CHAPTER 2

EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental system established in the present study to investigate the transient flow boiling heat transfer and associated bubble characteristics of the dielectric coolant FC-72 over a small heated copper flat plate flush mounted on the bottom of a horizontal rectangular channel is depicted schematically in Fig. 2.1. This system includes a degassing unit, a coolant loop, a hot-water loop, and a cold water loop. The test section along with the entrance and exit sections are shown in Fig. 2.2 by three-dimensional plots. The liquid coolant FC-72 is driven by a variable speed gear pump and the inlet temperature of the coolant is regulated by a pre-heater with a hot water circulation in it. The coolant vapor generated during boiling in the test section is then condensed in the condenser cooled by another water thermostat and then returns to the receiver. The details of each component in the testing system are described in the following.

2.1 Degassing Unit

Since any non-condensable gas dissolved in the coolant FC-72 can significantly affect the heat transfer performance and nucleate boiling phenomena, we must degas the coolant before beginning the experiments. After a recharge of the coolant or re-arrangement of the piping system, the coolant must be degassed. The degassing unit is a tank of 8 liters patched with a flexible electric heater on its inside surface to heat the coolant to its boiling point. During the degassing process, the air and any non-condensable gas dissolved in the coolant escape from the liquid FC-72 in the tank and pass through the released valve on the top of the tank. Besides, a pressure transducer and a thermocouple are equipped in the tank to measure the pressure and temperature of FC-72, respectively.

2.2 Coolant Loop

After degassing the coolant FC-72, we remove the non-condensable gases possibly existing in the coolant-loop by using a vacuum pump and then fill the degassed FC-72 liquid into the coolant-loop. The circulation system for the coolant consists of a variable-speed gear pump, a filter, a volume flow meter, a pre-heater, a test section including the inlet and outlet sections, a condenser, and a receiver. The head of this gear pump is coupled with a magnet-driven disk sealed inside an envelope to avoid any contamination from the shaft. The shaft is driven by an variable–speed AC induction motor which is in turn regulated by an inverter. The temporal oscillation of the coolant flow rate can be implemented by an optional external control of the inverter through a programmable DC current or voltage signal sequence. Besides, the average coolant flow rate can be further adjusted by regulating the bypass valve.

The coolant FC-72 at the outlet of the magnetic micro-pump must be kept subcooled to avoid any vapor flow through the volume flow meter. The pre-heater is used to heat the subcooled coolant FC-72 to a specific subcooled or saturated temperature at the test section inlet by receiving heat from the hot water in the hot-water loop. Finally, the vapor-liquid coolant mixture is generated in the test section when the subcooled or saturated coolant flows over the heated copper plate. The vapor flow leaving the test section is re-liquefied by the condenser in the cold-water loop.

After leaving the condenser, the liquid FC-72 flows back to the receiver at the bottom of the system. An accumulator is connected to a high-pressure nitrogen tank to dampen the fluctuations of the coolant flow rate and pressure. The filter is used to filter the impurities and non-condensable gas possibly existing in the loop. Varying the temperature and flow rate of the hot-water flowing through the pre-heater allows us to control the pressure of the coolant loop. Two absolute pressure transducers are installed at the inlet and outlet of the test section with a resolution up to ±2kPa. All the refrigerant and water temperatures are measured by calibrated copper-constantan thermocouples (T-type) with a calibrated accuracy of ±0.2℃. The test section is thermally insulated with a polyethylene insulation layer so that heat loss from it can be reduced significantly.

2.3 Test Section

The test section mainly consists of a circular copper plate flush mounted on the bottom of the horizontal rectangular channel. The rectangular flow-channel includes a gradually diverging section, the main test section, and a gradually converging section (Fig. 2.3). They are all made of stainless steel plate. The installation of the inlet and exit sections avoids the sudden change in the cross section of the channel. The test section is 20 mm in width, 5 mm in height, and 150 mm in length, and the aspect ratio of the test section is 4.0. The heated plate is placed around the geometric center of the bottom plate of the test section. A ladder-shaped acrylic window is installed on the upper lid of the test section right above the heated plate. The temperature and pressure of the FC-72 flow at the inlet and exit of the test section are measured by the calibrated thermocouples and pressure transducers, as schematically shown in Fig. 2.3.

The copper plate module schematically shown in Figs. 2.4 and 2.5 includes a hollow cylindrical Teflon block, a cylindrical Teflon bolt, a copper plate, two pieces of mica plates, a Teflon plate, and an electric-heater. The diameter of the copper plate is 10 mm and the plate is heated by passing DC current through the electric-heater. Besides, three thermocouples are fixed at the back surface of the copper plate to estimate the temperature of the upper surface of the copper plate and another two thermocouples are fixed at the top and bottom surface of the electric-heater to measure their surface temperatures. The locations of the thermocouples at the backside of the copper plate and at the electric-heater surface are shown in Fig. 2.5. The mica plates are placed between the heater and copper plate and between the heater and Teflon plate, intending to prevent the leaking of the DC current to the copper plate. The detailed structure of the module is shown in Fig. 2.6. The magnitude of heat loss from each surface of the Cylindrical-hollow Teflon block can be evaluated from the temperature measured at selected locations in the block. Locations of the thermocouples are schematically shown in Fig. 2.7.

