

## VAPOUR GENERATION FROM THE IMPELLERS IN BOILING STIRRED TANK REACTORS

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**Abstract.** The vapour generation in a boiling stirred tank was examined using a 0.2 m i.d. stirred tank with the 3kW electric heater and multiple-impeller systems. Dual and triple of six-flat blade disk turbines, four-pitched blade downflow disk turbines and six-concave blade disk turbines were used. At higher impeller speeds, rather large cavitations were formed behind the impeller blades and most vapour was generated from the top impeller rather than the lower impellers and the heater. With an increase in superficial vapour flow rate, the power consumption decreased. Although the vapour hold-up in the boiling systems continuously increased with increased power consumption or impeller speed, they were considerably smaller than those in the cold gas-sparged systems. We measured the liquid temperatures near the heater, the impeller blades and free surface. The temperatures decreased with increasing impeller speed. It was found that the difference between the vapour pressure near the heater under no impeller mixing condition ( $p_r$ ) and that near the vapour generation site based on the measured local temperature ( $p_0$ ) has a dependence on impeller speed  $N$  ( $(p_r - p_0) \propto N^{0.2}$ ).

**Key words:** boiling, vapour generation, stirred tank reactor, local liquid temperature

### 1. INTRODUCTION

There are many chemical processes in which considerable vapour evolution occurs in mechanically stirred tank reactors [1-2]. In a boiling reactor the reaction heat is often removed by condensation of an evaporating reaction mixture. However, very little information is available on the boil-off stirred tank reactors. The phenomena in boiling stirred tanks are quite different from those in cold gas-dispersing stirred tanks [2]. Smith and co-workers [3-6] and we [7-9] have studied mixing in stirred tanks with boiling liquids. It has been observed that rather large cavitations were formed behind the impeller blades and most vapour was generated from the impeller rather than the heater at higher impeller speeds. The most important factor responsible for the vapour generation from the impellers in boiling stirred tanks is local liquid temperature and vapour pressure. To our best knowledge, however, little published work is available on the mechanism of vapour generation in the boiling stirred tanks. The local liquid temperatures in a boiling stirred tank are not published in the open literature. It is desirable to provide quantitative information about liquid temperature near nucleation sites. The objective of this study is to examine vapour generation in boiling systems. We measured local liquid temperatures in the boiling stirred tank and examined the change in the nucleation site. The present results will have significant implications for elucidating the nucleation in the boil-off stirred tank reactor.

### 2. EXPERIMENTAL

The experimental set-up is shown schematically in Fig. 1. All experiments were carried out in the 0.20 m i.d. mechanically stirred tank constructed in plexiglass. The working volume was 12.6 L. The stirred tank was fitted with four baffles having width 1/10th that of the tank diameter and a dished bottom. The tank top was closed with a flat stainless steel plate and insulated using glass wool.

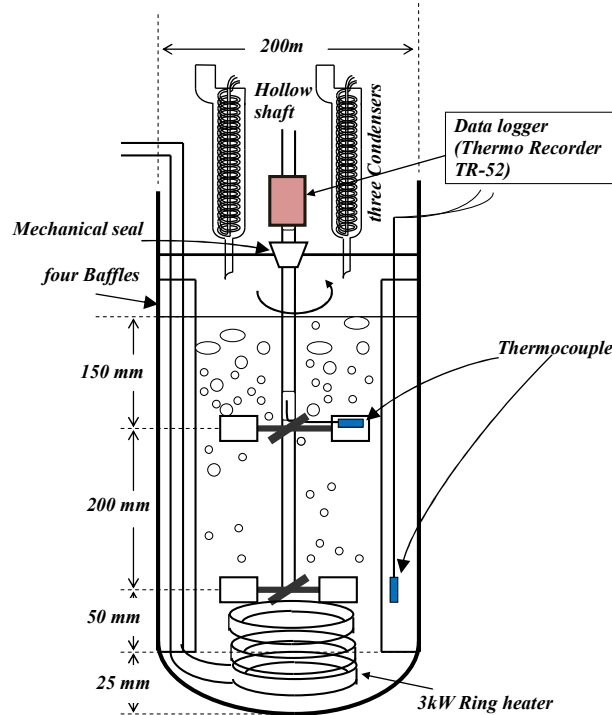


Fig. 1 A schematic of the experimental set-up (dual four-pitched blade turbine disk impeller system)

