Chapter 3

DATA REDUCTION

The single-phase liquid convection and two-phase flow boiling heat transfer coefficients of the coolant FC-72 flowing over the silicon chip in the horizontal rectangular-channel will be deduced from the measured raw data. The data reduction procedures are described in the following.

3.1 Single-phase Heat Transfer

Before the two-phase experiments, the total heat loss of the test section is evaluated from the difference between the total power input Q_t to the silicon chip and the effective power input Q_e to the coolant flow over the chip. The total power input can be calculated from the measured voltage drop across the electric-heater and the resistance of the heater. The effective power input can be calculated from the 1-D heat conduction across the copper and mica plates sandwiched between the silicon chip and heater plate by neglecting the heat loss from the side-walls of the cooper plate.

The total power input Q_t and the effective power input Q_e are hence evaluated respectively from the equations:

$$Q_t = V \cdot I \tag{3.1}$$

where V and I are individually the voltage drop across and current through the electric-heater, and

$$Q_e = \frac{\Delta T_{c,h}}{Rt_{c,h}} \tag{3.2}$$

where $\Delta T_{c,h} = T_{heater} - T_{cop}$ is the temperature difference between the heater surface and copper plate surface, and $Rt_{c,h}\ (= Rt_{m,h} + Rt_{mica} + Rt_{c,m} + Rt_{cop} + Rt_{chip,cop})$ is the total thermal resistance from the heater surface to copper surface. Here T_{cop} is the average measured temperature at the three thermocouple locations on the lower surface of the copper plate (Fig. 2.5). Besides,

$$\left.\begin{aligned} Rt_{m,h} &= \frac{t_{t\text{-}g}}{k_{t\text{-}g} \cdot A_{t\text{-}g}} \\ Rt_{mica} &= \frac{t_{mica}}{k_{mica} \cdot A_{mica}} \\ Rt_{c,m} &= \frac{t_{t\text{-}g}}{k_{t\text{-}g} \cdot A_{t\text{-}g}} \\ Rt_{cop} &= \frac{t_{cop}}{k_{cop} \cdot A_{cop}} \\ Rt_{chip,cop} &= \frac{t_{t\text{-}g}}{k_{t\text{-}g} \cdot A_{t\text{-}g}} \end{aligned}\right\} \quad (3.3)$$

are individually the thermal resistances of the thermal-grease sandwiched between the heater and mica plate, mica plate, thermal-grease between the mica and copper plates, copper plate, and thermal-grease between the copper plate and silicon chip. Here t is the plate thickness, k is the thermal conductivity, and A is the surface area of each plate. The imposed heat flux at the chip surface is defined as

$$q'' = Q_e \,/\, A_{chip} \quad (3.4)$$

where A_{chip} is the surface area of the bare chip. The relative heat loss from the test section is defined as

$$\varepsilon = (Q_t - Q_e) \,/\, Q_t \quad (3.5)$$

The average single-phase liquid convection heat transfer coefficient over the chip is defined as

$$h_{1\phi} = \frac{Q_n}{A_{chip} \cdot (T_{chip} - T_{in})} \quad (3.6)$$

where $Q_n = Q_t \cdot (1 - \varepsilon) = Q_e$ is the net power input to the FC-72, T_{in} is the coolant temperature at the inlet of the test section, and T_{chip} is the average temperature of the chip surface which is estimated from T_{cop} by accounting for the 1-D heat conduction across the chip.

3.2 Two-phase Flow Boiling Heat Transfer

In the subcooled flow boiling experiment the state of coolant FC-72 at the inlet of the rectangular flow-channel is evaluated from the energy balance for the pre-heater. The total heat transfer rate in the pre-heater is calculated from the temperature drop on the water side as

$$Q_{w,p} = \dot{m}_{w,p} \cdot c_{p,w} \cdot (T_{w,p,i} - T_{w,p,o}) \tag{3.9}$$

where $\dot{m}_{w,p}$ is the mass flow rate of the water in the pre-heater, $c_{p,w}$ is the specific heat of water, and $T_{w,p,i}$ and $T_{w,p,o}$ are respectively the temperatures of the water at the pre-heater inlet and outlet. Note that in the pre-heater the coolant FC-72 is still in liquid state. Hence on the coolant side in the pre-heater

$$Q_{w,p} = \dot{m}_r \cdot c_{p,r} \cdot (T_{r,p,o} - T_{r,p,i}) \tag{3.10}$$

where $\dot{m}_r$ is the mass flow rate of the coolant in the pre-heater, $c_{p,r}$ is the specific heat of coolant, and $T_{r,p,o}$ and $T_{r,p,i}$ are the temperatures of the coolant at the pre-heater outlet and inlet, respectively. Combining the above two equations allows us to calculate $T_{r,p,o}$, which is considered as the temperature of FC-72 at the test section inlet. On the other hand, the average two-phase heat transfer coefficient for the coolant flow over the silicon chip is defined as

$$h_{2\phi,sat} = \frac{Q_n}{A_{chip} \cdot (T_{chip} - T_{sat})} \quad \text{for saturated flow boiling,} \tag{3.11}$$

and

$$h_{2\phi,sub} = \frac{Q_n}{A_{chip} \cdot (T_{chip} - T_{r,bulk})} \quad \text{for subcooled flow boiling} \tag{3.12}$$

where T_{sat} and $T_{r,bulk}$ are individually the saturated and bulk temperature of the coolant FC-72.

3.3 Uncertainty Analysis

Uncertainties of the single-phase liquid convection and flow boiling heat transfer coefficients and other parameters are estimated by the procedures proposed by Kline and McClintock [49]. The detailed results from this uncertainty analysis are summarized in Table 3.1.

Table 3.1 Summary of the uncertainty analysis

Parameter	Uncertainty
Rectangular channel geometry	
Length, width and thickness (%)	±0.5%
Area (%)	±1.0%
Parameter measurement	
Temperature, T (°C)	±0.2
Temperature difference, ΔT (°C)	±0.3
System pressure, P (kPa)	±2
Mass flux of coolant, G (%)	±2
Single-phase heat transfer in rectangular channel	
Imposed heat flux, q (%)	±4.2
Heat transfer coefficient, $h_{1\phi}$ (%)	±12.3
Two-phase heat transfer in Rectangular channel	
Imposed heat flux, q (%)	±4.2
Heat transfer coefficient, $h_{2\phi}$ (%)	±12.3