3. EXPERIMENTAL FACILITIES

3.1 Small Bubble Column (0.108m i.d.)

The final form of the experimental facility as evolved over a period of two years is sketched in Fig. 3.1. The column was constructed from a 12.7 mm thick transparent Plexiglas tube, 2.254 m high comprising of a calming section (0.146 m), a test section (1.702 m), and a gas disengagement section (0.406 m). A bubble cap distributor plate (Fig. 3.2A) for the calming section and a perforated distributor plate (Fig. 3.2B) for the test section are used to ensure uniform distribution of gas at the column base. The gas enters at the bottom of the calming section bubble cap gas distributor aluminum plate (10), which is 19 mm thick and 76.2 mm is diameter, through a 8.6 mm orifice. At the top end of this plate five bubble caps are screwed at symmetrical positions. A bubble cap is fabricated from a hexagonal cap steel screw. Three equally spaced 2 mm diameter holes with an angular separation of 120^0 are drilled into the base of the cap at a 45^0 angle, and a 4 mm diameter hole is drilled axially along the length of the screw. The gas distributor plate assembly (11) consists of a 6.4 mm thick Plexiglas plate with 91 holes of 0.8 mm diameter arranged on an equilateral triangular pitch. To prevent any solids from weeping into the calming section, a wire mesh screen (12) is installed through an O-ring flange assembly. According to the criterion developed by Zahradnik and Kastanek [48], stable bubbling in the column will be ensured for superficial gas velocities greater than 5.9 cm/s and the gas will flow uniformly through all the holes of the distributor plate.

The air is supplied by a 18.65 kW two-cylinder, two-stage air-cooled Curtis compressor (1). The compressed air passes through a 1.65 m3 surge tank (2) and is dried by a refrigerator dryer (3) to a dew point temperature of 275 K. The dried compressed air passes through a cyclone-type oil filter (4). The processed air then flows through a pressure regulator (5) and a set of two rotameters (7). A copper-constantan (T-type) thermocouple is used to measure the air temperature.

The test section has a 12.7 mm internal diameter inlet (13) for liquid at the bottom. To operate the column in the continuous mode, a liquid circulation