A mechanical seal was used to the impeller shaft at the top plate. Three coil heat exchangers were installed to condense the boil-off vapour generated in the stirred tank. A ring heater of 3.0 kW on full power was mounted close to the bottom of the stirred tank. The ring diameter of the heater was 0.152 m. Using thermometers (Thermo Recorder TR-52, T&D Co.) the liquid temperatures near the free-surface, the impellers and the electric heater were measured within 0.1K. The measured temperatures were determined by averaging the twenty measurements during 10 min. A thermocouple connected to a portable data acquisition unit was used to measure the temperature of the liquid-phase in the tank. The small data logger was mounted on the shaft and rotated with the impeller. It was experimentally verified that the rotation of the data logger did not affect temperature measurements. The thermocouple was passed through the hollow impeller shaft and its top was attached to the back of one blade to measure the liquid temperature near the impellers. This allowed measurement of the liquid temperature immediately adjacent to the impeller. Multiple impeller configurations which consists of six-flat blade disk turbines (Rushton turbine; DT) having diameter ( $D$ ) of 0.08 m (blade height is 0.02 m, blade width is 0.02 m, disk diameter is 0.06 m), four-pitched blade downflow disk turbines (PDT) having diameter of 0.08 m (blade height is 0.02 m, blade width is 0.015 m, disk diameter is 0.06 m) or six-concave blade disk turbines (CD) having diameter of 0.07 m (blade height is 0.02 m, blade width is 0.015 m, disk diameter is 0.06 m) [3] were used. The bottom impeller was mounted at 0.05 m above the T.L. (the transition point from the curved bottom to the vertical wall). For dual impeller systems, the spacings between the impellers and that between the top impeller and the clear liquid surface were 0.20 m and 0.15 m, respectively. For triple impeller configurations they were 0.15 m and 0.05 m, respectively.

The impeller speed changed by means of a variable-frequency drive,  $N$ , and vapour generation rate controlled by the change in ampere to the ring heater,  $U_g$ , were varied in the range 0 to  $17.9 \text{ s}^{-1}$  and  $0.23$  to  $0.50 \text{ mLs}^{-1}$ , respectively. Tap water was used as the liquid-phase. The vapour generation rates determined experimentally by weighing the condensed vapour were almost independent on impeller speed [7]. Power consumption was measured using a torque meter (Three-One Motor RX, Shinnto Sci. Co.). Fractional vapour hold-up was estimated by the simple liquid height expansion technique.

### 3. RESULTS AND DISCUSSION

#### 3.1 Power consumption

Power consumption is an integral and important quantity in mixing processes. Fig.2 shows the variation of power consumption ratio,  $P/P_0$  with respect to the impeller speed,  $N$ . The power consumptions for single-phase systems,  $P_0$ , were measured at  $368.2\text{K}$  where no nucleation was observed. With an increase in superficial vapour flow rate,  $U_g$ , the power consumption ratio decreased. The power consumptions in the boiling systems for the Rushton turbine and pitched blade turbine impellers reduced to about 40% of those without boiling or vapour. With vapour generation the mechanical power consumption decreased due to the formation of cavity behind the impeller blades. Nucleation mainly occurred at the impeller instead of the heater at higher impeller speeds, whereas vapour was mainly generated from the heater at lower impeller speeds. In a low-pressure region behind the impeller blades generated by the impeller rotation vapour generated at the impellers and heater was accumulated and cavities were developed behind the blades. This caused the reduction in mechanical power consumption. As represented in Fig.2 the concave blade turbine impeller without vapour generation had significantly low power consumption  $P_0$  as compared with the disk turbine and pitched turbine impellers and further more the reduction in power consumption with vapour generation  $P$  was very small. This might be due to the absence of the vortices behind the blades. The concave configuration reduces flow separation and cavity formation behind the blades [3]. The change in vapour generation rate did not affect power consumption significantly in the region of  $U_g$  used in this study. This coincides with our previous results for  $U_g > 0.01 \text{ ms}^{-1}$ . The powers of triple impellers were 3/2 times that of dual impellers for all impeller configurations.

