CHAPTER 2

EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental system established in the present study to investigate the flow boiling heat transfer and bubble characteristics of the dielectric coolant FC-72 on a micro-pin-finned silicon chip flush mounted on the bottom of a rectangular flow-channel is schematically depicted in Fig. 2.1. The test section along with the entrance and exit sections are schematically shown in Fig. 2.2. The experimental apparatus consists of a degassing unit, a coolant loop, a hot-water loop, and a cold-water loop. They are described in the following.

2.1 Degassing Unit

Because air or non-condensable gas dissolved in the dielectric coolant FC-72 can significantly affect the heat transfer performance and nucleate boiling phenomena, we must degas the coolant before beginning the experiments. The degassing unit consists of a 8-liter tank with an electric-heated patch in it to heat the coolant to its boiling point and the coolant begins to evaporate. The air and non-condensable gas and a little amount of the coolant vapor can be removed from 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.

2.2 Coolant Loop

After degassing the coolant FC-72, we can remove the noncondensible gases possibly existing in the coolant-loop by using a vacuum pump and then fill the FC-72 into the coolant-loop. The coolant loop consists of a variable-speed magnetic micro-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 magnetic micro-pump is composed of an AC motor, a pump head and a controller. The coolant flow rate is mainly controlled by the AC motor through setting the inverter frequency of the controller. Besides, the 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 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 coolant flows through the rectangular flow-channel and is heated by the single silicon chip. 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 coolant and water temperatures are measured by copper-constantan thermocouples (T-type) with a calibrated accuracy of ±0.2°C.

2.3 Test Section

The test section in a rectangular flow-channel mainly contains a silicon chip flush mounted on the channel bottom. The rectangular flow-channel consists of 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. The chip 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 chip. 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 silicon chip module schematically shown in Figs. 2.4 and 2.5 includes a hollow cylindrical Teflon block, a cylindrical Teflon bolt, a silicon chip, a copper plate, two pieces of mica, a Teflon plate, and an electric-heater. The surface area of the silicon chip is 10 mm ╳ 10 mm and the chip is heated by passing DC current through the copper plates from the electric-heater. Besides, three thermocouples are fixed at the back surface of the silicon chip to estimate the surface temperature of the silicon chip and another one thermocouple is fixed at the electric-heater surface to measure its surface temperature. The locations of the thermocouples at the backside of the silicon chip and at the electric-heater surface are shown in Fig. 2.5. The mica plates are placed between the heater and copper plates, intending to prevent the leaking of the DC current to the chip. The detailed structure of the module is shown in Fig. 2.6.

The square micro pin-fins on the silicon chip are fabricated by the semiconductor manufacturing technique and the fabrication processes include the following steps:

1. The silicon wafer is cleaned through the RCA clean process.

2. The silicon wafer is coated with photoresistant AZ-5214E for about 2 μm in thickness by a track (a combinative-system of the automatic photoresistant spin coater & development).

3. The pattern is defined through the temporal exposure at first, then we conduct the phase reversely change process (let the positive and negative PR-pattern be exchanged) from aligners, and finally it is developed in the track.

4. Depositing an aluminum layer of 2400 Å thick by the PVD (Physical Vapor Deposition) sputtering.

5. Leafing off the photoresistant by the use of acetone.

6. Conducting the dry etching by the ICP (Induction Couple Plasma etching system).

7. After dry etching, using the Al (Aluminum) etchant to remove the Al layer.

8. Rinse the silicon wafer by the DI water and complete the fabrication process.

The flow chart for the fabrication processes is depicted in Fig. 2.7. Two types of the surface micro-structures in the form of square micro-pin-fins are manufactured on silicon chips and each individual fin has the same size of 200 μm ╳ 200 μm ╳ 70 μm for pin-finned 200 surface and 100 μm ╳ 100 μm ╳ 70 μm for pin-finned 100 surface. The space between the two adjacent fins (the fin pitch) is about equal to the fin width and the detailed photographs of the arrays of the micro pin-fins from the electronic microscope are shown in Fig. 2.8.

