CHAPTER 2

EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental apparatus used in the present study to investigate the characteristics of subcooled and saturated flow boiling heat transfer of refrigerant R-134a in a horizontal narrow annular duct is schematically shown in Fig. 2.1. The apparatus consists of three main loops, namely, a refrigerant loop, a water-glycol loop and a hot-water loop for preheater, along with a data acquisition system and a 50V-25A DC power supply. Refrigerants are circulated in the refrigerant loop. We need to control the temperature and flow rate in the water-glycol loop to obtain enough cooling capacity for condensing the refrigerant vapor and for maintaining the refrigerant liquid at a preset temperature. The liquid refrigerant in the narrow duct is heated by passing a DC current through the inner pipe in the test section from the DC power supply. To unravel the bubble characteristics in the boiling of refrigerant on the heating surface, a high-speed movie camera connected to a photographic microscope is set up beside the test section to observe the boiling flow.

2.1 Refrigerant flow loop

The main components in the refrigerant loop include an oil-free variable-speed refrigerant pump, an accumulator, a mass flow meter, a test section, a condenser, a sub-cooler, a receiver, a filter/dryer, and four sight glasses. An AC motor is used to control the refrigerant mass flow rate through the change of the inverter frequency. The flow rate can also be adjusted by regulating the by-pass valve installed in the by-pass flow path. The refrigerant at the outlet of the refrigerant pump is kept subcooled to avoid any vapor flow through the mass flow meter. The flow meter has an accuracy of ±1%. The preheater is used to heat the refrigerant to a specified refrigerant state before entering the test section. The vapor generated in the test section is reliquefied in an oversized condenser/subcooler in the cold water-glycol loop. Leaving the subcooler, the liquid refrigerant 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 flow rate and pressure. The filter/dryer is used to filter the impurities and noncondensable gas possibly existing in the loop. Varying the temperature and flow rate of the water-glycol mixture flowing through the condenser and subcooler allows us to control the pressure of the refrigerant loop. Two absolute pressure transducers are respectively installed at the inlet and exit of the test section with a resolution up to ±2kPa. All the refrigerant and water temperatures are measured by 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.

2.2 Test Section

The flow boiling for refrigerant R-134a flow in an annular duct with a small clearance between the inner and outer pipes is explored. As schematically shown in Fig. 2.2, the test section of the experimental apparatus is a horizontal annular duct with the outer pipe made of Pyrex glass to permit the visualization of boiling processes in the refrigerant flow. The outer Pyrex glass pipe is 160 mm long and 4 mm thick with inside diameter of 20 mm. Both ends of the pipe are connected with a copper tube of the same size by means of flanges and are sealed by O-rings. The inner smooth pipe has 16.0, 18.0, 19.0 or 19.6 mm nominal outside diameter (the pipe wall thickness is 1.5, 2.5, 3.0 or 3.3 mm) and is 0.41 m long, so that the hydraulic diameter of the annular duct D_h is 4.0, 2.0, 1.0 or 0.4 mm (corresponding to the gap size of 2.0, 1.0, 0.5 or 0.2 mm for the duct). In order to insure the gap between the ducts being uniform, we first measure the average outside diameter of the inner pipe and the mean inside diameter of the Pyrex glass by digital calipers having a resolution of 0.001mm. The absolute accuracy of the measurement is in the range of 0.01 mm. Then we photo the top and side view pictures of the annular ducts and measure the average distance between the inside surface of the Pyrex glass pipe to the outside surface of the inner tube, with an absolute accuracy also in the range of 0.01mm. Finally, we measure the roundness of the ducts for δ = 0.5 & 0.2 mm, again with an absolute accuracy in the range of 0.01mm. From the above procedures the duct gap is ascertained and its absolute uncertainty is estimated to be 0.019 mm. An electric cartridge heater of 160 mm in length and 12.5 mm in diameter with a maximum power output of 800W is inserted into the inner pipe. Furthermore, the pipe has an inactive heating zone of 10 mm long at each end and is insulated with Teflon blocks and thermally nonconducting epoxy to minimize heat loss from it. Thermal contact between the heater and the inner pipe is improved by coating a thin layer of heat-sink compound on the heater surface before the installation of the heater. Then, 8 T-type calibrated thermocouples are electrically insulated by covering their beads with the electrically nonconducting thermal bond before they are fixed on the inside surface of the inner pipe so that the voltage signals from the thermocouples are not interfered by the DC current passing through the cartridge heater. The thermocouples are positioned at three axial stations along the smooth pipe. At each axial station, two to four thermocouples are placed at top, bottom, or two sides of the pipe circumference with 180° or 90° apart. The outside surface temperature T_w of the inner pipe is then derived from the measured inside surface temperature by taking the radial thermal conduction through the pipe wall into account. Figure 2.3 shows the detailed thermocouple locations at each axial station and the arrangement of the cartridge heater.

