CHAPTER 3

POOL BOILING HEAT TRANSFER ON A PLAIN SURFACE

In this chapter, results from the experimental data are presented to illustrate the characteristics of saturated pool boiling heat transfer for dielectric fluid FC-72 on a plain surface. Specifically, the data for the boiling incipience superheat, CHF value, saturated boiling heat transfer coefficient affected by the test runs and orientation are examined in detail. In present study the system pressure is setting at 1 atm corresponding to the saturated temperature of 56.6℃. Moreover, the test results are compared with the empirical correlations of reference literatures to verify the accuracy of present pool boiling experiment. This boiling heat transfer results for FC-72 on a plain surface can be used not only in comparison with those on finned surfaces but also in analysis of the basic boiling heat transfer mechanism on finned surfaces.

3.1 Verify with Empirical Correlations

The test results for a plain surface in present study were compared with the well-know plain configuration and those predicted by Cooper [57]. The Cooper's correlation is given as

$$h_o = 55(q'')^{0.67} M^{-0.5} \Pr^{m}(-\log_{10}(\Pr^{-0.55})) \tag{3-1}$$

$$m = 0.12 - 0.2\log_{10} R_a \tag{3-2}$$

The atomic force microscope (AFM) images of plain test surface are shown in Figure 3.1. Figure 3.1 shows a comparison of 5 measured surface roughness on different locations of plain test surface respectively and data show that roughness is range of 0.3~0.5μm. Therefore, the surface roughness, R_a, is given as average value of 0.4μm in the this calculation. The surface roughness, R_a, only slightly affects the rate of heat transfer, as demonstrated by Cooper [57]. Predictions using the Cooper correlation typically are fairly consistent with data herein. Figure 3.2 reveals that the test data are within –30/+30% of the results obtained by using Cooper correlation. The experimental data indicated that for q''_b>3×10^4 Wm^{-2} the data by the Cooper correlation over-predict the present test results. This is attributed to the Cooper correlation with a fixed exponent (0.67) on heat flux.

In order to check the suitability of experimental facility for pool boiling heat transfer at vertical orientation, the plain surface boiling heat transfer data were measured and compared with modified Rohsenow's correlation proposed by Priarone [63]. The modified Rohsenow's correlation is given as

$$\frac{Cp_l \Delta T_{sat}}{i_{lv}} = C_{sf}\left[\frac{q''}{\mu_l i_{lv}}\sqrt{\left(\frac{\sigma}{g(\rho_l-\rho_v)}\right)}\right]^r \left(\frac{Cp_l \mu_l}{k_l}\right)^s \tag{3-3}$$

By setting the exponent s at 1.7, for the vertical plane copper surface boiling in saturated FC-72, they obtained r =0.32 and C_{sf} =0.00397. The results of the vertical plain surface are plotted in Figure 3.3. It is clear from the Figure 3.3 that the nucleate boiling data are within 35% of correlation.

3.2 The Effects of the Test Runs on Boiling Heat Transfer Performance

One of the difficulties associated with the use of dielectric liquids with a high wetting ability is a high wall superheat required for boiling incipience. You et al. [64] studied the boiling incipience superheat of R-113 on smooth surfaces. The boiling incipience superheat was highly non-repeatable and the data was best presented in a statistical form. However, Honda found that the boiling incipience superheat will be stable after 3 test runs with 12 hour non-boiling time. The effect of number of test times on boiling heat transfer performance of plain surface is analyzed in the present experiment. The detailed test process is described in the previous chapter. In present work, the test surface is keeping inside the vessel without removing from the working fluid between two successive test run to avoid the oxidation and particle trap mentioned previously. The boiling curves of three test runs of horizontal plain surface, as illustrated in Figure 3.4, begin with the heating process from zero heat flux, then enter the single-phase natural convection region, and complete with the fully nucleate boiling state. The last two test runs shown in Figure 3.4 are 24 and 48 hours behind the first one respectively. In natural convection region, the plots indicate no difference among three test runs except boiling incipience superheat. The boiling incipience superheat and temperature excursion change according to the test run. These differences are reduced when the level of heat flux increases, apparently disappear when the boiling is fully developed.