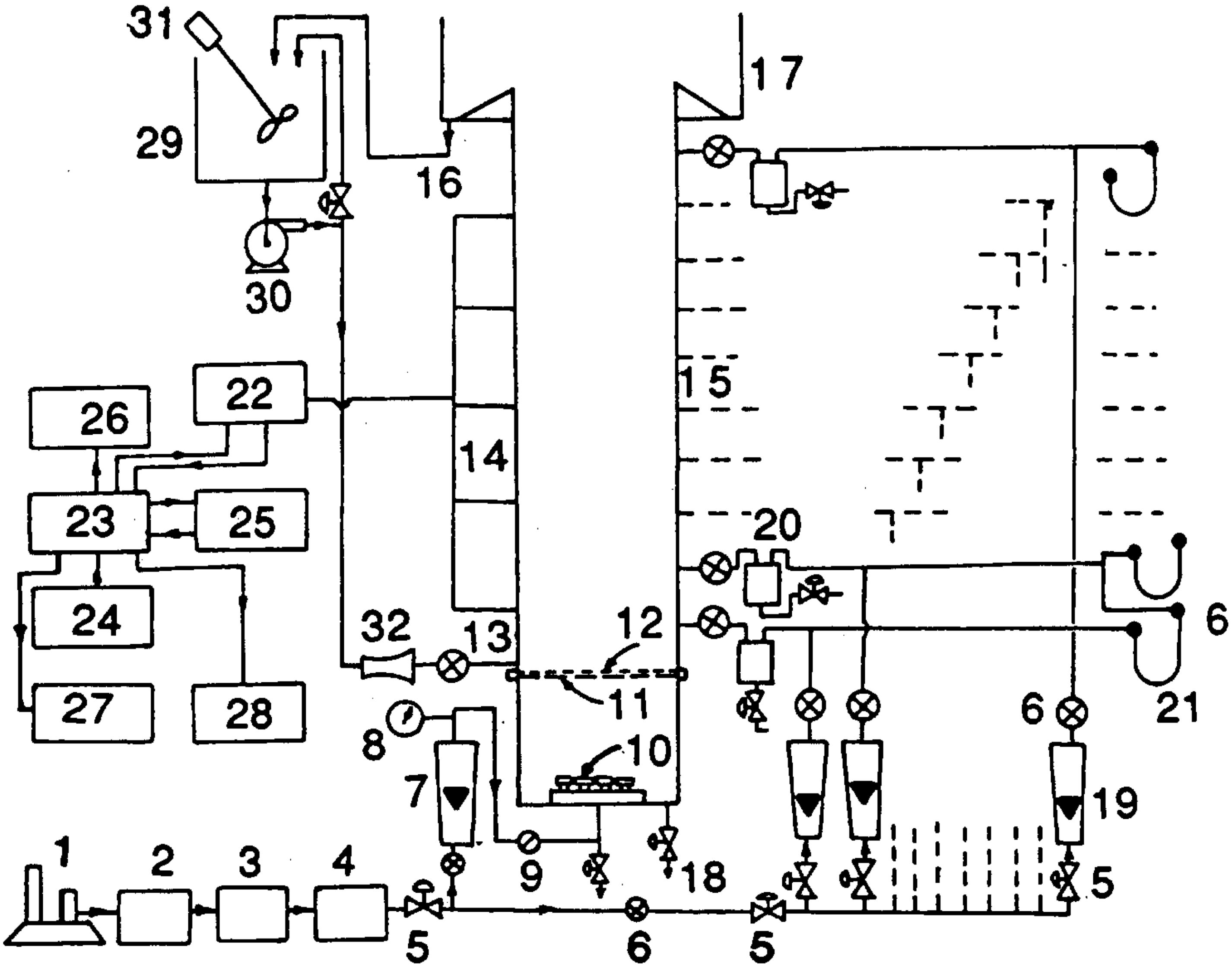

Fig. 3.1. Schematic of the 0.108 m diameter bubble column along with air supply loop, temperature and pressure measuring circuits and liquid circulation loop: (1) air compressor, (2) surge tank, (3) refrigerator drier, (4) oilscer filter, (5) pressure regulator valves, (6) gate valves, (7) rotameter, (8) pressure gauge, (9) one-way valve, (10) bubble cap distributor, (11) perforated-plate distributor, (12) stainless steel wire cloth, (13) water inlet, (14) thermocouples, (15) Plexiglas column, (16) water outlet, (17) disengaging section, (18) liquid drain, (19) purgemeters, (20) trap bottles, (21) manometers, (22) data acquisition system, (23) computer, (24) keyboard, (25) disc drive, (26) monitor, (27) printer, (28) plotter, (29) liquid storage tank, (30) liquid circulation pump, (31) stirrer and (32) venturimeter.