2.4 Hot-water Loop

In order to maintain the dielectric coolant FC-72 at the preset temperature at the test section inlet, a hot-water loop is used to preheat the coolant before it arrives at the test section inlet. The hot-water loop for the pre-heater includes a thermostat with a 20-liter hot water container and a 2 kW heater in it, and a 0.5-hp water pump which can drive the hot water at a specified flow rate to the pre-heater. Besides, a bypass valve in the loop can further adjust the water flow rate. The hot water passes through the container while the liquid coolant FC-72 flows through the inner coiled pipe in the pre-heater. The connecting pipe between the pre-heater and test section is thermally insulated with a 5-cm thick polyethylene layer to reduce the heat loss from the pipe.

2.5 Cold-water Loop

The cold-water loop is designed for condensing the liquid-vapor mixture of FC-72 delivered from the test section. The maximum cooling capacity of the thermostat is 2,000 Kcal/hr. The cold water at a specific flow rate is driven by a 0.5-hp pump to the condenser and a bypass loop is provided to adjust the flow rate. By adjusting the temperature and flow rate of the cold water, the bulk temperature of FC-72 in the condenser can be controlled at a preset level.

2.6 DC Power Supply

As described above, the copper plate flush mounted on the bottom of the test section is heated by the electric-heater. A 30V-3A (Topward 3303D) DC power supply delivers the required electric current to the heater. A Yokogawa DC meter is used to measure the DC current through the electric-heater with an accuracy of ±1%. Besides, a Yokogawa data logger is used to measure the DC voltage across the electric-heater with an accuracy of ±1%. Thus the power input to the electric-heater can be calculated.

2.7 Data Acquisition

The data acquisition system employed to acquire and process the data from various transducers is a 30-channel data logger (YOKOGAWA MX-100) along with a personal computer. All the voltage signals from the T-type thermocouples, pressure transducers, and volume flow-meters are converted to the temperature, pressure, and volume flow rate by the internal calibration equations in the computer and are displayed on the screen simultaneously.

2.8 Optical Measurement Technique

The optical measurement technique employed in the present study enables us to capture the bubble characteristics in the boiling flow near the copper plate in the present flow boiling experiments. The photographic apparatus consists of a high speed digital video camera (IDT High-speed CMOS Digital Camera), a micro-lens (Optem Zoom160), a three-dimensional positioning mechanism, and a personal computer. The high-speed motion analyzer can take photographs up to 143,307 frames/s. Here, a recording rate of 5000 frames/s is adopted to obtain the images of the bubble ebullition processes. The positioning mechanism is used to hold the camera at the required accurate position. The data for the bubble characteristics are collected in the regions near the geometric center of the plate surface. After the experimental system reaches a statistically steady state, we start recording the boiling activity. The high speed motion analyzer stores the images which are later downloaded to a personal computer. Then, the mean bubble departure diameter and frequency and active nucleation site density are calculated by viewing more than 500 frames for each case. In order to achieve the highest possible resolution and to eliminate errors in calibration, the camera lens is fixed at a constant focal length, resulting in a fixed viewing area. Typically, a total of over 150 bubble diameter measurements are used to construct the present data. The bubble departure frequency is measured by counting the total number of bubbles that emerge from the targeted heating surface area during a period of a second.

2.9 Experimental Procedures

Before conducting the transient flow boiling experiment, the liquid FC-72 is degassed and then filled into the coolant receiver. Besides, the non-condensable gases in the coolant loop are evacuated. In each test, we first turn on the controller for setting the required variable rotation rate of the AC motor to regulate the FC-72 flow rate to the preset mean level and the period and amplitude of the oscillation. Then the temperature and flow rate of the hot-water loop are selected so that the FC-72 temperature at the test section inlet can be maintained at a preset level. The imposed heat flux from the electric heater to the coolant in the test section is adjusted by varying the electric current delivered from the DC power supply. In addition, we can calculate the heat transfer rate to the coolant by measuring the DC voltage across the electric-heater and the current delivered to the electric-heater. Temperature and flow rate of the cold water in the cold-water loop can be adjusted to condense and subcool the liquid-vapor mixture of FC-72 from the test section. Next, we regulate the FC-72 pressure at the test section inlet by adjusting the gate valve locating right after the outlet of the test section. All measurements proceed when the experimental system has reached statistically stable state. Finally, the scanning rate for each data channel is 2 Hz and all the data channels are scanned for a period of 180 seconds.

