Results and Discussion



Figure 1. Droplet cap surface temperature and base surface temperature on 40 °C, 60 °C and 80 °C substrate

In figure 1 we show the calculating results of droplet cap surface temperature predicted by the thermal circuit model and experimental results of droplet cap surface temperature tested by the IR camera with nondimensional time (defined as the ratio of evaporation time and the total evaporation time). The predicted cap surface temperatures match well with the experimental data for substrate temperatures from 40 °C to 80 °C. It is observed that there is a large mismatch between the droplet cap surface temperature and the substrate temperature. This is because of the evaporative cooling of the droplet cap surface, which has been discussed by Dash et al. []. During the evaporation at the constant substrate temperature, it is observed that the surface temperature increases in the CCR mode and the surface temperature keeps almost constant in the CCA mode. Same observation was demonstrated by Saenz et al. [] in their numerical simulations. During the CCR mode, the droplet cap surface gets close to the substrate surface because of the decrease of the droplet volume. As a result, the temperature of the cap surface increases to approach the substrate temperature. During the CCA mode, decrease of the contact area causes less heat transfer into the droplet, which slows down the temperature increase of droplet cap surface and thus the surface temperature keeps unchanged. In figure 1, We also show the calculating results of the droplet base surface temperature. There is also a large temperature mismatch between the droplet base temperature and the substrate temperature. That temperature difference is caused by the evaporative cooling at the droplet base. The temperature differences are about 1.5 °C, 4 °C and 6 °C for droplet evaporation on micropillar substrates with temperature 40 °C, 60 °C and 80 °C respectively.



Figure 2. Droplet evaporation rate on hot substrate

In figure 2 we show the total evaporation rate, cap surface evaporation rate and base evaporation rate of droplet on substrates with different temperatures. Droplet evaporation rates (total, droplet cap surface and droplet base) decrease during the evaporation. It is observed that the decrease rate of evaporation rate from the droplet cap surface (red line) is slow. The decrease of the evaporation rate from the droplet cap surface is due to the decrease of the droplet contact angle. The decrease of droplet evaporation rate means less heat is transferred from the substrate into the droplet. During the CCR mode, the contact area between the droplet and the substrate keeps constant and the thermal resistances between the droplet base and the substrate is also unchanged. Thus, the temperature difference between the substrate and the droplet base will decrease and the droplet base temperature will increase. The increase of the droplet base temperature is shown in figure 1. The increase of the droplet base temperature causes the increase of the droplet cap surface temperature which leads to the increase of the evaporation rate from the droplet cap surface. The effect of increasing cap surface temperature mitigates the effect of decreasing contact angle on the droplet cap surface evaporation rate. As a result, the evaporation rate from the droplet cap surface in the CCR mode decreases very slowly. In the CCA mode, both the evaporation rates at the droplet cap surface and the base surface decrease while the decreasing rate of the droplet cap surface evaporation rate is larger than that at the droplet base surface in contrast to the changes in the CCR mode. The decrease of the contact radius causes the decrease of evaporation rate droplet cap surface. Different from the temperature increase in the CCR mode, the droplet cap surface temperature keeps essentially constant in the CCA mode, which will not mitigate the decrease of evaporation rate. Thus, the decreasing rate of the droplet cap surface evaporation rate is large. During the evaporation, the confined space will cause an increase of relative humidity in the vapor cavities between the droplet base and the substrate. The increase of the relative humidity results in the decrease of evaporation rate at the droplet base during the evaporation. In summary, the total evaporation rate of the droplet decreases during the evaporation. In the CCR mode, the decrease of total evaporation rate is mainly caused by the decrease of droplet base surface evaporation rate. In the CCA mode, the decrease of total evaporation rate is mainly caused by the decrease of droplet cap surface evaporation rate.

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Figure 3. Evaporation ratio from droplet base

In figure 3, we show the variation of evaporation ratio *φ* from the droplet base with nondimensional time. The evaporation ratio *φ* increases with the substrate temperature for droplets with large volume (larger than 1.5 μL). The increase of substrate temperature will cause a direct temperature increase of the droplet base surface and the temperature increase of the droplet base surface will then cause the temperature increase of the droplet cap surface. Due to the thermal resistance in the droplet bulk, the temperature increase of the droplet cap surface is smaller than that at the droplet base with the increase of the substrate temperature. Thus, the substrate temperature increase leads to a higher evaporation rate increase at the droplet base surface for large volume droplet. As a result, the evaporation ratio *φ* increase with the rise of the substrate temperature for droplet with large droplet volume. For droplets with small volume (smaller than 1.5 μL), the evaporation ratio *φ* decreases with the increase of the substrate temperature. Because of the small volume, the thermal resistance of the droplet bulk is small and the increase of the substrate temperature will cause a higher temperature increase at droplet cap surface for droplets with small volume. Thus, the increase of the substrate temperature causes a higher evaporation rate increase than at the droplet base surface for droplets with smaller volume. As a result, the evaporation ratio *φ* decreases with rise of the substrate temperature for droplet with small volume. It is observed in figure 3 that the evaporation ratio decreases in the CCR mode and increases in the CCA mode during the evaporation on a substrate with constant temperature. As we discussed above, the decrease of the total evaporation rate is manly caused by the decrease of droplet base surface evaporation rate in the CCR mode. Thus, less evaporation happens at the droplet base surface and the evaporation ratio *φ* decreases in the CCR mode. In the CCA mode, the decrease of the total evaporation rate is manly caused by the decrease of evaporation rate at the droplet cap surface. Thus, more evaporation happens at the droplet base surface and the evaporation ratio *φ* increases in the CCA mode.



Figure 4. Droplet cap surface temperature and base surface temperature on 100 °C and 120 °C substrate

The calculating results of cap surface temperature, base surface temperature and the experimental testing temperature for droplets evaporation on 100 °C and 120 °C are shown in figure 4. The substrates are heated to a high temperature over the boiling temperature of the water droplet. However, no water boiling is observed in the droplet even when the substrate temperature is about 120 °C. That is because of the effect of evaporative cooling at the droplet base. Evaporation at the droplet base surface will cool down the surface temperature and we calculate the average temperature of the droplet base surface (dash lines). For droplet evaporation on 100 °C substrate, the base surface temperature is about 88 °C and for droplet evaporation on 120 °C substrate, the base surface temperature is about 102 °C. Moreover, vapor flow underneath the droplet will further cool the droplet base surface down and the droplet base temperature always is lower than the boiling temperature. That accounts for the delay of onset boiling for droplet evaporation on heated substrate. We calculate the droplet cap surface temperatures with the same method as in low temperatures and the results are shown in figure 4 with solid lines. However, there is a large difference between the thermal circuit predicting temperatures and the experimental temperatures tested by the IR camera. That is because the effect of internal flow of the droplet evaporation on high temperature substrates. The internal flow of the droplet will promote the heat transfer inside the droplet and the actually thermal resistance of the droplet becomes smaller. To take the effect of internal flow into account, here we use the effective conductivity of water to modify the thermal circuit model when calculating the heat transfer process in the water droplet []. For evaporation on 100 °C substrate, we use an effective conductivity of water and for evaporation on 120 °C substrate we use an effective conductivity of water . The modified results (dot lines) match better with the experiment data. There will be radiative heat transfer between the heated substrate and the droplet surface which is not considered in our thermal circuit model. This radiative heat transfer accounts for the small difference between our modified temperature and the experimental data.