2.3 Water loop for preheater

In order to maintain the preset refrigerant temperature at the test section inlet, a water loop is used to preheat the refrigerants before it arrives at the inlet. The water loop for the preheater system includes a double-tube, having a heat transfer area of $0.12 m^2$, a 125-liter hot water container with three 2.0-kW heaters in it, and a 0.5-hp water pump which can deliver the hot water at specified temperature and flow rate to the preheater. In the preheater the hot water passes through the outer pipe while the liquid refrigerant flows in the inner pipe. The water flow rate is controlled by an AC motor through the change of the inverter frequency and by the by-pass valve. The connecting pipe between the preheater and test section is thermally insulated with a 5-cm thick polyethylene layer to reduce the heat loss from the pipe.

2.4 Water-glycol loop

The water-glycol loop is designed for condensing the refrigerant vapor and for subcooling the liquid refrigerant. The water-glycol loop is cooled by a water cooled R-22 refrigeration system. The cooling capacity is 3.5-kW for the water-glycol mixture at -20℃. The cold water-glycol mixture at a specified flow rate is driven by a 0.5-hp pump to the condenser as well as to the subcooler. A by-pass loop is provided to adjust the flow rate. By adjusting the mixture temperature and flow rate, the bulk temperature of the refrigerant in the subcooler can be controlled at a preset level.

2.5 DC Power Supply

As described above, the inner pipe in the test section is heated by a 800-W cartridge heater. A 50V-25A DC power supply delivers the required electric current to the cartridge heater. A Yokogawa DC meter is used to measure the DC current through the cartridge heater with an accuracy of ±1%. Then the voltage drop across the heater is measured by a Yokogawa multimeter. Thus the power input to the heater can be calculated.

2.6 Photographic System

The photographic apparatus established in the present study to record the bubble characteristics in the subcooled and saturated flow boiling in the annular duct consists of an IDT X-Stream$^{\text{TM}}$ VISION XS-4 high speed CMOS digital camera, a Mitutoyo micro lens set, a 3D positioning mechanism, a Personal computer, and a Nikon digital camera. The high-speed digital camera can take photographs up to 143,307 frames/s with an image resolution of 512×16. Here, a recording rate of 10,000 frames/s with the highest image resolution of 512×256 is adopted to obtain the images of the bubble ebullition processes in the flow boiling. The digital camera shutter speed can be as short as 1/4000 second in taking to take the overview flow boiling field. The data for some bubble characteristics are collected in the regions around the middle axial location ($z = 80$ mm). Note that the symbol z denotes the axial coordinate measuring from the inlet of the test section. After the experimental system reaches a statistically steady state, we start to record the boiling activity. The high-speed digital camera can store the images which are later downloaded to the personal computer. Then, the mean bubble departure diameter, bubble generation frequency and active nucleation site density are calculated by viewing more than 1000 frames at each location. Typically, a total of over 150 bubble diameter measurements are used to construct the present data. The mean bubble generation frequency is measured by counting the total number of bubbles that emerge from the heating surface during one second.