2.10 Experimental Parameters

The ranges of the experimental parameters to be covered in the present study are listed in Table 2.1. Moreover, the thermodynamic and transport properties of the dielectric coolant FC-72 are given in Table 2.2 [37].

Table 2.1 Experimental parameters

Parameter	**Range**	**Unit**
Flow velocity (V)	16.7 ~ 30	cm/s
Mean mass flux ($\overline{G}$)	300 ~ 400	kg/m^2*s
Oscillation amplitude ($\zeta = \triangle G/\overline{G}$)	±5% ~ 10%	-
Oscillation period	10 ~ 30	sec
Subcooling temperature (ΔT_{sub})	0 ~ 10	°C
Imposed heat flux (q”)	0.1 ~ 10	W/cm^2
System pressure (P)	99.0	kPa

Table 2.2 Thermodynamic and transport properties of the dielectric coolant FC-72 [37]

Temperature T		Pressure P	Latent heat h_{fg}	Density ρ		Dynamic viscosity μ		Specific heat C_p		Conductivity K		Thermal expansion coefficient β	Surface tension σ	Thermal diffusion coefficient α		Prandtl No. Pr	
°C	K	Mpa	kJ/kg	kg/m^3(l)	kg/m^3(v)	mPa*s(l)	uPa*s(v)	J/kg*K(l)	J/kg*K(v)	mW/mK(l)	mW/mK(v)	1/K(l)	mN/m(l)	m^2/s(l)	m^3/s(v)	liquid	vapor
20	293.15	0.024	90.4	1687	3.43	0.69	10.76	1045	844	57.9	10.4	0.00157	10.9	3.29E-08	3.6	12.4	0.87
25	298.15	0.03	88.5	1674	4.28	0.64	10.94	1053	851	57.4	10.8	0.00159	10.47	3.26E-08	3	11.8	0.86
30	303.15	0.038	86.7	1660	5.27	0.6	11.11	1061	858	56.9	11.1	0.0016	10.04	3.23E-08	2.5	11.2	0.86
35	308.15	0.046	84.8	1647	6.44	0.56	11.29	1068	866	56.3	11.5	0.00161	9.62	3.20E-08	2.1	10.6	0.85
40	313.15	0.057	82.9	1634	7.78	0.53	11.47	1076	873	55.8	11.8	0.00162	9.2	3.17E-08	1.7	10.2	0.85
45	318.15	0.069	81.1	1621	9.31	0.5	11.64	1084	880	55.2	12.2	0.00164	8.78	3.14E-08	1.5	9.7	0.84
50	323.15	0.083	79.1	1607	11.06	0.47	11.82	1092	887	54.7	12.5	0.00165	8.36	3.12E-08	1.3	9.3	0.84
54.3	327.45	0.097	77.5	1596	12.75	0.44	11.97	1098	892	54.3	12.8	0.00166	8.01	3.09E-08	1.1	9	0.83
55	328.15	0.099	77.2	**1594**	**13.03**	**0.44**	**12**	**1099**	**893**	**54.2**	**12.9**	0.00166	**7.95**	3.09E-08	**1.1**	9	0.83
55.7	328.85	0.1013	76.9	1592	13.33	0.44	12.02	1101	894	54.1	12.9	0.00167	7.9	3.09E-08	1.1	8.9	0.83
60	333.15	0.117	75.2	1581	15.25	0.42	12.17	1107	900	53.6	13.2	0.00168	7.55	3.06E-08	1	8.6	0.83
70	343.15	0.16	71.1	1554	20.49	0.38	12.53	1123	913	52.5	13.9	0.00171	6.75	3.01E-08	0.7	8.1	0.82
80	353.15	0.213	66.7	1528	27	0.34	12.88	1138	926	51.5	14.6	0.00174	5.97	2.96E-08	0.6	7.6	0.82