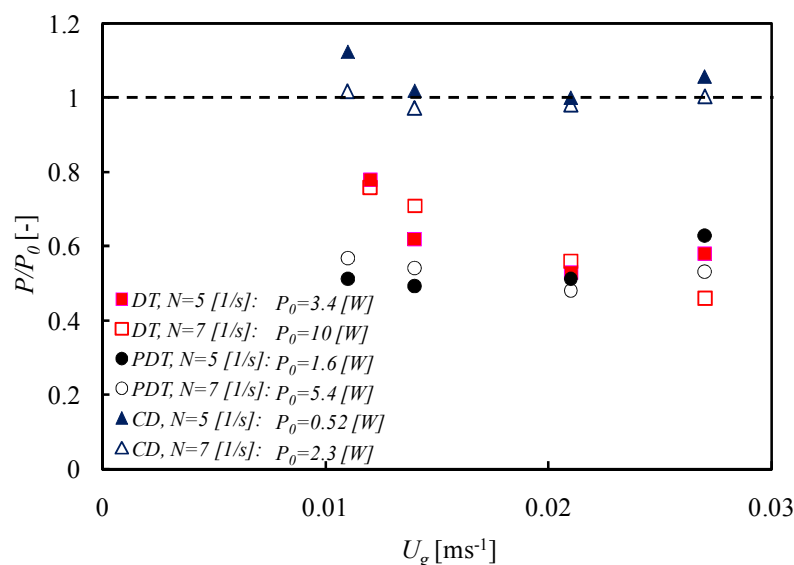


Fig.2. Power consumption (dual impeller systems)

### 3.2 Vapour hold-ups

In Fig.3 vapour hold-up,  $\varepsilon_g$ , is plotted against the power consumption,  $P$ . Although the vapour hold-up continuously increased with increased power consumption or impeller speed, the increase in vapour hold-up was insignificant at larger power consumption. The increase in the power consumption resulted in smaller bubbles formed by bubble break-up causing an increase in vapour hold-up. At higher impeller speeds, most vapour was generated from the top impeller rather than the heater and large bubbles rose upwards and escaped from the liquid surface with short residence time. This suppressed the increase in vapour hold-up with an increase in  $P$ . For reference, the predictions of Figueiredo and Calderbank [10] for cold gas-sparged systems are presented in Fig.3. It can be seen from the figure that vapour hold-ups in the boiling systems were considerably smaller than gas hold-ups in the cold gas-sparged systems. This is due to that in the boiling systems large vapour bubbles having high rising velocities were mainly generated and few small bubbles existed.