2.7 Data acquisition

The data acquisition system includes a recorder (Yokogawa HR-2300), a 24V-3A power supply, and a controller. The water flowmeter and differential pressure transducer need the power supply as a driver to output an electric current of 4 to 20 mA. The data signals are collected and converted by a data acquisition system (Hybrid recorder). The converted signals are then transmitted to a host computer through a GPIB interface for further calculation.

The system automatically monitors all the T-Type thermocouples, pressure transducers, differential pressure transducer and mass flowmeters. The thermodynamic and transport properties of the refrigerants are obtained by a manual from AlliedSignal Co. Ltd. and by the ASHRAE handbook.

2.8 Experimental procedures

Before a test is started, the temperature of the refrigerant under investigation in the test section is compared with its saturation temperature corresponding to the measured saturation pressure and the allowable difference is kept in the range of 0.2-0.3K. Otherwise, the system is re-evacuated and then re-charged to remove the air existing in the refrigerant loop. In the test the liquid refrigerant at the inlet of the test section is first maintained at a specified temperature by adjusting the water-glycol temperature and flow rate. In addition, we adjust the thermostat temperature in the water loop to stabilize the refrigerant temperature at the test section inlet. Then, we regulate the refrigerant pressure at the test section inlet by adjusting the opening of the gate valve locating right after the exit of the test section. Meanwhile, by changing the current of the DC motor connecting to the refrigerant pump, the refrigerant flow rate can be varied. The imposed heat flux from the heater to the refrigerant is adjusted by varying the electric current delivered from the DC power supply. By measuring the current delivered to and voltage drop across the heater and by photographing the bubble activity, we can calculate the heat transfer rate to the refrigerant and obtain the bubble characteristics. All tests are run at statistically steady-state conditions. The whole system is considered to be at a statistically steady state when the time variations of the system pressure and imposed heat flux are respectively within ±1% and ±4%, and the time variations of the heated wall temperature are less than ±0.2℃ for a period of 100 minutes. Then all the data channels are scanned every 5 seconds for a period of 50 seconds.

2.9 Experimental Parameters

The ranges of the experimental parameters and the corresponding dimensionless groups to be covered in the present study are listed in Table 2.1. Moreover, the thermophysical properties of the refrigerants R-134a, R-407C and R-410A are given in Table 2.2.

Table 2.1 List of conditions of the experimental parameters for R-134a

δ (mm)	Inlet Condition	G (kg/m^{2}s)	q" (kW/m^2)	T_{sat} (℃)	ΔT_{sub} (℃)	Re	N_{conf}	Bo
2.0	Subcooled & Saturated	400-500	0-50.0	10,15	0, 3.0, 6.0	6700-8920	0.22	6.0×10^{-4}
1.0		500-600	0-50.0	10,15	0, 3.0, 6.0	4187-5349	0.46	5.0×10^{-4}
0.5		500-600	0-50.0	10,15	0, 3.0, 6.0	2093-2674	0.91	5.0×10^{-4}
0.2		500-700	0-50.0	10,15	0, 3.0, 6.0	1005-1248	2.28	4.0×10^{-4}