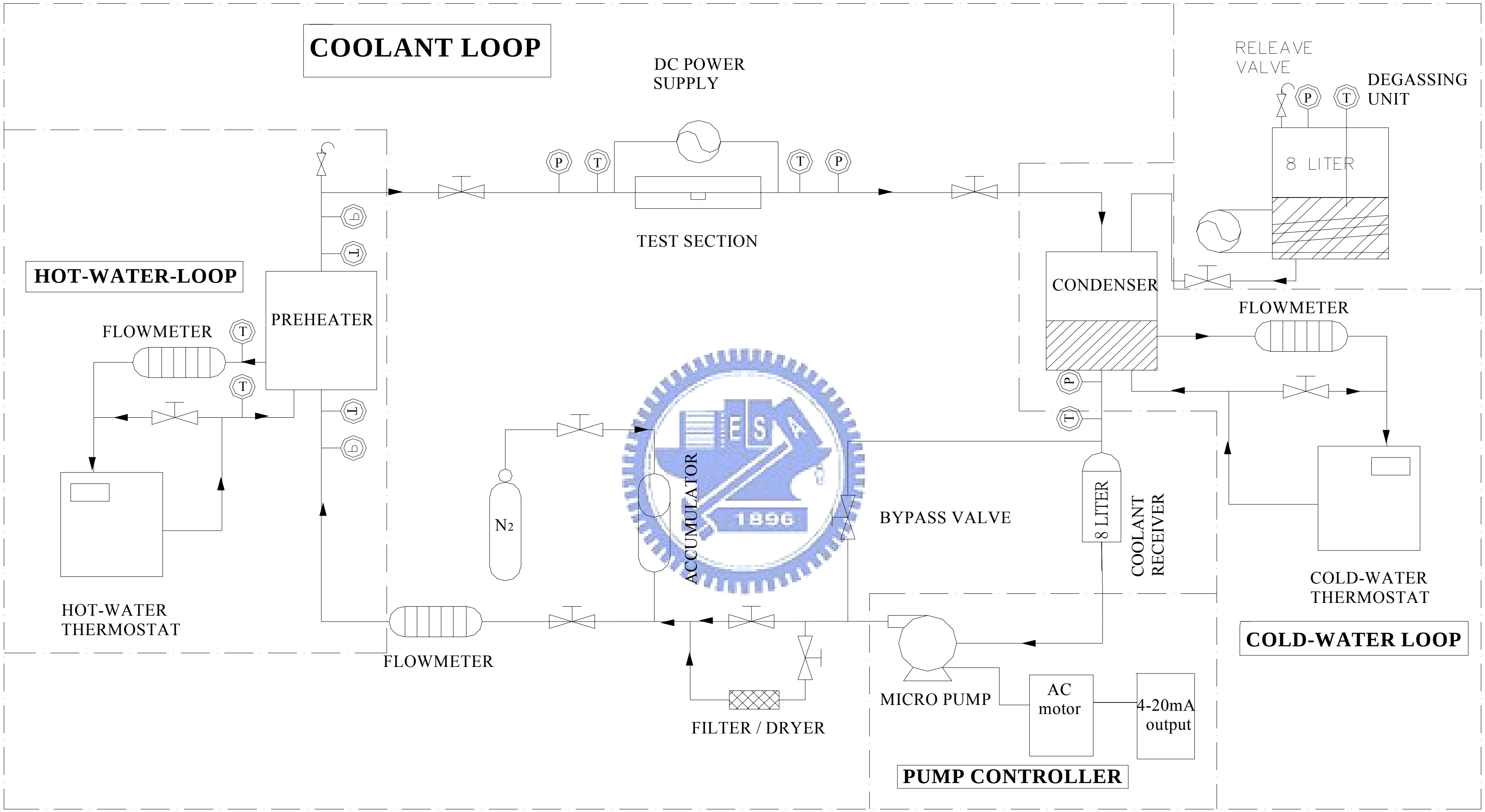

Fig. 2.1 Schematic diagram of experimental apparatus.