The plots illustrate extreme high boiling incipience superheat (27.3K) and significant temperature excursion (19.2K) in the first test run but shrink in the last two test runs. High boiling incipience superheat and significant temperature excursion of the first test run can be ascribed to low nucleate cavity density on a new clean surface with high polished treatment. Moreover, small contact angle between the solid heating surface as well as the dielectric fluid and low surface tension of dielectric fluid also result in poor gas trapped inside cavities during wetting process. Hence, the liquid above the heating surface needs higher temperature (more energy) to reach boiling. The boiling incipience superheat value in present study is seen to fit the range of 25-40K as reported by Chang and You [60] for their 10mm╳10mm non-porous coating plain surface. Comparing with the result of first test run, the last two test runs exhibit a dramatic decrease in boiling incipience superheat (15.0 and 13.4K) and temperature excursion (6.0 and 6.9K) respectively. It is also observed that an slightly increase in boiling heat transfer performance (about 40 to 48%) in moderate nucleate boiling heat flux region of the last two test runs. The lower boiling incipience superheat and enhancement in heat transfer can be ascribed to the increasing number of nucleate sites already activated by the first test run. However, Figure 3.4 reveals that the boiling curves in the moderate and high heat flux region are virtually the same which indicate that the heat transfer characteristics in the moderate and the high heat flux nucleate boiling regime are not affected by test run times substantially. The CHF values of last two test run range from 19.0 to 19.5 Wcm^{-2} which are slightly higher than that of the first test run of 18.0 Wcm^{-2}. In comparison, Zuber's[11] correlation given by:

$$q''_{Z,CHF} = \frac{\pi}{24} i_{lv} \rho_v^{0.5} [g\sigma(\rho_l - \rho_v)]^{0.25} \tag{3-4}$$

predicts $q''_{Z,CHF}$ =15.1 Wcm^{-2} for saturated FC-72.

3.3 Orientation Effects on Boiling Heat Transfer performance

As shown in Figure 3.5 (a), (b), and (c), the flow pattern observations show that the departing bubbles from the horizontal upward-facing surface can detach and rise vertically without any obstruction. At low heat fluxes, small rarefied bubbles are formed on the surface and immediately detached by buoyancy forces. As heat flux increases, the bubbles become bigger and more densely cluster on the surface and move turbulently. For the test surface at vertical orientation, as shown in Figure 3.6 (a), (b), and (c), bubble movement is no longer directly detach from the heating surface. Consequently, the bubbles remain in the thermal boundary layer on the vertical surface, thereby increase agitation in the thermal boundary layer.

The relationship between heat flux and wall superheat for horizontal and vertical orientation are plotted in Figure 3.7. Comparison of the two curves reveals the effect of orientation on boiling heat transfer performance. As shown in Figure 3.7, the boiling curves can be subdivided into different regions: low heat fluxes (up to 9.7 Wcm^{-2}, about 54% of CHF) and high heat fluxes (greater than 9.7 Wcm^{-2}). In low heat fluxes region, orientation exerts a noticeable influence: a greater heat flux is transferred at the same wall superheat on vertical surface than that on horizontal surface. Similar behavior is reported by Nishikawa et al. [6] and El-Genk et al. [65]. This is attributed to that superior heat transfer mechanism in low heat flux region is the sensible heat transport as well as the movement of the slipping bubbles along the vertical surface disturb the superheated thermal layer and hence enhance heat transfer. Moreover, the movement of the slipping bubbles also activates more nucleate sites on its flow path. For high heat flux region, on the other hand, a different trend is seen that a lower heat flux is transferred at the same wall superheat on vertical surface. This is attributed to the growing accumulation and coalescence of departing vapor bubbles which in turn blanket the heating surface and obstruct the boiling heat transfer rate. The experimental results in present study confirm the behavior observed by Chang and You [60] for FC-72 and by El-Genk et al. [65] for HFE-7100.

The results of CHF value are also compared with the empirical CHF orientation correlation developed by Chang and You [60]. The correlation is given by:

$$q''_{p,CHF,\theta} / q''_{p,CHF,0^\circ} = 1.0 - 0.0012 \cdot \theta \cdot \tan(0.414\theta) - 0.122 \cdot \sin(0.318 \cdot \theta) \qquad (3\text{-}5)$$

The experimental result of CHF in present experiments $q''_{p.CHF,90^\circ} / q''_{p,CHF,0^\circ} = 0.8$ which is almost the value as compared in above equation $q''_{p,CHF,90^o} / q''_{p,CHF,0^\circ} = 0.88$.