Table 2.2 Comparison of thermophysical properties of some new refrigerants

Thermophysical properties		R-410A		R-407C		R-134a	
Temperature (℃) (Saturated Pressure)		10.46 (110 kpa)	14.88 (125 kpa)	10.04 (776 kPa)	15.05 (900 kPa)	10 (414.6 kPa)	15 (488.6 kPa)
Viscosity μ ($\mu N\cdot s/m^2$)	Liquid μ_l	145.8	137.9	184.6	173.4	238.8	224.3
	$\triangle\mu = \mu_l - \mu_g$	**132.9**	**124.67**	**172.4**	**160.95**	**227.65**	**212.94**
	Vapor μ_g	12.9	13.23	12.2	12.45	11.15	11.36
Density ρ (kg/m^3)	Liquid ρ_l	1128	1109	1199	1179	1261	1243.5
	$\triangle\rho = \rho_l - \rho_g$	**1085.53**	**1060.39**	**1165.93**	**1140.53**	**1240.77**	**1219.735**
	Vapor ρ_g	42.47	48.61	33.07	38.47	20.23	23.765
Enthalpy i (kJ/kg)	Liquid i_f	216.1	223.0	214.3	221.7	213.6	220.5
	$\triangle i = i_g - i_f$	**207.7**	**201.7**	**201.7**	**196.3**	**190.7**	**186.55**
	Vapor i_g	423.8	424.7	416	418	404.3	407.05
Conductivity k (W/m·K)	Liquid k_l	**0.1074**	**0.1046**	**0.09588**	**0.09585**	**0.0876**	**0.08545**
	Vapor k_g	0.01295	0.01359	0.01264	0.013113	0.0124	0.01286
Surface Tension σ (N/m)	Liquid	**0.00709**	**0.00644**	**0.00914**	**0.00839**	**0.01014**	**0.00944**