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 pre-heater while the liquid coolant FC-72 flows through the inner coiled pipe of 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 from the test section. The maximum cooling capacity of the thermostat is 2000 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 silicon chip flush mounted in the test section are heated by an electric-heater. A 30V-3A DC power supply delivers the required electric current to the heater. A Yokogawa data logger is used to measure the DC voltage across the heater with an accuracy of ±1%. The resistance of the electric-heater is provided from the manufacturer. 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 20-channel data logger (YOKOGAWA DA-100) along with a personal computer. The voltage signals from the 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 silicon chip surface in the present flow boiling experiments. The photographic apparatus consists of a high speed digital video camera (Kodak Motion Corder Analyzer), a micro-lens (Zoom160), a three-dimensional positioning mechanism, and a personal computer. The high-speed motion analyzer can take photographs up to 10,000 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 chip surface. After the experimental system reaches a statically 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 the beginning of the experiments, the coolant FC-72 is degassed and then filled into the coolant receiver. In each test, we first turn on the pump controller and set the inverter frequency to the required rotation rate of the AC motor to regulate the FC-72 flow rate to a preset level. 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 current delivered to and voltage drop across the 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. At the same time, we use the bypass valve to further adjust the coolant flow rate to the required level during the experiments. All measurements proceed when the experimental system has reached statistically stable state. Finally, all the data channels are scanned every 1 second for a period of 30 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 [48].

Table 2.1 Experimental parameters

Parameter	**Range**	**Unit**
Flow velocity (V)	16.7 ~ 30	cm/s
Mass flux (G)	280 ~ 502	kg/m^2*s
Subcooling temperature (ΔT_{sub})	0 ~ 4.3	^{o}C
Imposed heat flux (q”)	0.1 ~ 10	W/cm^2
System pressure (P)	Atmospheric pressure	kPa
Micro pin-fins geometries	W_f ╳ L_f ╳ H_f 200 ╳ 200 ╳ 70 100 ╳ 100 ╳ 70 Space ≈ W	μm

Table 2.2 Thermodynamic and transport properties of the dielectric coolant FC-72 [48]

