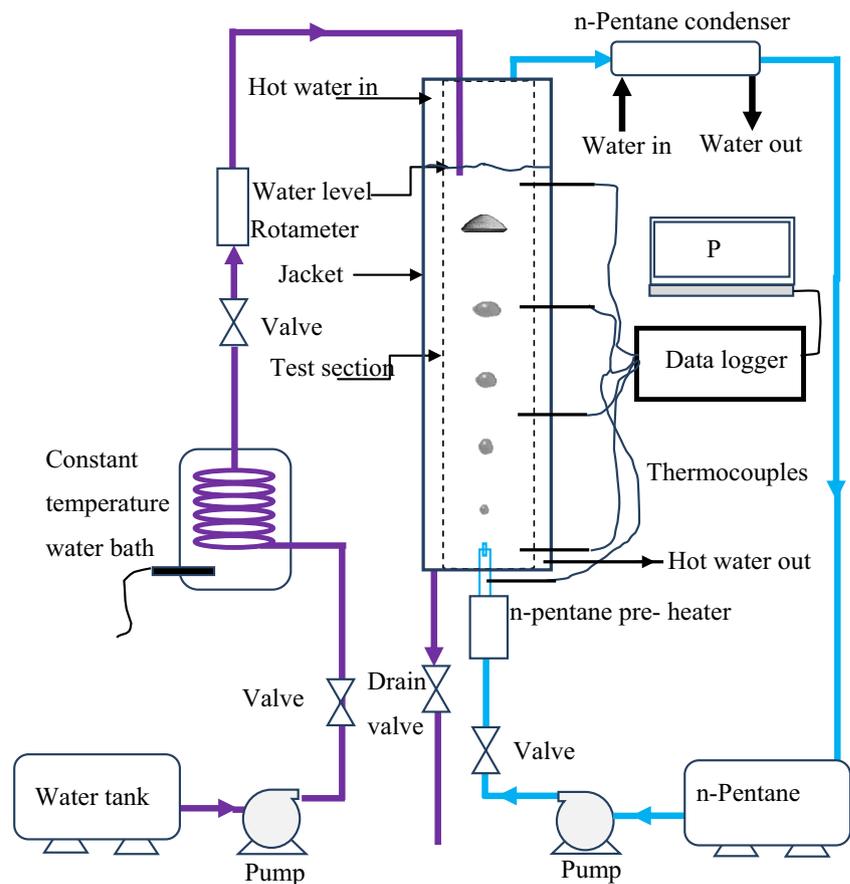
pictures were transferred for analysis into a PC using the camera software, V.3.21. The following procedure was used to determine precisely the actual size of the two-phase bubble evaporating along the column (see Fig. 2a).

For each run, an image of the two-phase bubble at actual size was imported into AutoCAD. The volume of the two-phase bubble was then determined by tracing the border of the bubble. By rotating about the vertical axis, a 3-D model of the bubble was generated. This, of course, assumes that the bubbles are axisymmetric. The volume of this virtual bubble could then be straightforwardly generated by the software. This procedure was repeated for each individual run (drop) and therefore an accurate history of the volume of the two-phase bubble was constructed.
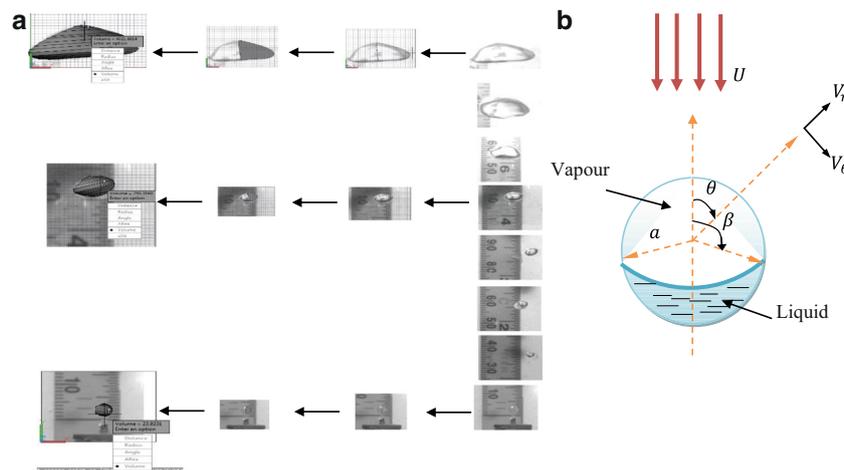