3.4 Concluding Remarks

An experimental investigation of pool boiling phenomena for plain surface immersed in saturated FC-72 at atmospheric pressure is described in this chapter. The effects of test runs and orientation on the nucleate boiling heat transfer performance are also reported. Analysis of the experimental results leads to the following conclusions:

1. The test results of plain surfaces in both orientations are compared with the empirical correlations of reference literatures to verify the accuracy of present pool boiling experiment.
2. The test results indicate a higher boiling incipience superheat, temperature excursion and a lower CHF value for a new plain surface at the first test run and slightly improve at the last two test runs.
3. The nucleate boiling curves based on horizontal and vertical orientation can be subdivided into the different regions: low heat flux (up to 9.7 Wcm^{-2}) and high heat flux (greater than 9.7 Wcm^{-2}) regions which are consistent with the results of literature.
4. In low heat flux region, the nucleate boiling heat transfer performance of plain surface in

vertical orientation is found better than those on horizontal orientation due to the facilitating convective heat transfer by the drift movement of bubbles along the vertical surface. However, in high heat flux region, vapor bubble departure behaviors obstruct the heat transfer and result in worse boiling and CHF performance.

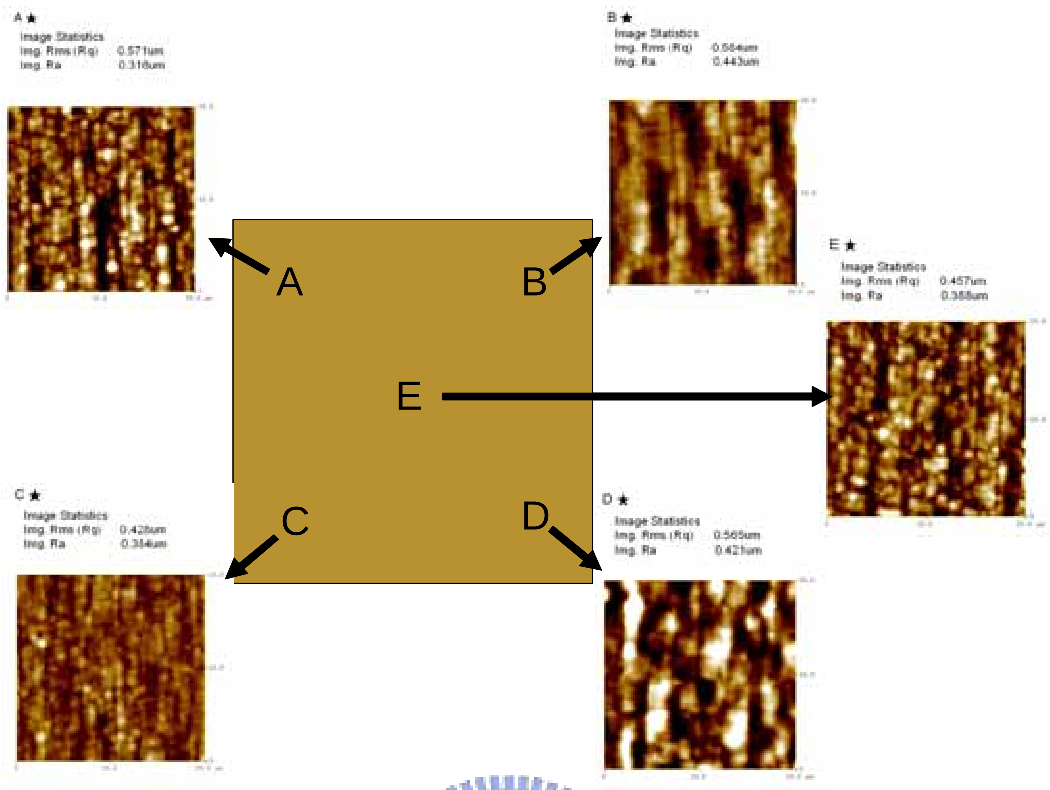


Figure 3.1 The plain surface roughness measurement by AFM.