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

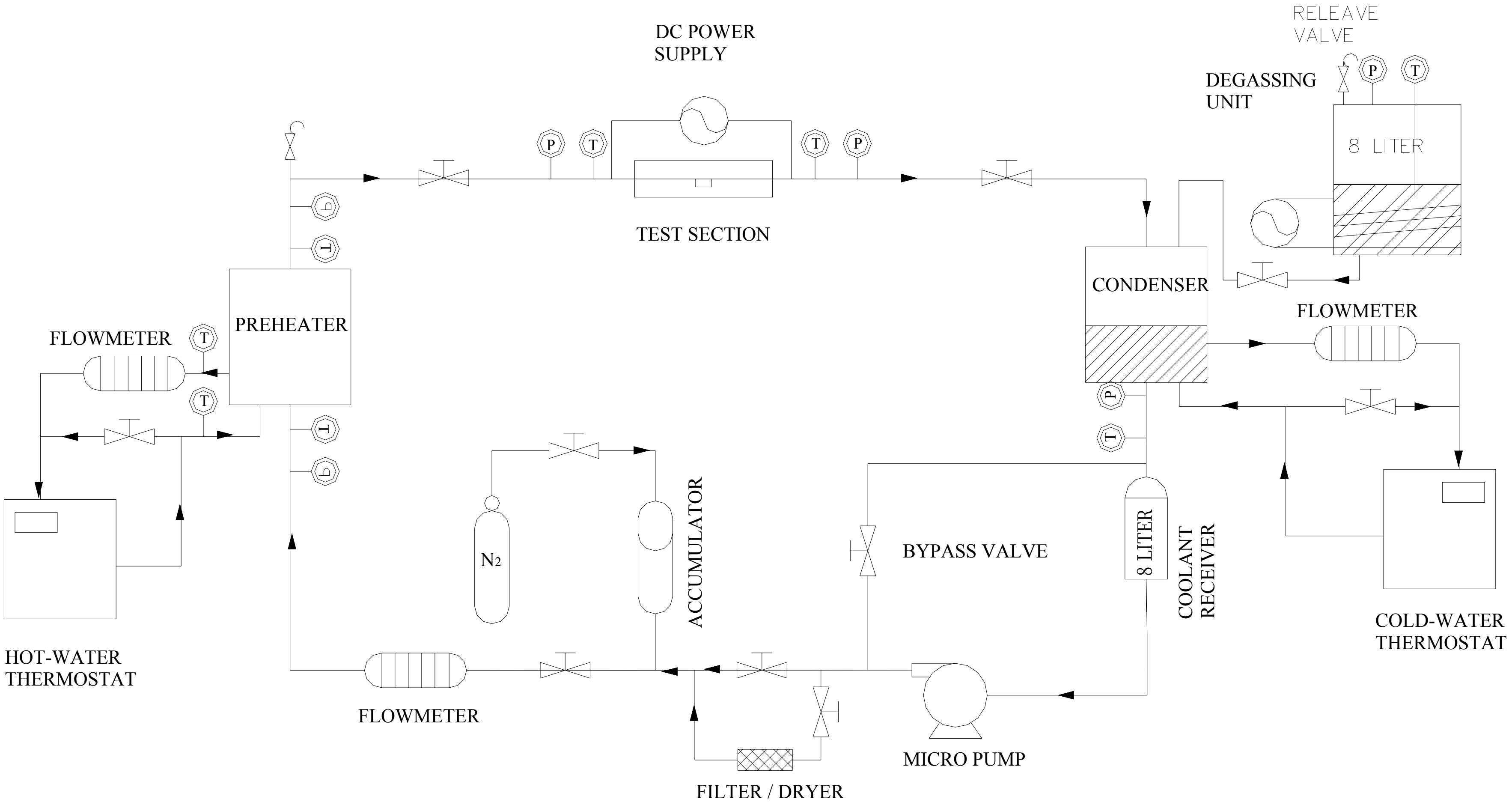


Fig. 2.1 Schematic diagram of experimental apparatus.