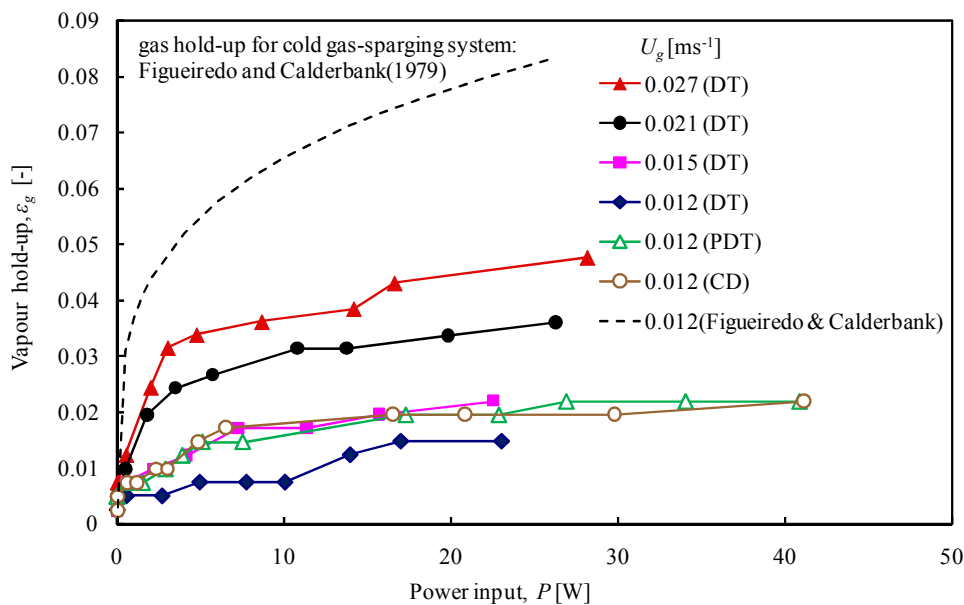


Fig.3. Vapour hold-up in the boiling stirred tank with dual impeller systems

### 3.3 Local liquid temperature

It is not as yet possible to measure the precise temperature of the exact nucleation sites. Therefore, we measured the liquid temperatures near the nucleation sites, i.e. the impeller blades and the heater. The typical local liquid temperature data for the dual Rushton impeller system are depicted in Fig.4. It can be clearly seen that the local temperatures near the free surface, top impeller and heater continuously decreased with increasing the impeller speed. Since the heat supply by the heater was constant, the decrease in the boiling temperature with impeller speed seems change the vapour generation rate. Since, however, the latent heat increases with decreasing temperature, the temperature decrease of less than 2 K does not cause the increase or decrease in the vapour generation rate. Unlike the present results, incidentally, Smith and Millington [4] found the bulk temperature was independent of the impeller speed. In boiling systems the processes of the initiation and development or collapse of vapour cavities are crucial. The impeller rotation or large centrifugal forces might generate a low-pressure region behind the impeller blades. Since the boiling temperature decreases with decreasing pressure, at a certain impeller speed the reduction in pressure was sufficient to start the nucleate boiling behind the top impeller blades instead of the heater. The vapour generation occurred exclusively from the top impeller might be attributed to the hydrostatic

pressure around it, which is lower than the hydrostatic pressures around the lower impellers and the heater. For the dual Rushton turbine system at  $U_g=0.027 \text{ ms}^{-1}$  the nucleation started from the top impeller besides the heater around  $N=5 \text{ s}^{-1}$  and vapour generation exclusively occurred from the top impeller beyond  $N=8 \text{ s}^{-1}$ . Due to the decrease in boiling temperature with a decrease in pressure the local liquid temperature in the boiling stirred tank also decreased. The change of nucleation sites was controlled by the pressure and temperature distributions in the stirred tank. By the formation of the low-pressure region behind the impeller blades the nucleation sites were shifted from the heater to the regions behind the impeller blades.

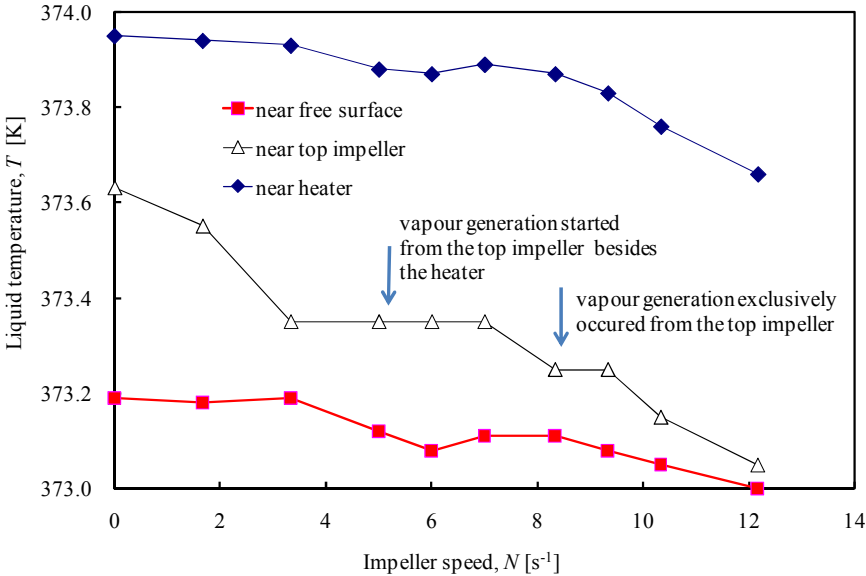


Fig.4 Changes in local liquid temperatures and nucleation site with dual Rushton turbine system at  $U_g=0.027 \text{ ms}^{-1}$