Fig. 2 a Schematic representation of the image analysis procedure for the two-phase bubble (run 1). **b** Configuration of a two-phase bubble evaporating in an immiscible liquid (a represents the two-phase bubble radius, U denotes the continuous phase velocity, V_r and V_θ are the radial, tangential velocity components, θ is the angle in spherical coordinate and β is the opening angle of vapour phase in the two-phase bubble)

3 Results and discussion

The effect of the flow rate and temperature driving force on the evolution of the diameter ratio of the two-phase bubble was investigated. The experimental measurements revealed that the shape of the two-phase bubble was similar to that observed earlier [12]. That is to say, as the evaporation process proceeded, a distinctive vapour layer accumulated at the top of the drop/bubble while the liquid drained toward the bottom, as shown by Fig. 3. The liquid content within the drop can only be identified by this visual method for a vaporization mass ratio (i.e. the mass of the vapour phase to the total mass in the two-phase bubble) of up to 8%. Thereafter, the non-vaporised liquid occupied only a relatively small proportion of the volume of the bubble.

A sloshing motion of the liquid inside the two-phase bubble was observed, beginning at a vaporisation ratio of about 0.1%, and increasing gradually until it dissipated at a vaporisation ratio of about 8%. Of course, as it rose, the shape of the growing two-phase bubble varied depending on the mass ratio. It was completely spherical over the first few centimeters of the test section (on average for about the first 5–8 cm of rise from the nozzle) and then changed to spheroid, large spheroid and finally to a spherical-cap. No effect of the continuous phase flow rate on the sequence of shape transition of the two-phase drop-bubble was observed under the present experimental conditions, which are summarised in Table 1.

The image processing technique described above was used to analyse the pictures obtained by the high speed camera. As

Table 1 Parameters ranges through the experiments

| Parameter	value
Initial diameter, D_o	3.3 mm
Temperature difference, ΔT	1.6, 5.5 and 11.8 $^\circ C$
Flow rate of continuous phase, Q	10, 20, 30 and 40 L/h

discussed previously, this innovative technique can accurately determine the total volume of the two-phase drop or bubble. Due to the difficulty of identifying precisely the vapour and liquid interface within the bubble, a simple mass balance of a constant mass two-phase bubble was used [19] to establish the vaporisation ratio. Depending on the diameter ratio measured, (the diameter is taken as diameter of a sphere of equivalent volume) this mass balance can be used to determine the vaporisation ratio of the two-phase bubble. The following formula is used [22]:

$$x = \left(\left({}^{D}/_{D_o} \right)^3 - 1 \right) (m-1)^{-1} \qquad (1)$$

where x and m represent the vaporisation ratio and the ratio of liquid to vapour density in the bubble. Thus, the open angle of the vapour (β), which represents the opening angle of the vapour phase in the two-phase bubble (see Fig. 2b), can be predicted using the empirical correlation of [23]:

$$\beta = N^{P1} \cdot (\tan(0.7854 VR))^{6.205} \cdot VR^{-6.032} \qquad (2)$$

Fig. 3 Evaporation process of n-pentane drops with $D_o = 3.3$ mm

$m_v / m_o =$
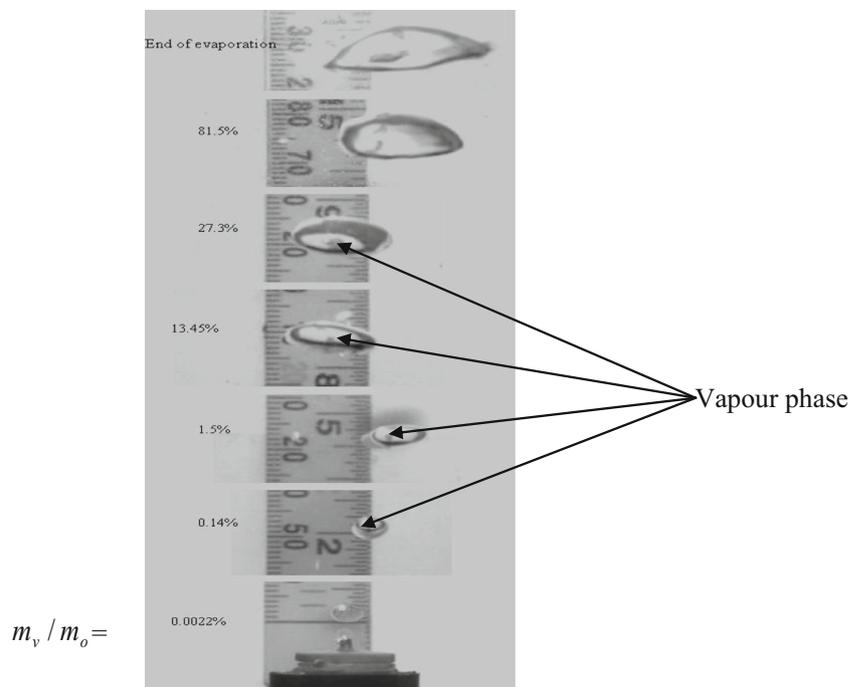
Where

$$N = \frac{1.82}{8}(\rho_c - \rho_{dL} - VR(\rho_{dv} - \rho_{dL}))^2 \cdot \left(\frac{\rho_{dL}}{\rho_{dL} + VR(\rho_{dv} - \rho_{dv})}\right)^{1/3} \frac{D_o \mu_w^2 g}{\sigma^2 \rho_c^2} \quad (3)$$

$$P1 = -0.0079 D_o - 0.1565 \quad (4)$$

VR= ratio of vapour volume to the total volume in the two-phase bubble

All other variables are listed in the nomenclature.

The variation of diameter ratio of the growing two-phase bubble with dimensionless time is shown in Fig. 4 for three different Ja (the ratio of sensible heat to latent heat absorbed during the drop evaporation in an immiscible liquid ($Ja = \rho_c C_p (T_c - T_d)/\rho_{dv} h_{fg}$)) and four different continuous phase Reynolds number ($4Q_c \rho_c / \pi d_c \mu_c$). It is clear that the diameter ratio increases with time for all cases under study. Although, the final diameter ratio of the two-phase bubble has the same value for different Ja, the time required for complete evaporation does not. Obviously, the higher the average Ja, the less time is required for evaporation due to the increased driving force for heat transfer. In general, the final two-phase bubble diameter ratio was found to have approximately the same value for all experiments performed, (about 6). This is in agreement with others [1], who stated that the final diameter ratio of a drop which has evaporated in direct contact with an immiscible liquid depends only on the density ratio of the vapour and liquid of the evaporating fluid, i.e.:

$$\frac{D}{D_o} = \left(\frac{\rho_{dL}}{\rho_{dv}}\right)^{1/3} \quad (5)$$

Eq. (5), for the n-pentane used in these experiments, predicts the final diameter ratio of the bubble at the end of evaporation is 6.03, which is consistent with the measured value.

In addition, Fig. 4 illustrates the effect of the continuous phase Reynolds number on the temporal development of the diameter ratio of the two-phase bubble at constant Ja. It is clearly that the continuous phase Re has a substantial effect on the time needed for complete evaporation of the drop. It is once again clear that there is no effect of Re on the final diameter ratio of the bubble. It can be seen that the higher the continuous phase Re, the shorter the time required for complete evaporation. This could be due to the high relative velocity produces by the countercurrent flowing continuous phase. The high relative velocity, however, increases the heat transfer coefficient of evaporating two-phase bubble in the column consequently enhances the direct contact heat transfer process. In addition, the flowing continuous phase tends to result in a uniform temperature due to enhanced mixing. The effect of the continuous phase Re being more pronounced at higher Ja. Where, the higher the Ja, the higher the effect of continuous phase Re.

Practically, the heat transfer is significantly affected by the change of phase in the two-phase bubble. Thus, information about the vaporisation ratio in the two-phase bubble represents the key factor for accurate prediction of heat transfer during the evaporation process. As the evaporation progresses, the vapour content confined to the drop will increase on account of the evaporating liquid content. Thus, the liquid-liquid contact area which is responsible for the majority of the heat exchange between the warm continuous phase and the two-phase bubble will decrease. When combined with the poor thermal conductivity of the vapour phase, the heat transfer rate to the evaporating drop tends to reduce. Furthermore, it is generally assumed in the literature that there is a spherical shape for both the vapour and liquid sections in the mother bubble. This assumption is seriously flawed due to the significant distortion of the spherical shape over the course of evaporation. Nonetheless, the spherical shape can be represented by a narrow range of vaporisation ratios (less than 0.2%). Therefore, one can be concluded that both assumptions above would involve inevitable error. Hence, accurate measurements of the evaporation ratio (x) should provide an accurate basis for design.