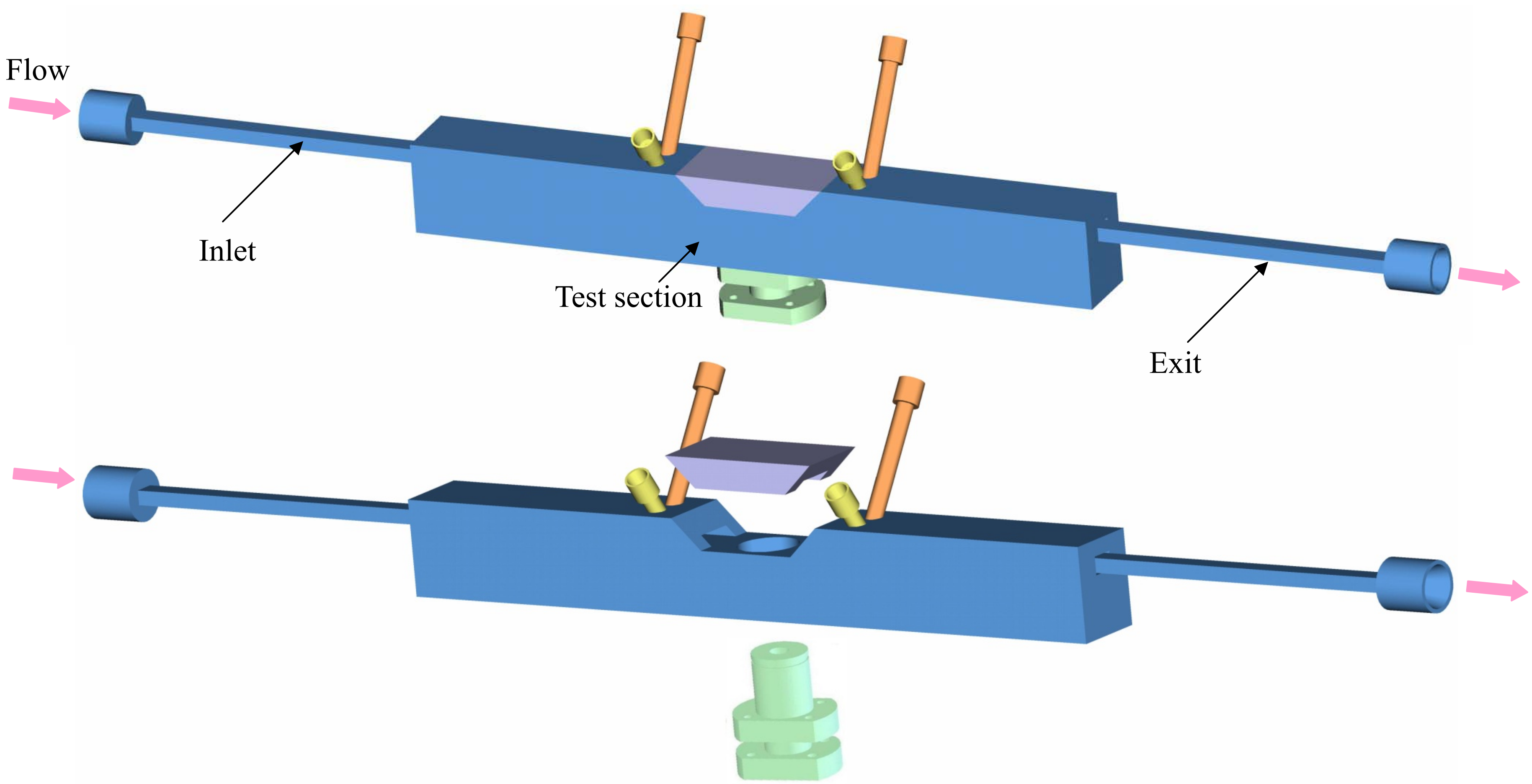

Fig. 2.2 Three-dimensional plots of test section along with inlet and outlet sections.