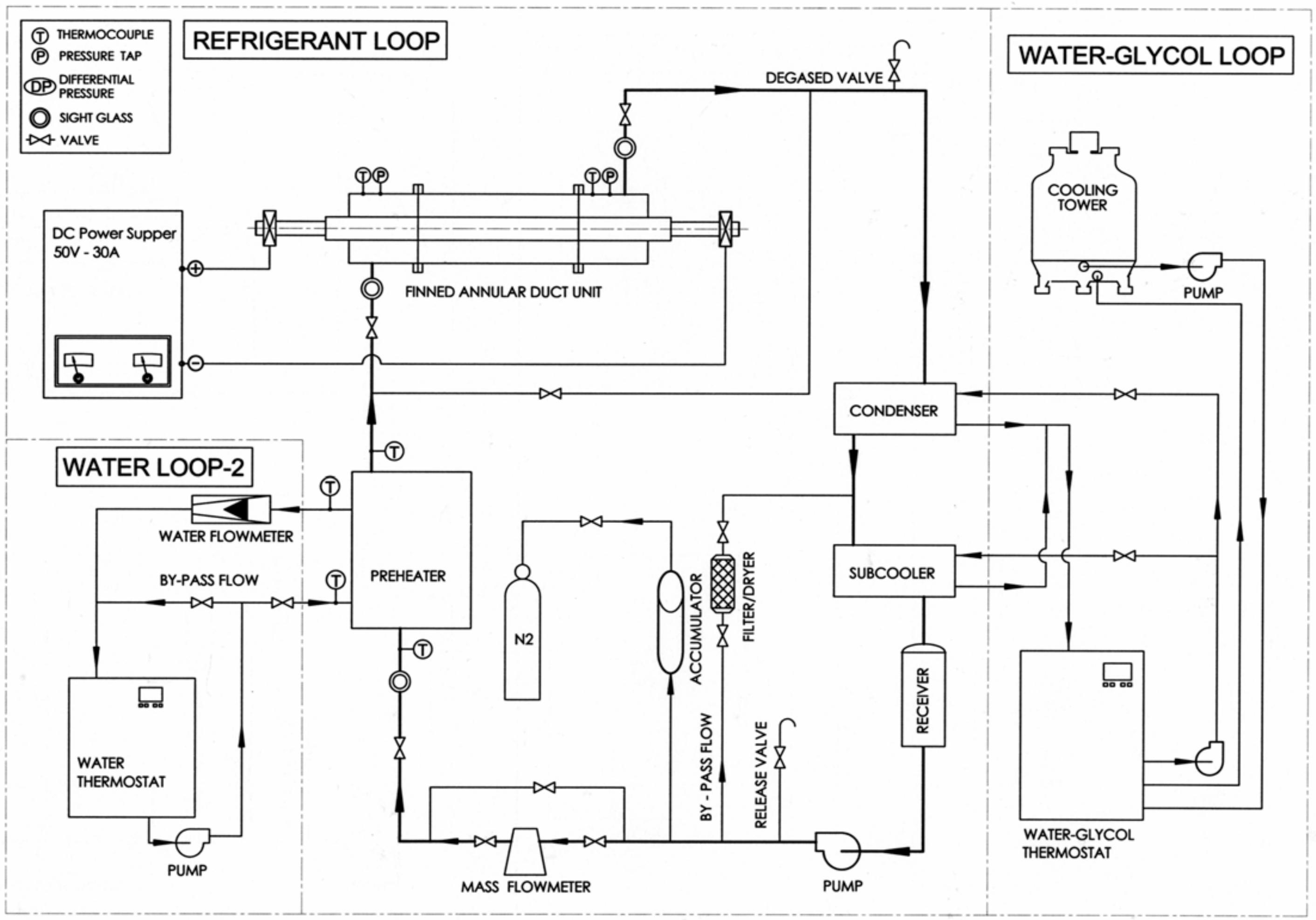


Fig. 2.1 Schematic of experimental system for the annular duct

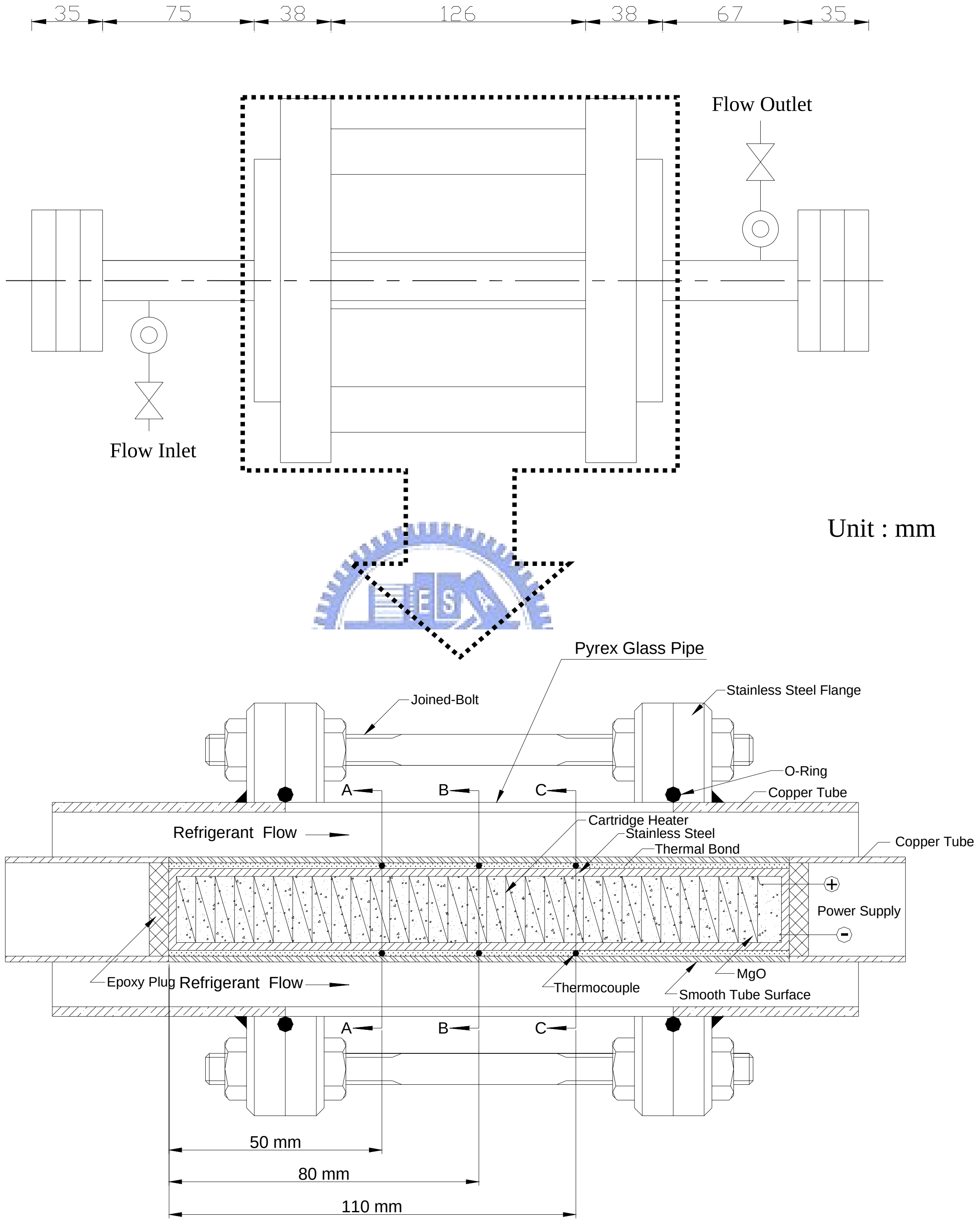
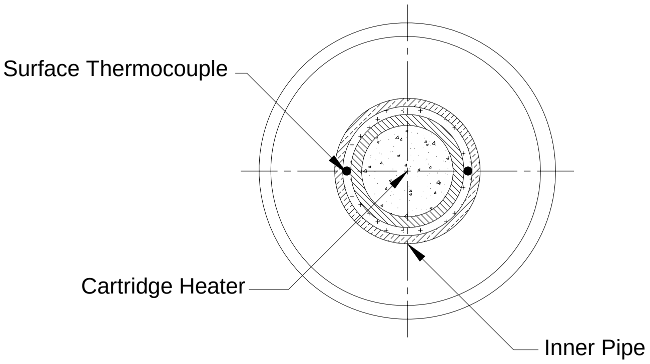
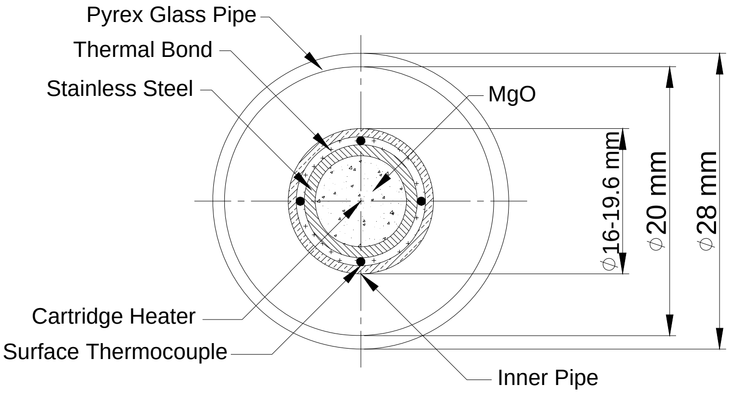


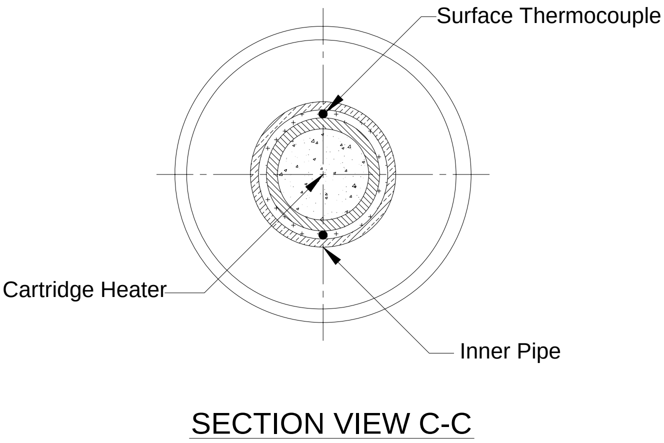
Fig. 2.2 The detailed arrangement of the test section for the annular duct



SECTION VIEW A-A



SECTION VIEW B-B



SECTION VIEW C-C

Fig. 2.3 The cross-sectional view of the annular duct showing the heater and locations of the thermocouples.