As mentioned above, the image processing technique employed herein to measure the size of the two-phase bubble is unable to measure the evaporation ratio in the two-phase bubble directly with sufficient accuracy. However, a mass balance technique does provide an acceptable alternative. From the principle of conservation of mass, the vaporisation ratio (x) is directly related to the two-phase bubble diameter ratio, as shown by Eq. (1).. These calculated values are show in Fig. 5, which represents the variation of the vaporisation ratio with time at a specific Ja and four different continuous phase Re.

Clearly, the variation of the continuous phase Re was not observed to influence the completion of vaporisation. The only impact is upon the time required for complete vaporisation. These observations might be justified by that the increase of Ja improves the direct contact heat transfer between the contacting two phases, as discussed above (Fig. 4). Consequently, the amounts of vapour produced due to the convective evaporation will accordingly rise during a shorter time. This is same for the continuous phase Re, since the direct contact heat transfer enhances by increasing the
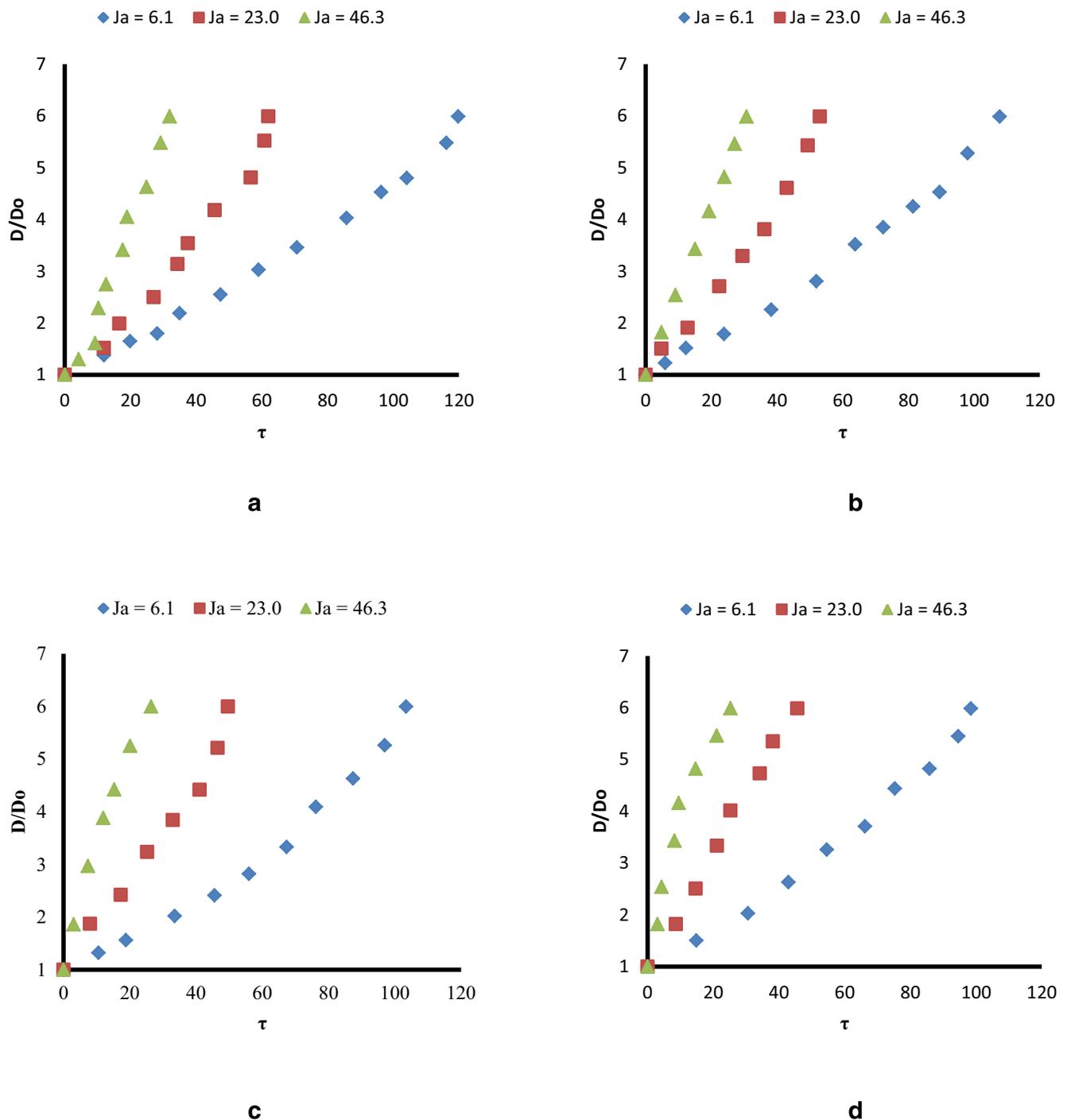
a