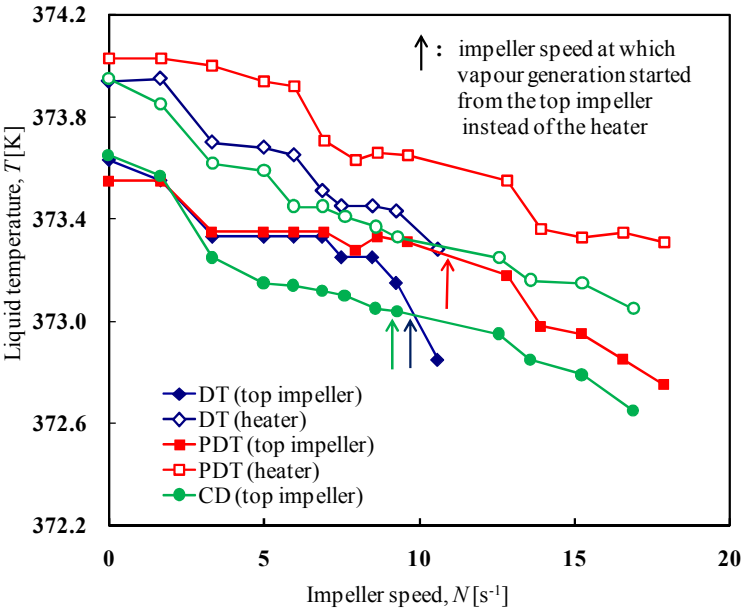


Fig.5 Changes in local liquid temperature and nucleation site with different impeller types (dual impeller systems at  $U_g=0.012 \text{ ms}^{-1}$ )

Fig.5 depicts the changes in local liquid temperature near the top impeller and heater with different impeller types. The impeller speeds at which vapour generation exclusively occurred from the top impeller were close to each other for all impeller configurations. It can be seen in Fig.5 that the shift of the nucleation site was found for the concave blade turbine impeller as well as the Rushton turbine and pitched blade turbine impellers. The concave configuration reduces flow separation and cavity formation behind the blades but does not eliminate them completely.

The most important of the thermal factors for the nucleation from the impeller is the temperature of the liquid near the impeller. The true pressure in a boiling cavity will be very close to the vapour pressure of the liquid around it. Therefore, we have examined to correlate the local liquid temperature data as the corresponding vapour pressure against the liquid phase mixing intensity. The Cavitation number,  $CN$ , has been widely used to examine the phenomena of cavities [3].

$$CN = \left\{ (p_L - p_B) / (\rho_L v^2 / 2) \right\} \quad (1)$$

where  $p_L$  is the local pressure at a given site,  $p_B$  is the vapour pressure of the liquid at its local temperature,  $\rho_L$  is the liquid density and  $v$  is the characteristic velocity. The Cavitation number, which is the relationship between the difference of a local absolute pressure from the vapour pressure and the kinetic energy per volume, characterizes the potential of the liquid to cavitation. In a stirred tank, the low pressure regions are formed as the liquid accelerates around and moves past the blades. The faster the blades move, the lower the pressure around it can become. As it reaches vapour pressure, the liquid vaporizes and forms vapour bubbles. It should be noted that vapour generation can initiate explosively from liquid that is locally superheated. The cavitation is defined as the phenomenon of formation of vapour bubbles of a flowing liquid in a region where the pressure of the liquid falls below its vapour pressure. We modified the Cavitation number to consider the vapour generation from the impellers besides the heater in a boiling stirred tank as:

$$CN^* = (p_r - p_o) / \left\{ \rho_L (DN)^2 \right\} \quad (2)$$

where  $p_r$  is the vapour pressure at the liquid temperature near the heater with  $N=0 \text{ s}^{-1}$ , which characterizes the vapour pressure at the nucleation site on the heater. In other words, this vapour pressure based on the temperature near the heater is an indirect index for the nucleation from the heater under no impeller mixing or is a characteristic maximum vapour pressure corresponding to the nucleation site. The vapour pressure at the liquid temperature near the impeller  $p_o$  is a characteristic vapour pressure at the nucleation site behind the impeller blades. We selected the vapour pressure at the liquid temperature near the heater with  $N=0 \text{ s}^{-1}$  as the reference pressure because it is the corresponding vapour pressure occurred cavitation at the heater where is the original nucleation site under no mixing condition. Since the extent of pressure reduction depends on the kinetic head  $(\pi DN)^2 / 2$  [11], the denominator of Eq.(2) is reasonable for the cavitation in a boiling stirred tank. The vapour pressure  $p$  at the liquids having the measured temperature  $T$  can be calculated by Antoine's equation:

$$\ln p = a - b / (T + c) \quad (3)$$

where  $a=23.1964$ ,  $b=3816.44$  and  $c=-46.13$  for water [12].

For the experiments, as shown in Figs 5 and 6, the correlation found to fit the data for all impeller configurations well is:

$$CN^* = 4.05Fr^{-0.88} \quad (4)$$

where  $Fr=N^2D/g$ . Eq.(4) could unified the data for dual and triple impeller systems with three different impeller types. The correlation indicates that the difference between the vapour pressure near the heater under no impeller mixing condition ( $p_r$ ) and that near the vapour generation site based on the measured local temperature ( $p_0$ ) is proportional to  $N^{0.2}$ .