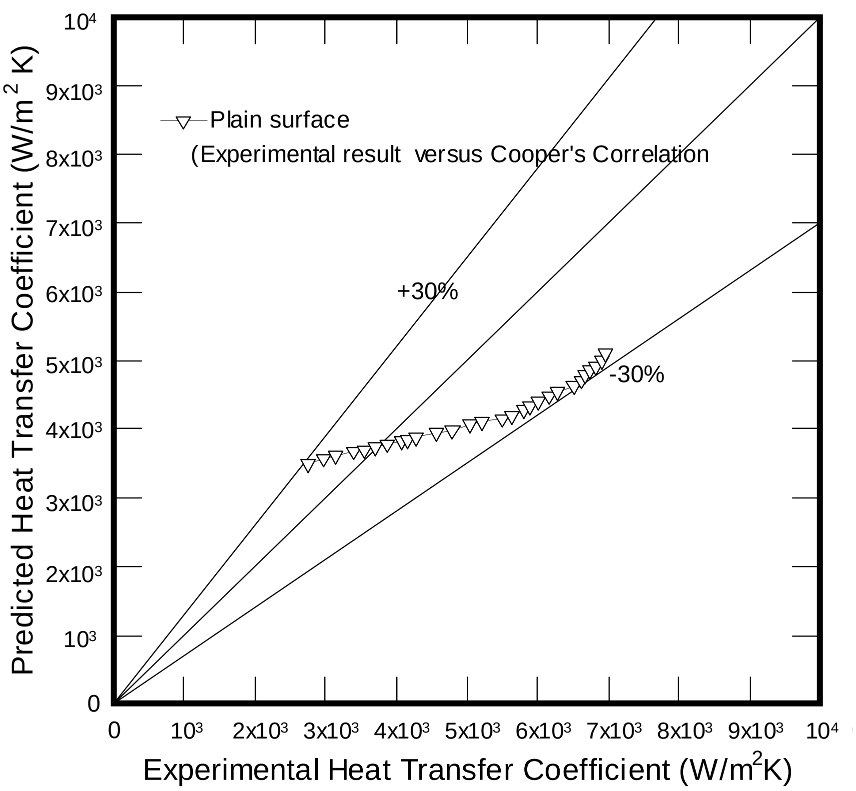


Figure 3.2 Experimental result of plain surface versus Cooper's correlation.

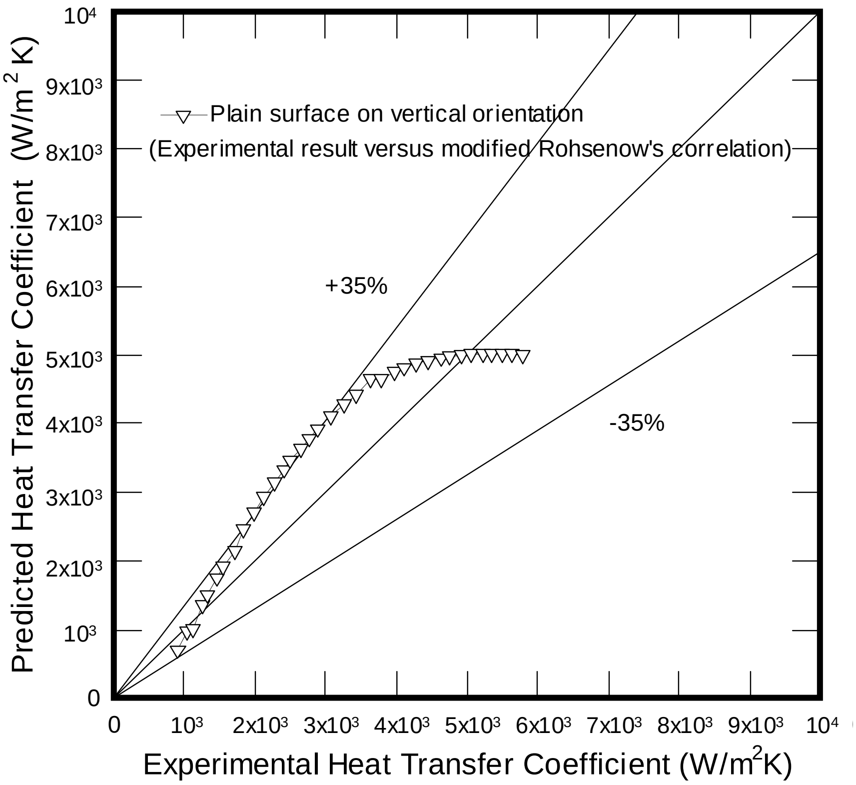


Figure 3.3 Experimental result of plain surface versus modified Rohsenow's correlation[63].