b

c

d

Fig. 4 The variation of the drop/bubble dimensionless diameter with dimensionless time at three different average Jacob numbers (Ja) and continuous phase Reynolds number (Re): a) Re = 3250 b) Re = 6500 c) Re = 9700 d) Re = 13,000

continuous phase Re, as discussed above. Again, and unsurprisingly, the effect of the continuous phase Re becomes more obvious with increasing the Ja.

From the results above, it is apparent that the continuous phase Re and Ja have impacted the time, and hence total height required to complete the droplet evaporation. Practically, the height required for

evaporation represents the most crucial factor in determining the cost of the direct contact heat exchanger [24, 25]. It was found by Baqir et al., [25] that the total height of a real direct contact heat exchanger is decreased by increasing of the flow rate of the continuous phase. The same behaviour is evident in Fig. 6 for the single two-phase bubble evaporating in this work. Both
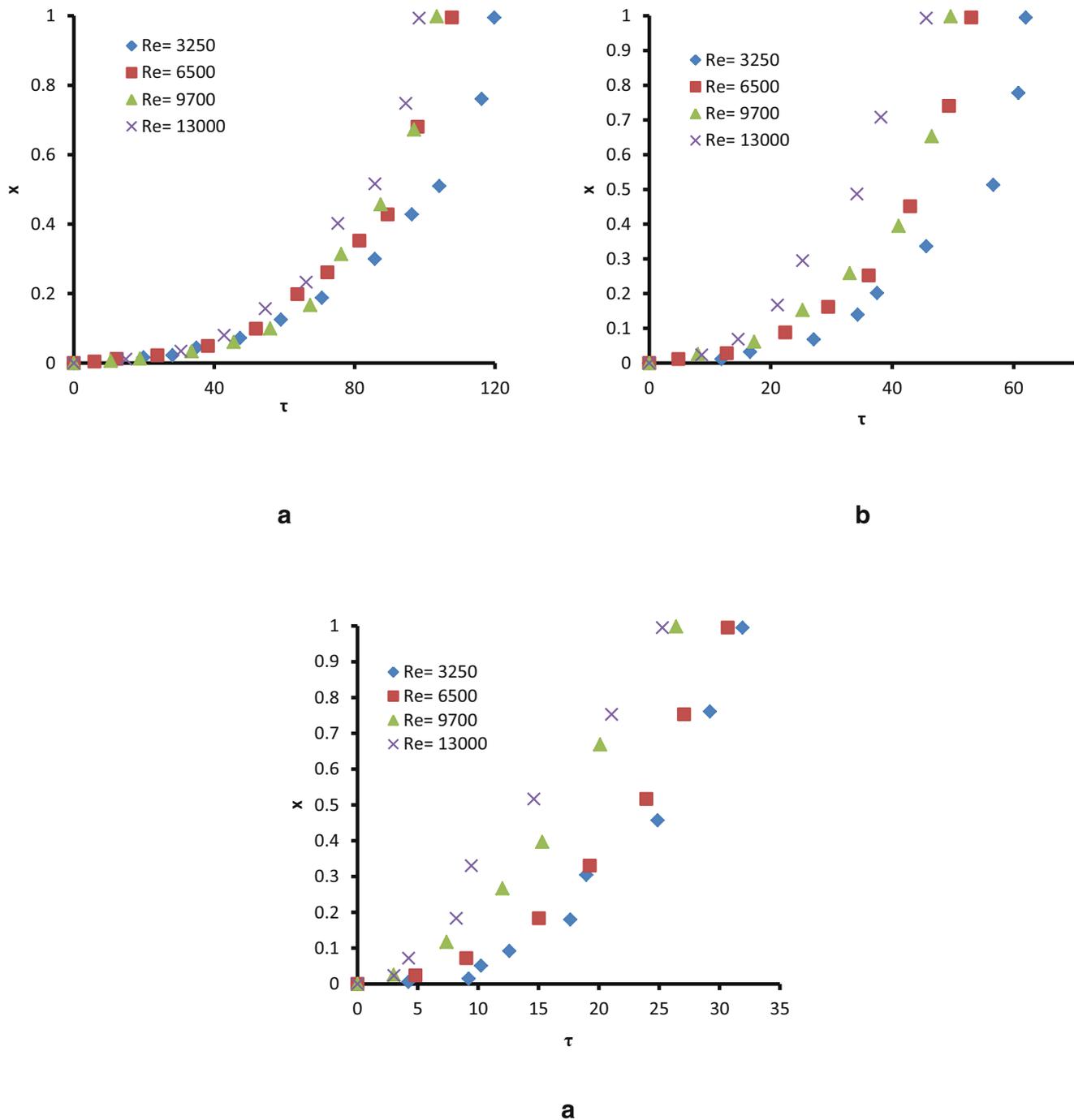
Fig. 5 Effect of continuous phase flow rate on the vapour content in the drop/bubble for four different continuous phase flow rates and a) $Ja = 6.1$ b) $Ja = 23$ c) $Ja = 46.3$