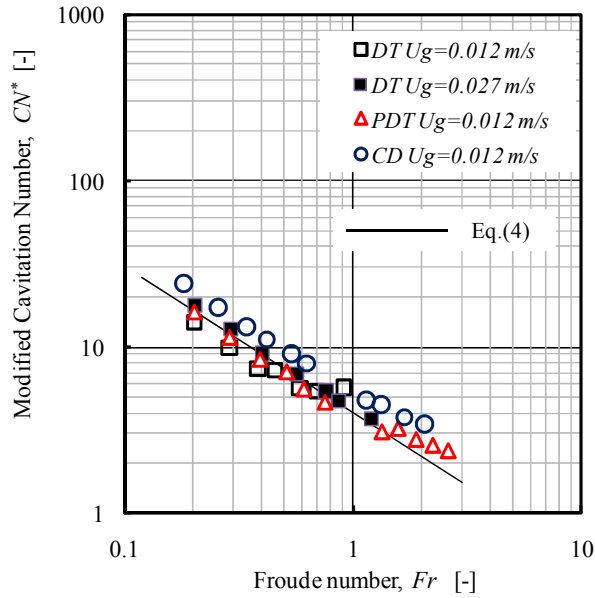


Fig.6 Modified Cavitation number near the top impeller with Froude number (dual impeller systems)

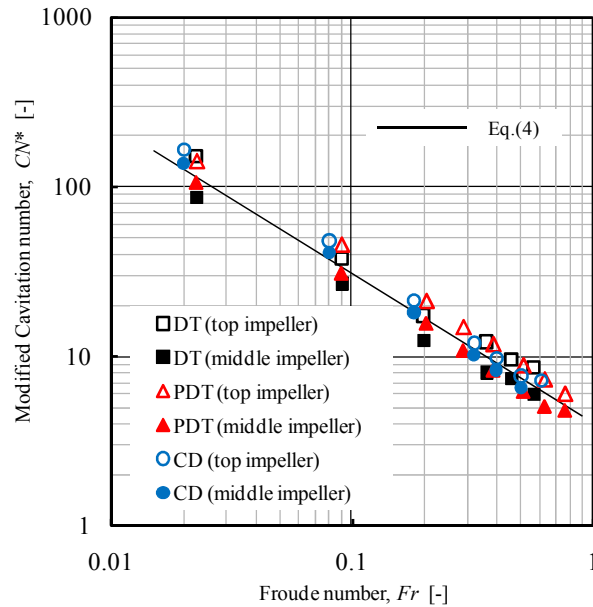


Fig.7 Modified Cavitation number near the impellers with Froude number (triple impeller systems at  $U_g=0.012$  ms<sup>-1</sup>)

The location of vapour generation may be dependent on the temperature homogeneity in the liquid which is strongly affected by the impeller design and impeller speed. It should be noted, furthermore, that the operating pressure may influence the shift of the nucleation site.

## 4. CONCLUSIONS

It was observed that vapour was generated from the impeller besides the heater at higher impeller speeds. Rather large cavitations were formed behind the impeller blades and most vapour was generated from the top impeller rather than the heater. The mechanical power consumption decreased due to vapour generation. The increase in the power consumption resulted in smaller bubbles formed by bubble break-up causing an increase in vapour hold-up. At higher impeller speeds, most vapour was generated from the top impeller rather than the heater and large bubbles rose upwards and escaped from the liquid surface with short residence time. This suppressed the increase in gas hold-up with an increase in the power consumption. We measured the liquid temperatures near the heater, the impeller blades and free surface. The liquid temperatures continuously decreased with increasing impeller speed. By the generation of the low pressure region behind the blades, the nucleation sites shifted from the heater to the impellers and the boiling temperature and then the liquid temperature decreased with an increase in impeller speed. The measured local liquid temperatures near the impeller blades responsible for the vapour generation in the stirred tank were correlated as the corresponding vapour pressures against the liquid phase mixing intensity. The single dimensionless correlation based on the Cavitation number could unify the data for dual and triple impeller systems with three different impeller types. The difference between the vapour pressure near the heater under no impeller mixing condition and that near the vapour generation site was found to be proportional to  $N^{0.2}$ . For more detailed and precise discussion, it is highly desirable to make measurements of temperatures or vapour pressures at nucleation sites in larger stirred tanks.

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