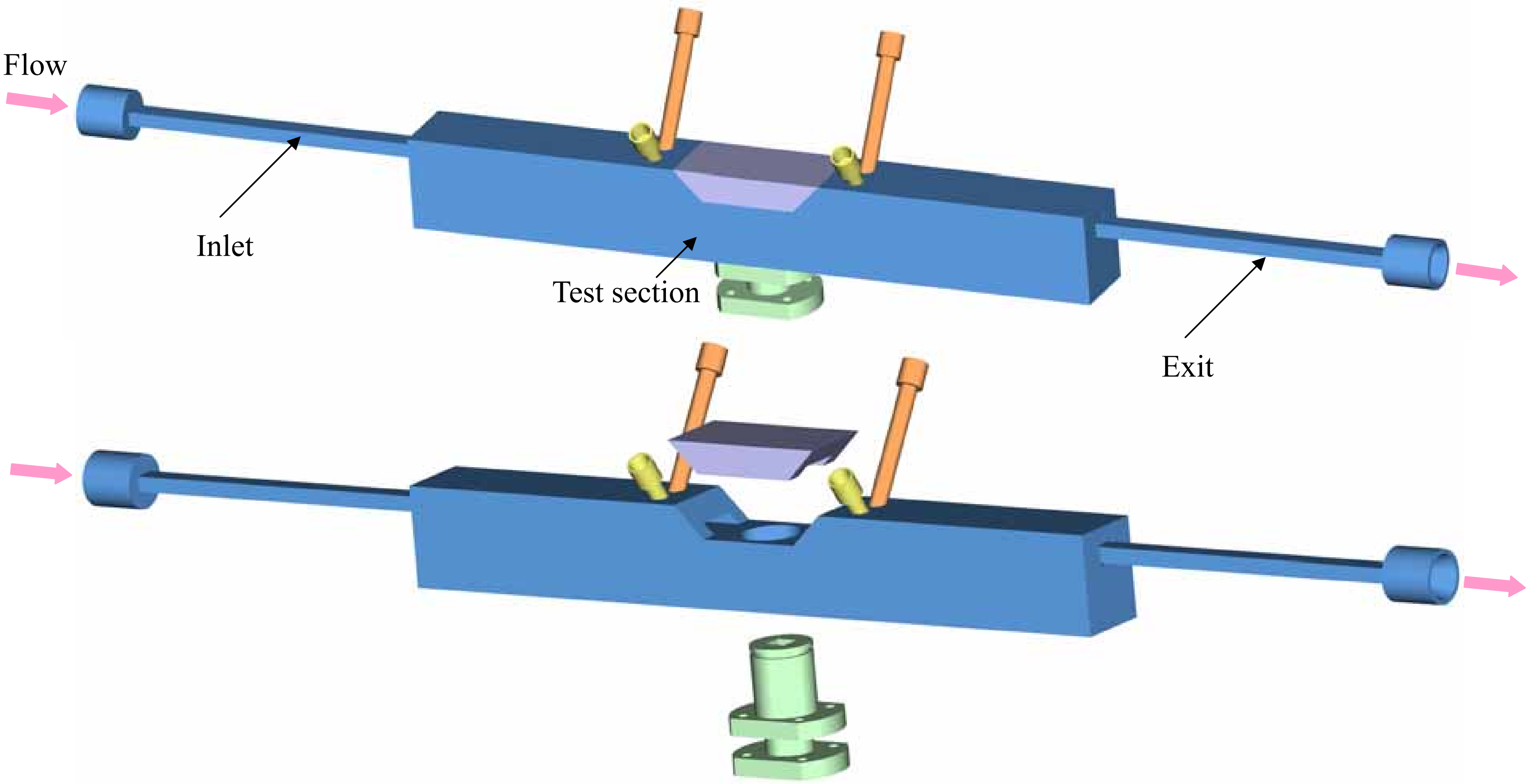


Fig. 2.2 Three-dimensional plots of test section along with inlet and outlet sections.

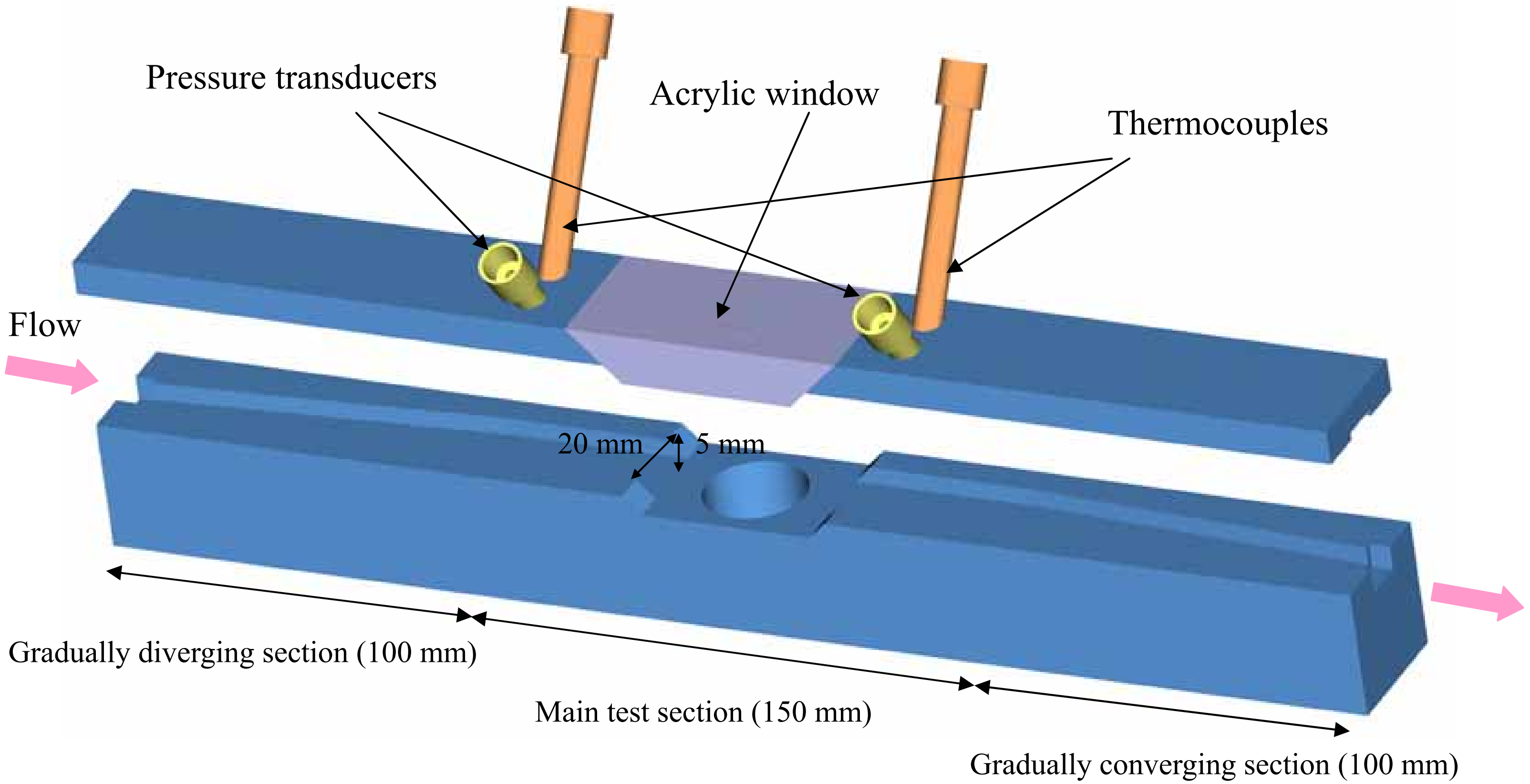


Fig. 2.3 Three-dimensional plots illustrating the test section in the rectangular flow-channel.

