CHAPTER - 1

INTRODUCTION
It is only a few years since the world began to recognise the inevitability of an energy crisis. Right now the global oil needs are very large. It is, therefore, not surprising that the search for alternative source of energy to replace oil has become important.

The energy from the sun gets stored in the surface layers of oceans in the form of hot water. The ocean thermal energy conversion (O.T.E.C) uses these surface layers of oceans and converts the accumulated thermal energy to electricity. It is one of the main renewable resource systems currently under development, that is capable of providing base-load power to utilities and process industries. Since the economic viability of OTEC as a means of harnessing solar thermal energy depends on the ability to control marine fouling and corrosion on OTEC heat exchanger surfaces, it was felt that these disadvantages could be overcome by using low energy metal surfaces (by treating surfaces with fluoro-chemicals to reduce wettability).

The surfaces of the selected metals were chemically modified with a monolayer of a fluoro-chemical to minimize their surface energy. Even this method did not help as these surfaces resisted wetting by the salt water only for a very short period. Once the
surfaces were wetted by sea water, fouling became evident.

Direct contact heat transfer with phase change provides the advantage of eliminating metallic heat transfer surfaces which are prone to corrosion and fouling, in addition to smaller required temperature differences, convenient separation of the fluid and very high heat transfer coefficients. These advantages can lend themselves to producing economical process systems in instances where the use of a shell and tube heat exchanger would make the process not economically feasible. Two such processes of current world wide importance are power generation (17), utilizing the temperature gradient of geothermal brine and desalination of sea water (89, 155, 191, 227, 231). Some other representative applications of this mode of heat transfer include various schemes associated with cooling of nuclear reactor (154) and refinery operations (3).

A direct contact heat exchange is obtained when two immiscible fluids of different temperature are mixed. When the change of phase of one of the fluids (evaporation/condensation) takes place, extremely high heat transfer rates result (196). For direct contact heat transfer, the transfer fluid should have the following properties (83, 155, 231):
(a) Specific gravity appreciably different from the process fluid,
(b) No tendency to form stable emulsions,
(c) Low solubility in the process fluid,
(d) Low viscosity,
(e) Low surface tension,
(f) Non-corrosive,
(g) Low vapour pressure,
(h) Non-toxic,
(i) High heat capacity and latent heat,
(j) Chemical stability,
(k) Availability at low cost.

Although extensive work, both experimental and theoretical, on the transfer mechanism between the drop and the continuous liquid medium has been reported and reviewed (189, 196) relatively less work has been done on direct contact heat transfer with phase change.

Desalination processes provided the impetus for Sideman and Hirsch (193); Sideman et al. (190); Sideman and Isenberg (194); Sideman and Taitel (197); Klipstein (115); Raina et al. (163) and Raina and Wanchoo (167) to investigate the basic mechanism of evaporation of a volatile liquid dispersed in an immis-
cible liquid. However, it is obvious that for practical application of this mode of heat transfer, the transfer agent must operate in a closed cycle, and provision must be made to recondense the vapours for reuse. Among earlier investigations on condensation of a bubble in an immiscible liquid medium are those reported by Isenberg et al. (93); Moalem and Sideman (138), Moalem et al. (135); Moalem and Sideman (137); Higeta et al. (94) and Kalman et al. (111). These investigations reveal that the dynamics of a collapsing bubble and the mechanism of heat transfer between two immiscible phases are, relatively, more complex than either that of a drop or a bubble of constant radius. There is no satisfactory theory so far available which can explain the experimental results and be consistent with the physical phenomenon. Therefore, a basic study of single bubbles is essential for the understanding and effective utilization of this important mode of heat transfer.

Sideman and Hirsch (192) performed experiments of condensation of isopentane bubbles in water. They observed that a vapour bubble turned into a two-phase bubble in which the condensate accumulated at the bottom and presumed that heat transfer occurs exclusively across the condensate continuous phase interface occupying the rear part of bubble surface as in the vaporization of a drop in similar systems (Sideman and Taitel, (197)).
Later Isenberg and Sideman (100) presented a different model. They supposed a two-phase bubble to be covered with a thin film of condensate flowing downward along the surface into the puddle at the bottom. In this model heat transfer is assumed to occur substantially at the front part of bubble surface across the thin film of condensate contrary to the former model. They have also assumed bubble velocity to remain constant and either the flow of liquid moving past the bubble is potential flow or is as if the bubble were a rigid sphere. Isenberg et.al. (99) proposed an approximate analytical solution for bubble collapse based on potential flow and quasi-steady-state assumptions. An empirical velocity correction factor was used to approximate the viscous effects. These authors have also neglected the resistance of the condensate film and assumed the bubble surface to remain at the instantaneous saturation temperature of the vapour.