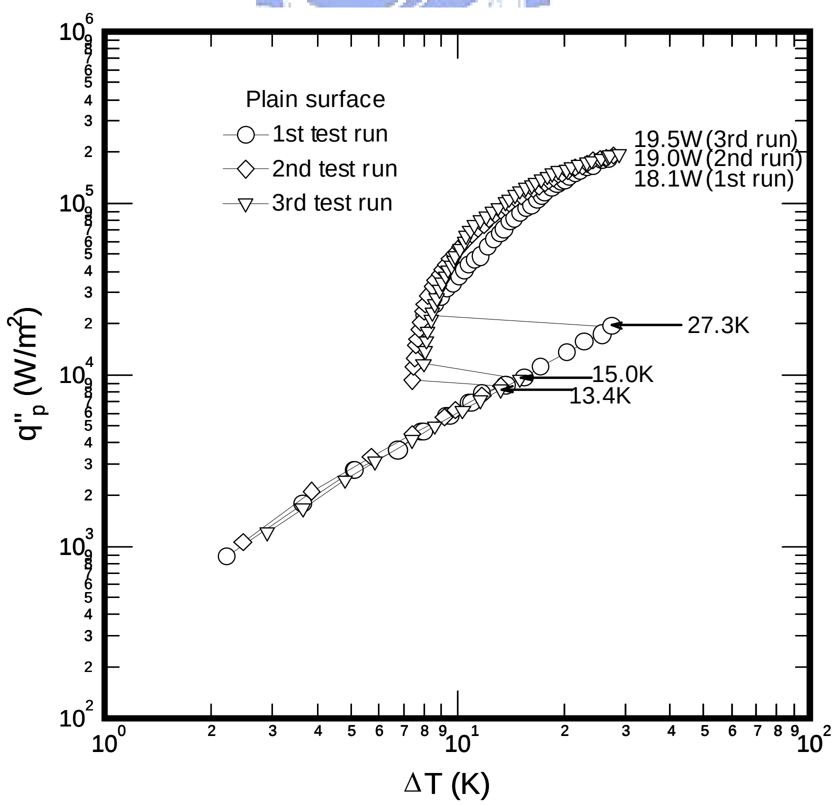
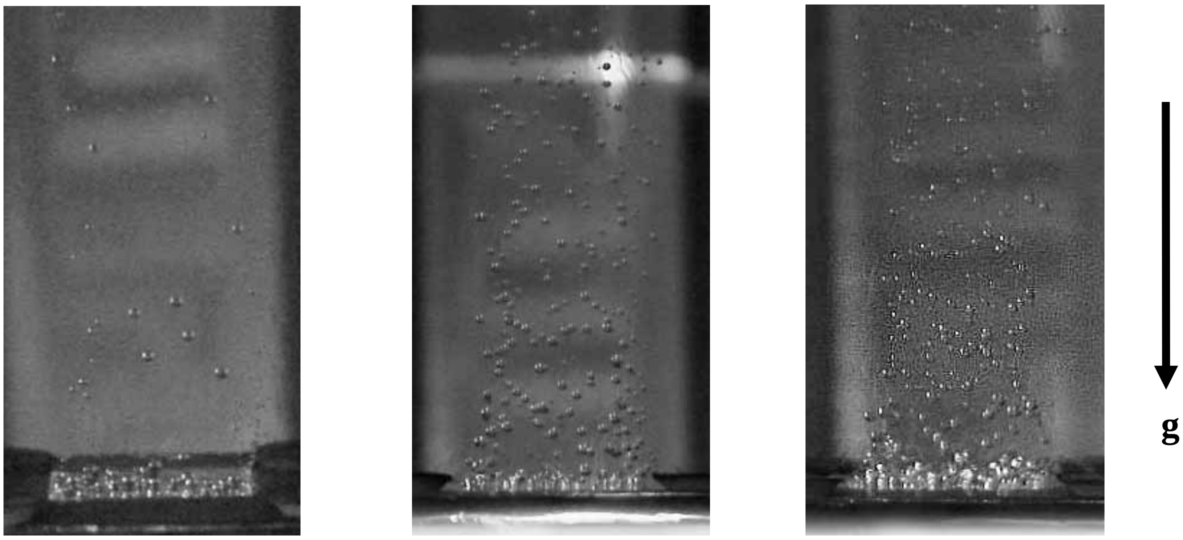
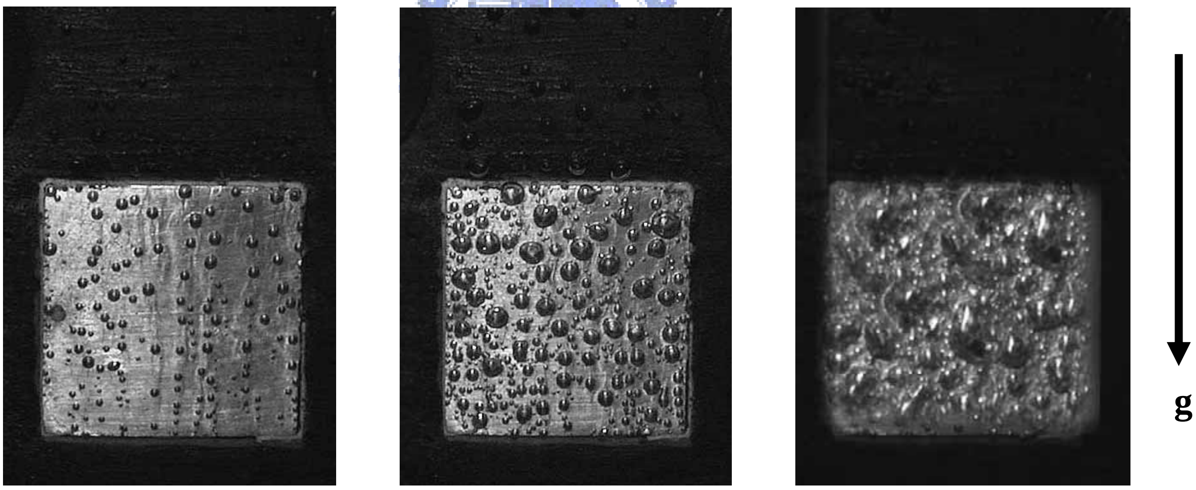