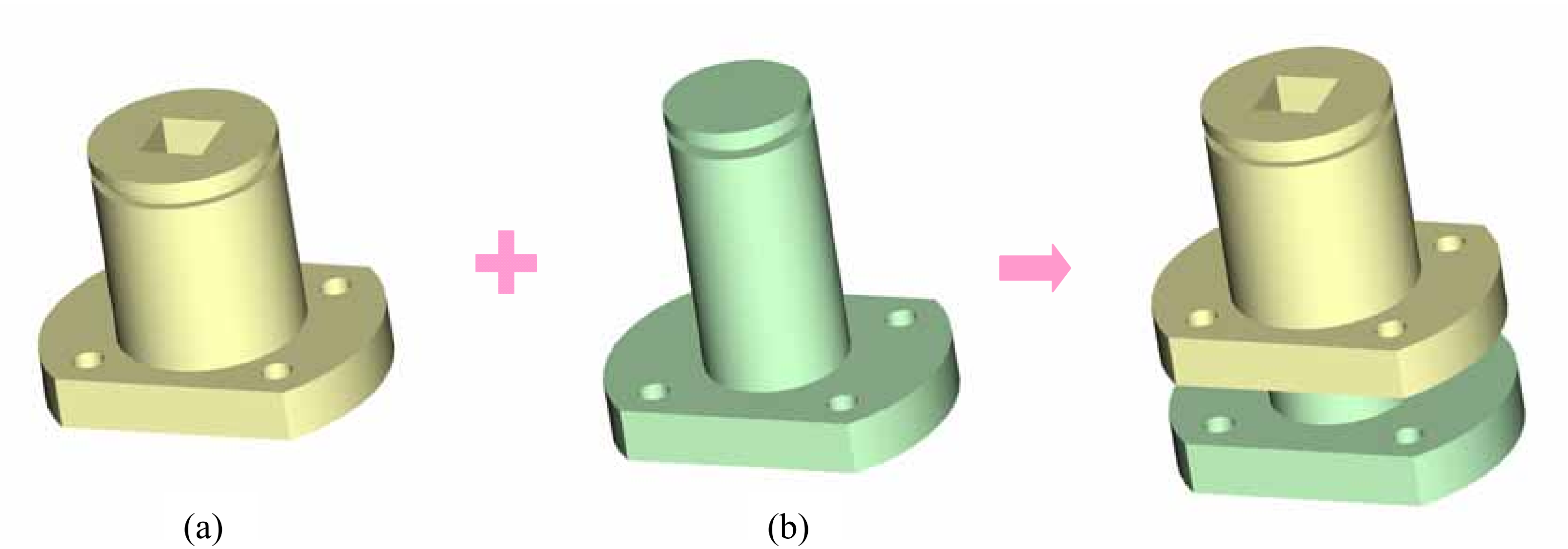


Fig. 2.4 Three-dimensional pictures showing (a) hollow cylindrical Teflon block and (b) cylindrical Teflon bolt.