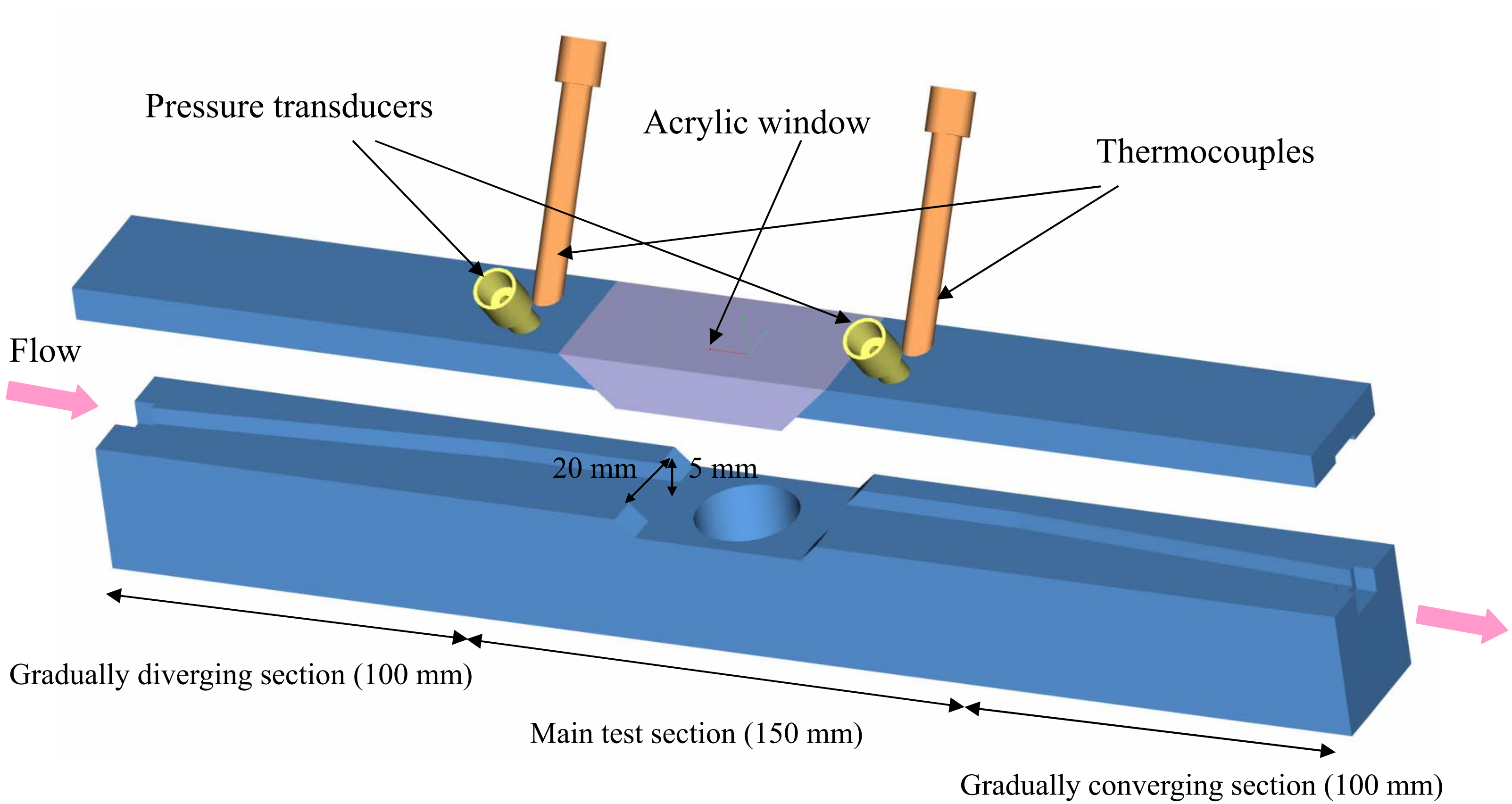

Fig. 2.3 Three-dimensional plots illustrating the test section in the rectangular flow-channel.

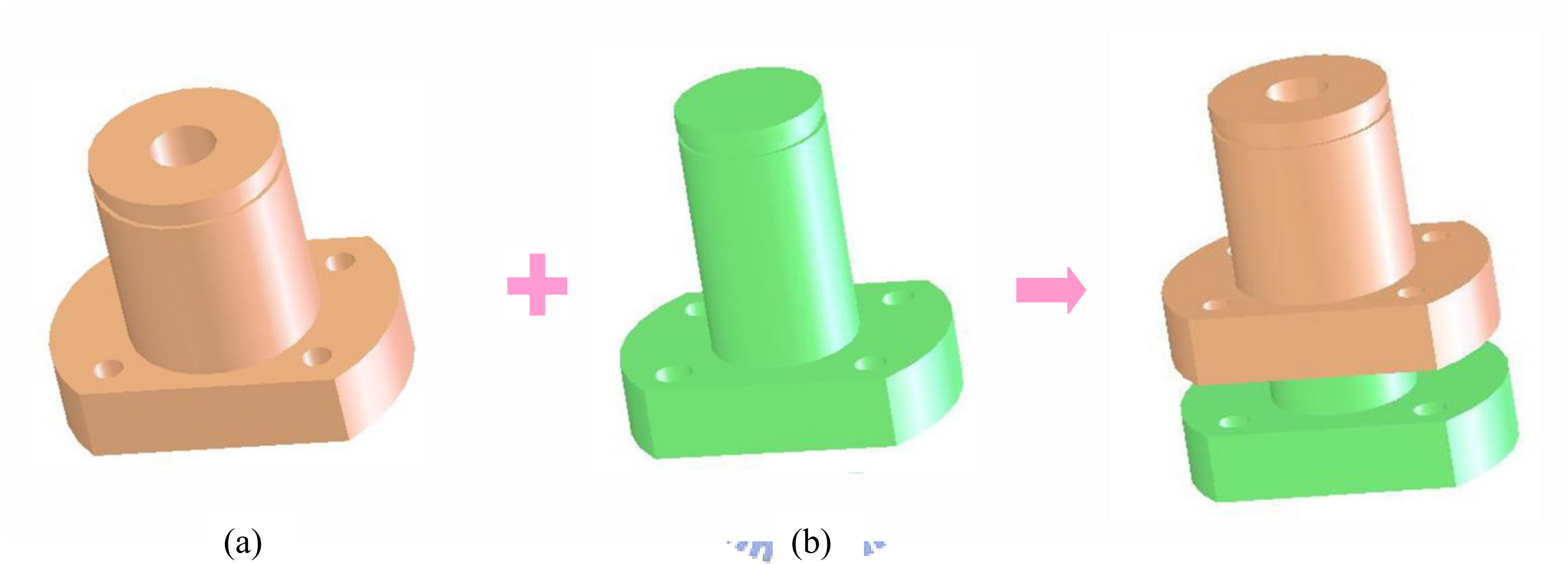

Fig. 2.4 Three-dimensional pictures showing (a) hollow cylindrical Teflon block and (b) cylindrical Teflon bolt.