Jacobs et.al. (103) observed that the existence of a condensate film within the bubble in a two-component system could have a significant effect on its collapse, particularly if the condensate’s thermal conductivity was small. Based on the assumption of quasi-steady state and potential flow, their results showed that the condensate film could contribute 30 percent of the resistance to heat transfer. Further, they
concluded, that the assumption of potential flow in the condensate film as well as the external liquid over-predicts the collapse rate. Theoretical models developed so far either overpredict the experimental data or predict the initial collapse rates only.

In most of the practical applications the process occurs at moderately high Reynolds number where conventional theories for heat transport to drops or bubbles (Levich, (125) and Boussinesq (21) ) fail to describe the system successfully. Consequently, the design of processes involving collapse of a bubble in an immiscible liquid depends heavily on experimental correlations.

The purpose of this research is to determine the basic mechanism of heat transfer between a condensing dispersed immiscible phase and a continuous phase liquid medium. In contrast to bubble collapse in single component systems where the condensed phase merges with the continuous medium, the condensed liquid in two-component systems remains within the confines of the bubble. The investigation is devoted to the study of single bubbles in order to furnish a proper foundation for analysis of the transfer mechanism.

The present study is divided into two main
parts: experimental and theoretical. In the experimental portion of the study, Cine-photography has been used to record the collapse of n-pentane, isopentane and furan bubble in distilled water or aqueous glycerol (75% wt and 98.3% wt). From this record, the heat transfer and the dynamic characteristics of a collapsing bubble were determined. In order to ensure the bubbles under study where completely vaporous and free from noncondensables, a new technique to vaporize the dispersed phase was used (Chapter-5). This technique enabled to have a better control over the bubble release and eliminate the presence of noncondensables in the dispersed phase.

The experimental study and visual observations have revealed that:

(a) throughout the motion of a collapsing two-phase bubble through the continuous phase medium, the vapour phase was always located on the top of the liquid phase and the two phases were in contact with each other throughout the process.

(b) There was a sharp decrease in the velocity of the two-phase bubble towards the last stages of collapse.
(c) The dispersed phase bubble would maintain its spherical shape in high viscous continuous phase liquid (like glycerol) irrespective of initial bubble diameter.

(d) The amplitude of oscillations was found to decrease with increase in viscosity of the continuous phase liquid. These oscillations were negligible for furan-glycerol system.

(e) The temperature driving force appeared to have an effect on the collapse rate. At higher values of $\Delta T$, the condensation was almost instantaneous, whereas at low values of $\Delta T$ ($< 2.5^\circ C$), condensation was negligible.

Having visualised proper configuration of the two-phase bubble, an analytical model based on quasi-steady state and potential flow with perturbations has been developed (Chapter-6) for a bubble collapsing in an immiscible liquid at high Reynolds number. The actual heat transfer is assumed to occur at the interface of the bubble wall above the angle of separation of the boundary layer, denoted by $\beta_s$ (Fig. 6.8). This theoretical model represented by Eq. (6.59) explains the present experimental results and shows an excellent
agreement with the experimental data of Isenberg and Sideman (100), and Sideman and Hirsch (192) than their own models. The present model has also been compared with other existing models, and the results are shown in Figure 1.1 and 1.2.

This model was then modified for high viscous continuous phase medium (for Re → 1), by incorporating the transfer area correction factor. The modified analytical expression for high viscous systems (Eq. 6.62) is in good agreement with the experimental data of Higeta et al. (94). The results are exhibited in Figure 1.3.

Two semitheoretical expressions were next developed for the instantaneous velocity of a collapsing two-phase bubble (Eqs. 6.80 and 6.82). Each expression is valid for a particular Reynolds number range. These expressions predict very well the present experimental data (Chapter-7).

Using these expressions (Eqs. 6.59, 6.62, 6.96 and 6.98) for heat transfer coefficient, and instantaneous velocity, corresponding expressions were next derived for the collapse rate (Eqs. 6.89 and 6.90) and total time of condensation (Eqs. 6.96 and 6.98). These expressions predict reasonably well, the present
experimental data than other existing models (99, 103, 194) (Figs. 7.6 to 7.10).
System: Pentane - Aq Glycerol (70%)  

- Exptl data (100) 
- $D_0 = 5.84$ (mm) 
- $\Delta T = 5.13^\circ$C

**FIG 11** Comparison of predicted heat transfer coefficient with experimental data of Isenberg and Sideman (100)
System: Iso-Pentane - water

- Exp. data (192)
- \( D_0 = 4.6 \) (mm)
- \( \Delta T = 3.6^\circ C \)

**FIG 1.2** Comparison of Predicted heat transfer coefficient with experimental data of Sideman and Hirsch (192)
System = Pentane - Glycerol (100%)  

$D_e = 9.6$ mm  
$\Delta T = 4.15^\circ C$

**FIG 1.3** Comparison of predicted heat transfer coefficient with experimental data of Higeta et al. (94)