Ja and the continuous phase Re significantly influenced the total height for complete evaporation of the droplet. Higher Ja again means that there is a higher temperature difference between the contacting phases, and thus there is a more rapid evaporation of the liquid within the droplet. As a result, the evaporation is completed closer to the injection nozzle.

With respect to the structure of the two-phase bubble, it should be recalled that the vapour concentrates at the top of the bubble and liquid (unevaporated fluid) settles at the bottom under the influence of gravity. The geometry of this split can be summarised with the open angle (β) of vapour, which evolves as the evaporation progresses, varying from zero to 2π. Due to the rapid oscillations in the shape of the two-phase
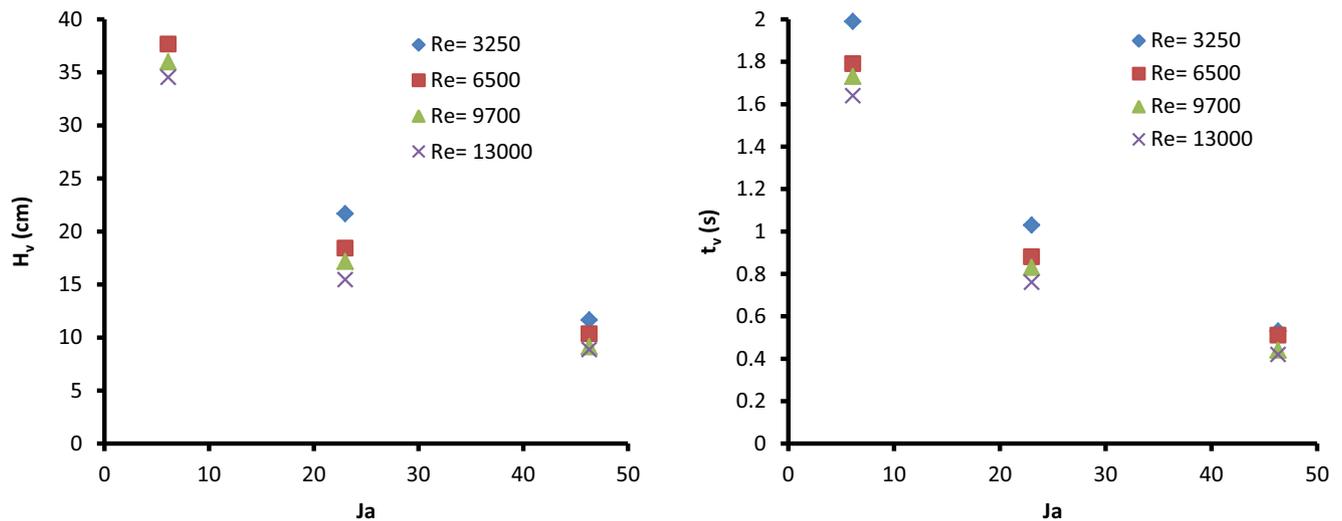
Fig. 6 Variation of the (**a**) total height for complete evaporation and (**b**) total evaporation time with *Jacob* number (*Ja*) for four different continuous flow rate

bubble, the direct measurement of the open angle is challenging and involves a significant error [10]. Therefore, an indirect method has been implemented here to estimate the values of the open angle (β). This method was described by [23], who measured and correlated the surface areas and the open angle of vapour for a two-phase bubble evaporating in an immiscible liquid.