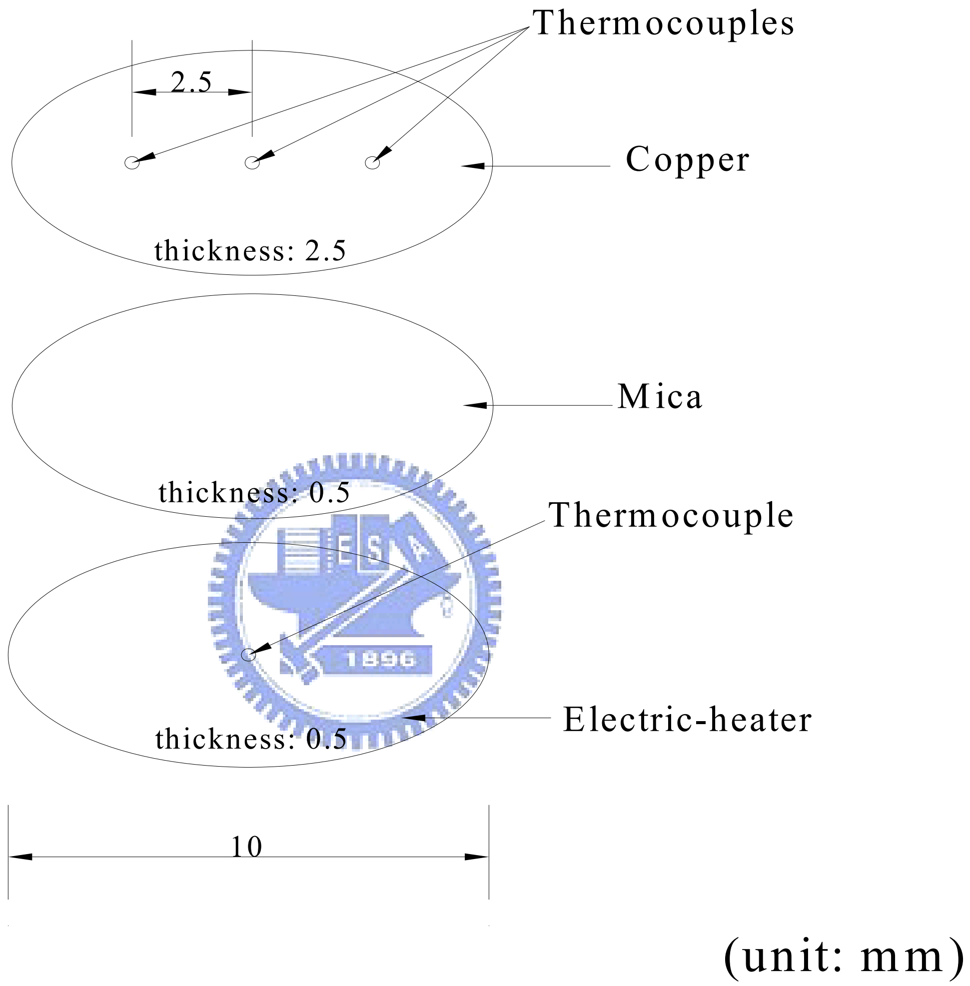

Fig. 2.5 Locations of thermocouples.