Figure 3.4 Boiling curves of horizontal plain surface with various test runs.



(a) 12% of CHF (b) 36% of CHF (c) 73% of CHF

Figure 3.5 Flow patterns of plain surface at horizontal orientation.



(a) 9% of CHF (b) 34% of CHF (c) 79% of CHF

Figure 3.6 Flow patterns of plain surface at vertical orientation.

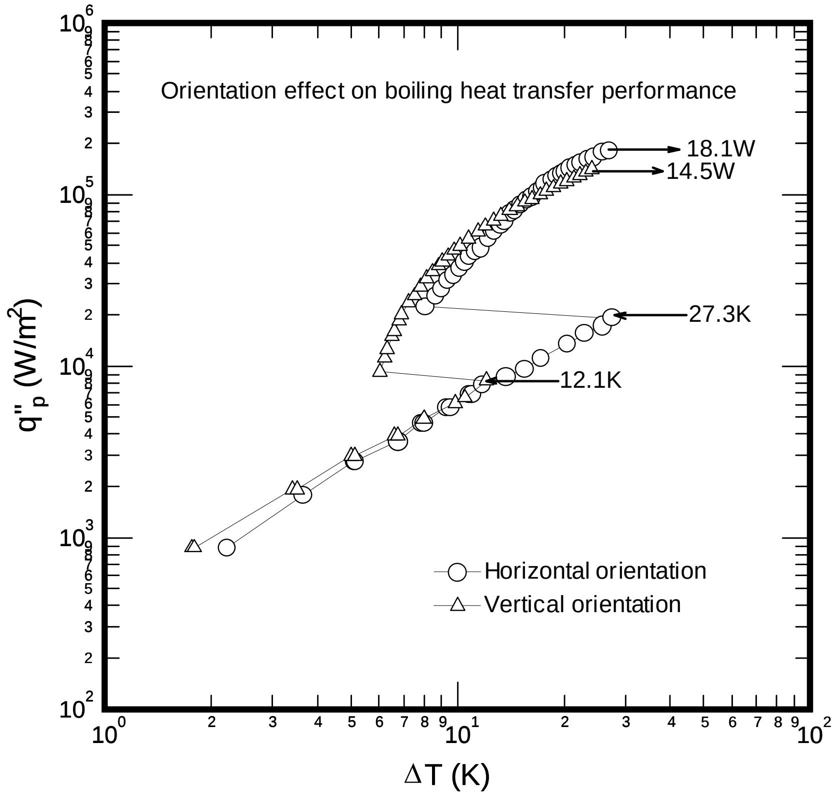


Figure 3.7 Orientation effect on boiling heat transfer performance.