Figure 7 shows the variation of the open angle of vapour with time for four continuous phase Re and three different *Ja*. In all cases, (β) increases from its lowest value ($\beta = 0$) where is no contact between the dispersed drop with the continuous phase towards the maximum value at the end of evaporation process ($\beta \approx$ 6 *rad*). The behaviour of (β) is identical for all *Ja* and continuous phase Re. One can also distinguish three distinctive regions of (β) for all cases: (i) the convective evaporation zone, (ii) the steady slow evaporation zone and (iii) the fast convective evaporation zone. In the first zone, the open angle of vapour rises suddenly from zero to an angle value nearly equal to $\beta \sim 1$ rad. This represents the intensive convective evaporation of the drop. At this stage, the temperature difference between the contacting fluids is a maximum therefore a high heat exchange rate is take place. This is in agreement with the observation [26, 27] for the direct contact condensation of two-phase bubbles in a countercurrent condenser. Furthermore, the injection of the drops at their saturation temperature could result in a sudden evaporation once they first contact the warm continuous phase.

Through the second zone, the two-phase bubble is growing with time, as does the heat transfer resistance due to the increasing vapour fraction and reduced the liquid-liquid interface. Consequently, the rate of heat exchange is slowed. The temperature difference between

the evaporating drop and the continuous phase is reduced since the drop has warmed up. The evaporation process and hence the open angle of vapour increase steadily. This region encompasses almost all of the evaporation process, which is consistent with [26] observation for condensation. If the efficiency of the evaporation process is to be improved therefore, it is this region that should receive the bulk of the attention. Interestingly, this zone ends for virtually all of the cases considered at the same value $\beta \sim 2$ rad. The evaporation is completed in a final zone, where a fast convective evaporation process can be seen. In this zone, the two-phase bubble rapidly evaporates and the open angle of vapour increases sharply to its final value. At this point of the evaporation, the surface area of the two-phase bubble has increased dramatically due to the high vapour content. Thus, the shape of the two-phase bubble begins changing and the sloshing phenomenon observed in the liquid layer, which greatly enhances mixing and hence heat transfer, can be seen to occur more dramatically. Furthermore, at this stage the probability of collisions amongst the large two-phase bubbles is increased and hence the splitting of the two-phase bubbles into small liquid drops and vapour bubbles could occur to a more significant degree. This helps to increase the direct contact between the warm continuous phase and the unevaporated drops and hence increases the evaporation rate in the drops.