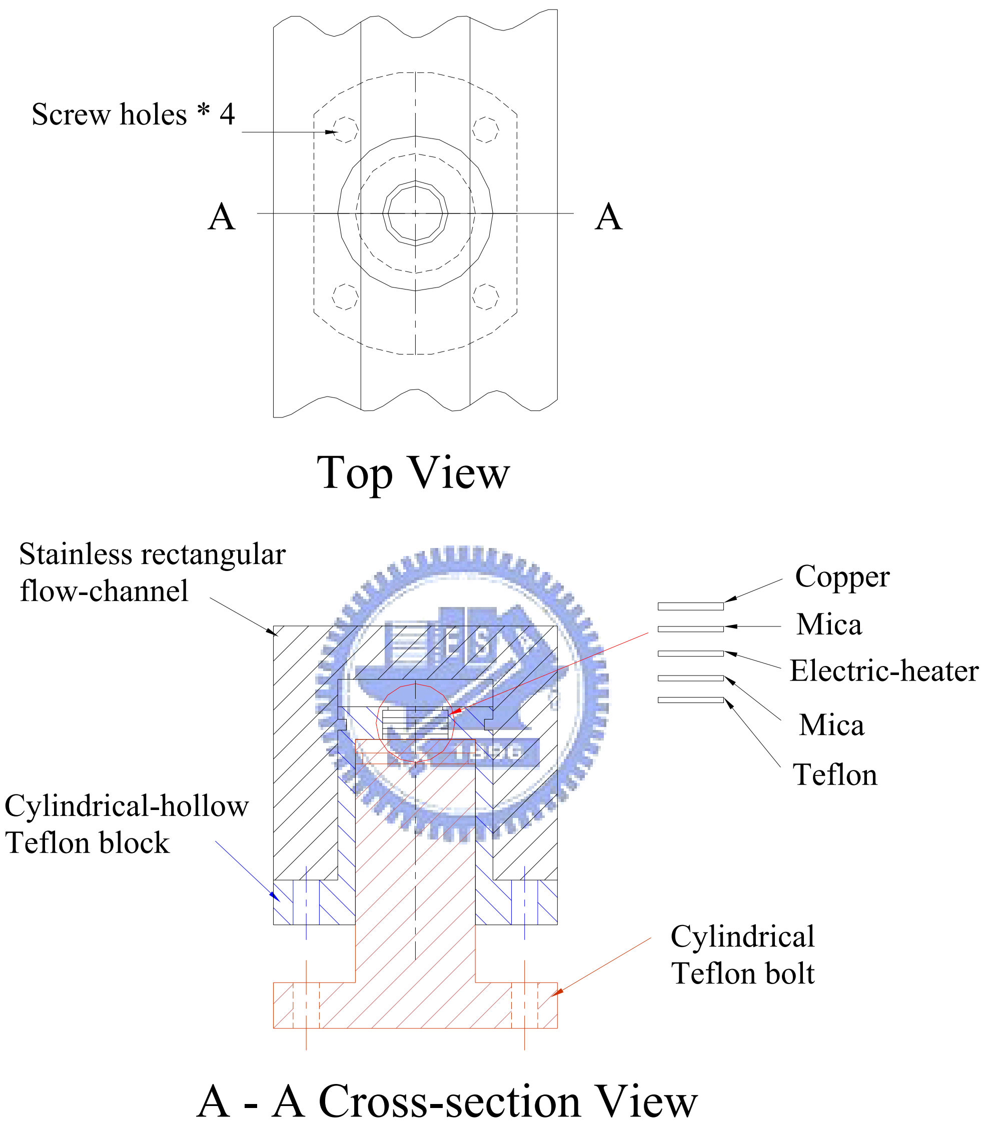

Fig. 2.6 Schematics of the copper plate module.

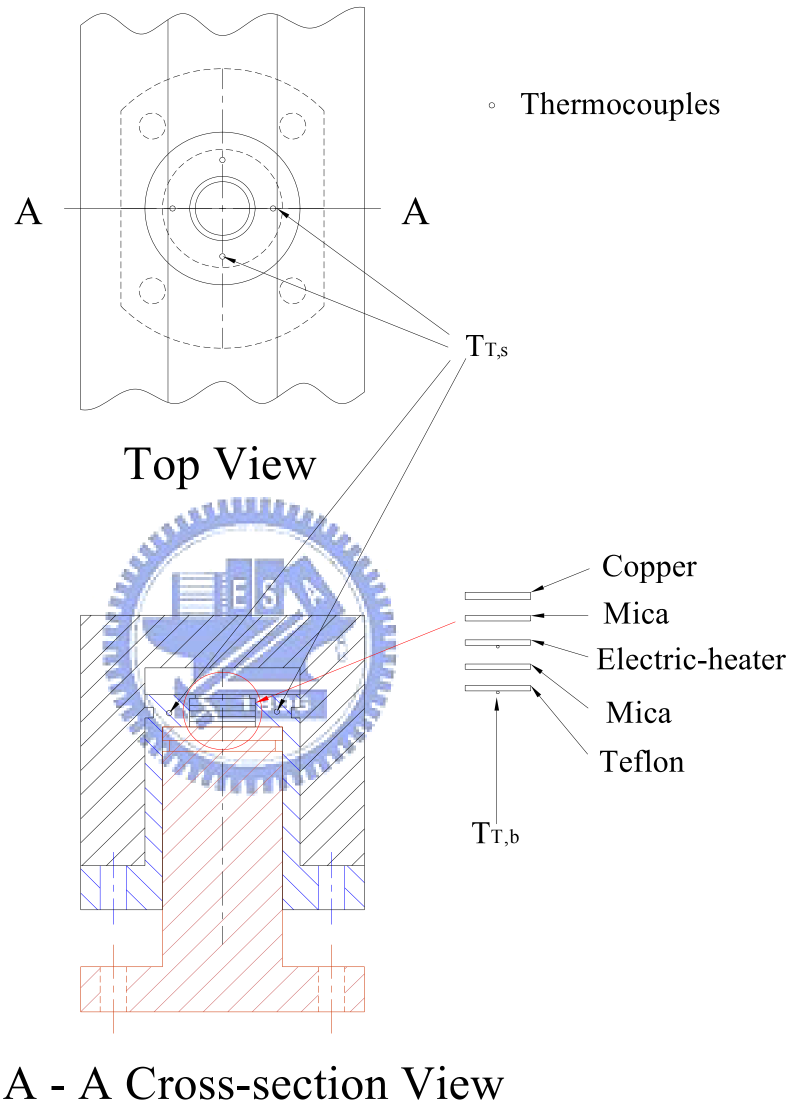

Fig. 2.7 Locations of the thermocouples inside the cylindrical-hollow Teflon block