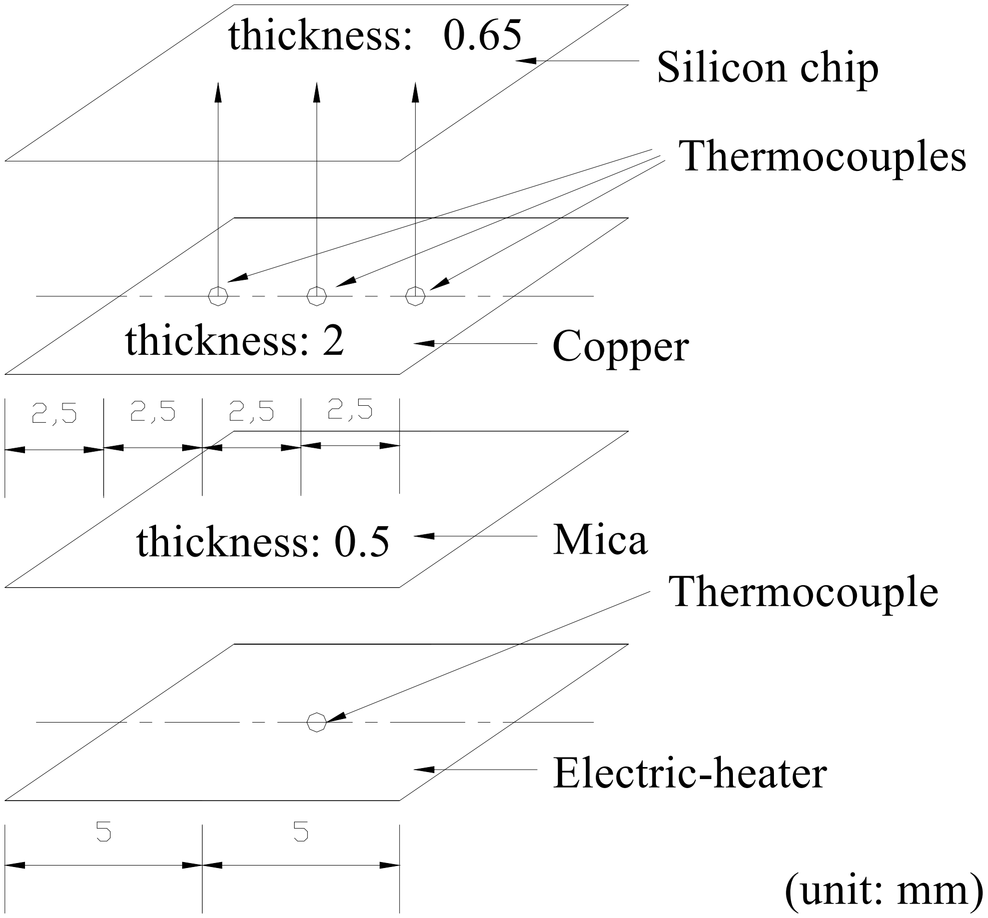
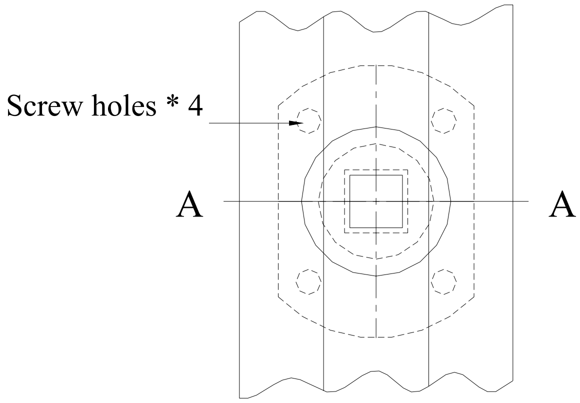
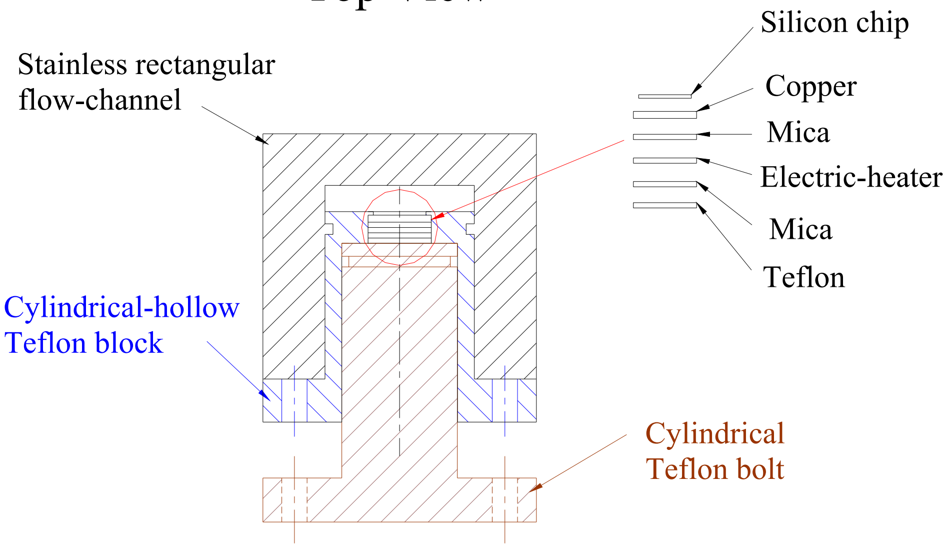


Fig. 2.5 Locations of thermocouples.