Fig. 7 also shows as the effect of *Ja* on the open angle of vapour at invariant continuous phase Re. It is obvious that *Ja* has positively affected (β). The higher the *Ja*, the faster the evaporation process is. Consequently, (β) will reach it is maximum value at shorter time.
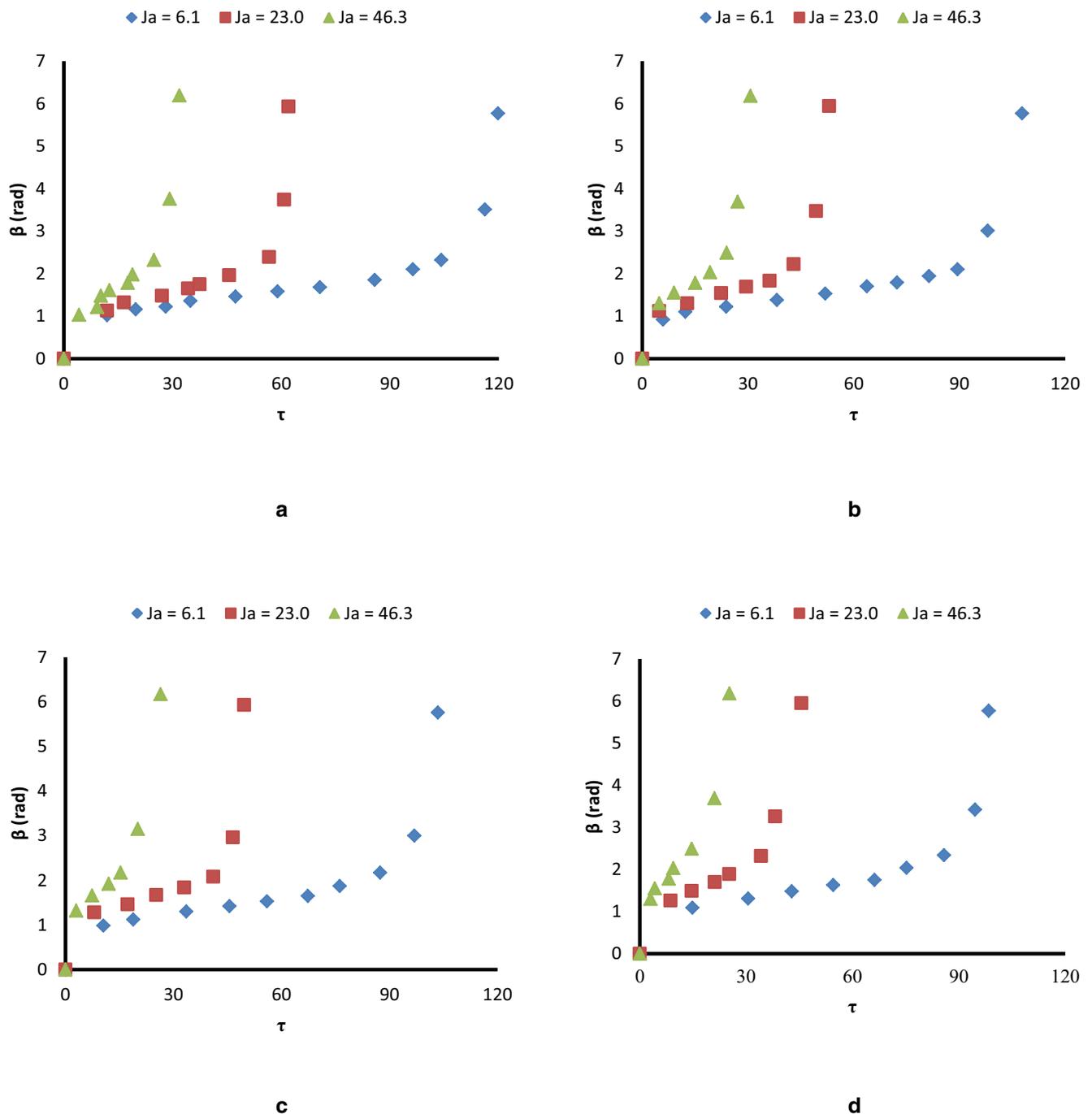
Fig. 7 The variation of the open angle with time at three different average *Jacobs* number (*Ja*) and four continuous phase Re: **a**) 3250 **b**) 6500 **c**) 9700 **d**) 13,000

4 Conclusions

An experimental study which measured the changing size of a single two-phase bubble (n-pentane) evaporating in a warm flowing immiscible liquid (water) has been carried out. A Photron FASTCAM high-speed camera, with software version V3.31.2, coupled with AutoCAD for post-processing the camera images were

used. The effect of the continuous phase Re on the growth rate of the two-phase bubble was investigated, this is in contrast to previous studies hat studied the growth of a two-phase bubble in a stagnant liquid. A novel image processing technique was applied to fit calculate the size of the evaporating two-phase bubble. From the reported experimental results, the following conclusions can be drawn:

1- Similarly to a drop evaporating in a stagnant liquid, a drop which evaporates in a flowing immiscible medium starts as a spherical drop and then becomes a spheroid, a large spheroid, a spheroid- spherical cap and ends as a spherical-cap bubble.

2- Sloshing can be seen in a manner similar to that which appears in a stagnant system. It was found that the sloshing of liquid within the two-phase bubble being affected significantly up to 8% of mass ratio.

3- The continuous Re was found to have a significant impact on the two-phase bubble growth. This was more pronounced with increasing Ja.

4- Similarly, the continuous phase Re affected the vaporisation ratio as well as the open angle of vapour. This impact again was more obvious with increase in Ja.

5- The continuous phase Re was found to have a considerable effect on the total height required to complete the evaporation of the drop. This finding shows there is promising potential to reduce the cost of a three-phase direct contact heat exchanger by reducing the size.

6- The AutoCAD assistance image processing technique seems to produce an accurate measuring for the volume of the growing two-phase bubble in an immiscible flowing liquid. And the AutoCAD processing can be perfectly suggested to exploit in such system and even for another isothermal system.

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