Top View



A - A Cross-section View

Fig. 2.6 Schematics of the silicon chip module.

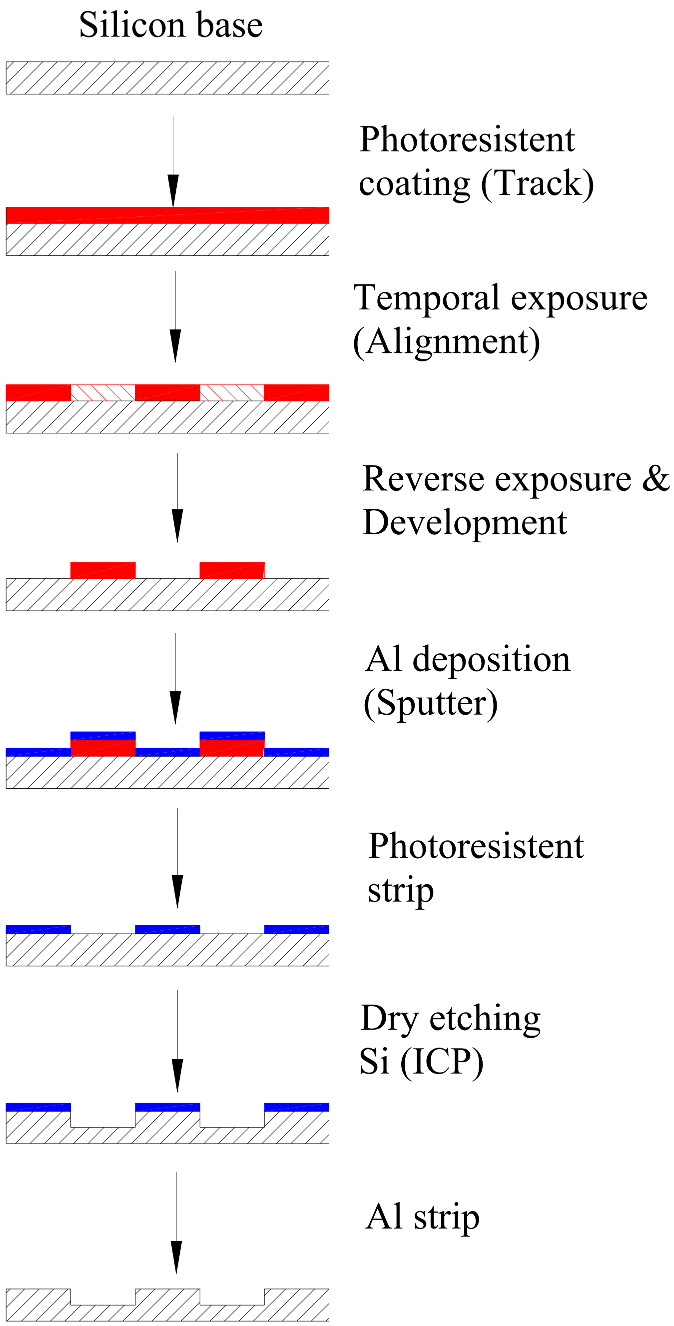
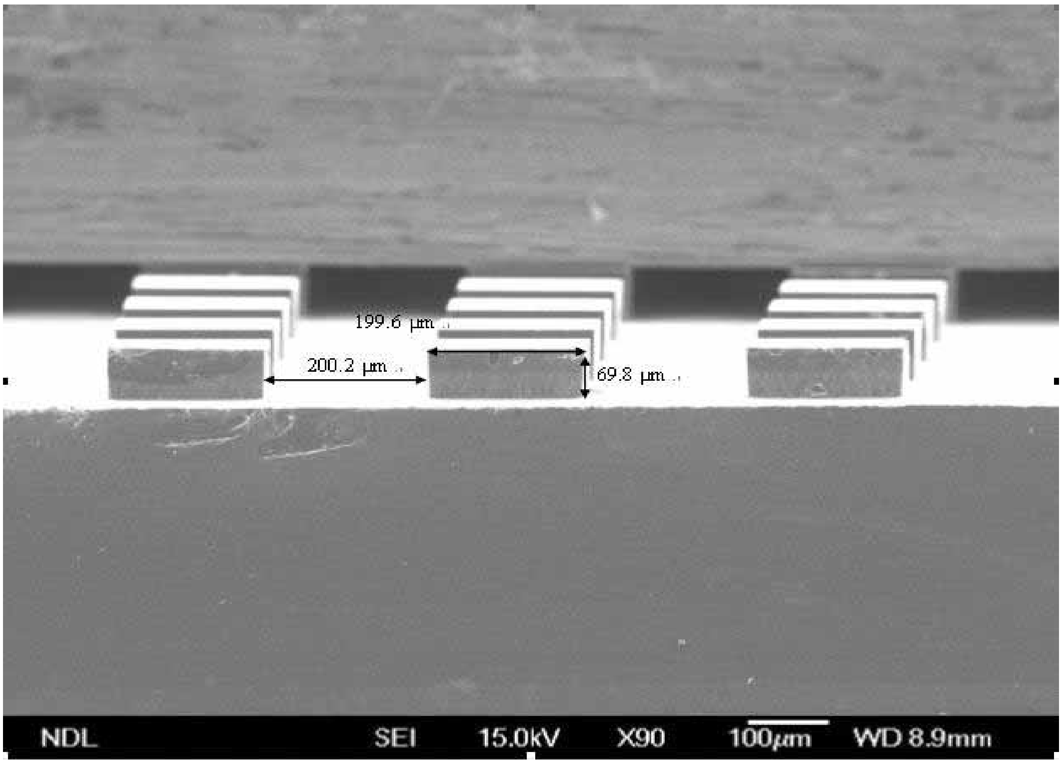
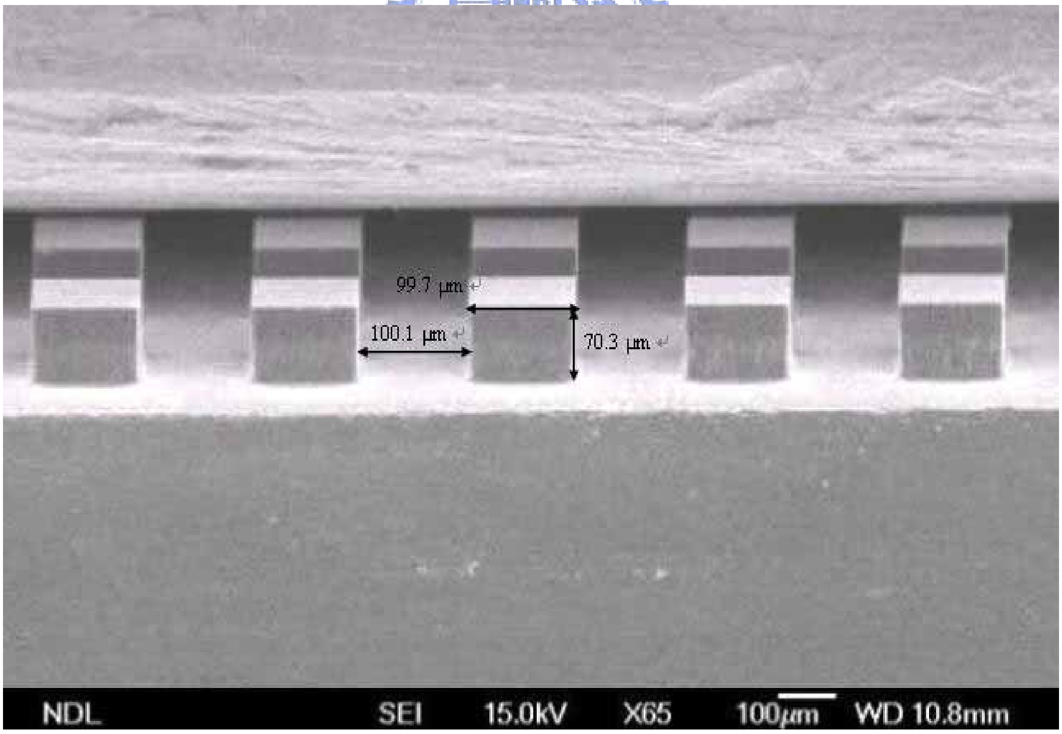


Fig. 2.7 Flow chart for the micro pin-fins fabrication.



Width Ｘ Length Ｘ Height: about 200 µm Ｘ 200 µm Ｘ 70 µm , Space: 200 µm



Width Ｘ Length Ｘ Height: about 100 µm Ｘ 100 µm Ｘ 70 µm , Space: 100 µm

Fig. 2.8 Photographs of micro pin-fins on the silicon chip taken by SEM.