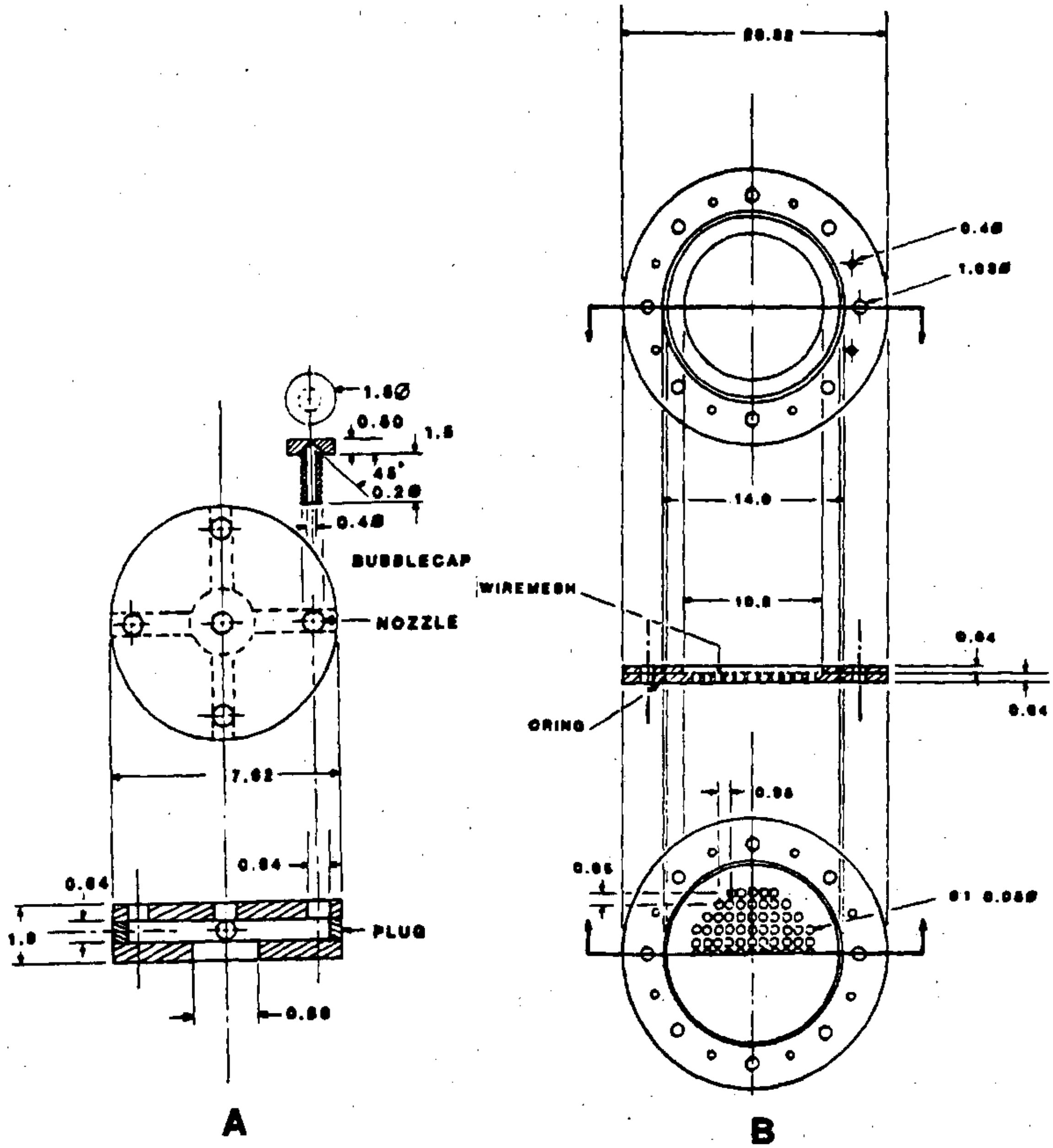

Fig. 3.2. Design details of the bubble column cap air distributor plate for the calming section (A), and of the air distributor plate for the slurry bubble column (B). All dimensions are in cm.

loop comprised of a tank (29) fitted with a stirrer (31), and a venturimeter (32) is provided. The slurry pump (30) is a Moyno-SP progressing cavity pump (Model 331) with a delivery capacity of 2 GPM at 303 kPA. The flow rate is controlled by a Reliance Electric DC-1 speed controller. A bypass line with a gate valve across the pump is provided to enable greater flexibility in controlling the liquid flow rate to the column.

To determine gas holdup (total and local) in the column, the pressure profile along the bubble column height must be established. To obtain this, a complicated measurement and control system is devised as shown in Fig. 3.1 and in greater detail in Fig. 3.3. Ten ports of 6.4 mm, for pressure measurement, are provided along the column height at equal intervals of 152.4 mm above the distributor plate. The pressure measurement system consists of a battery of 10 air purgemeters (19) with built-in needle valves for flow control and 10 bottle traps (20) connected in appropriate fashion through three-way connectors and finally communicating to the pressure ports on the column wall through an additional 10 ball valves (6). The flow resistance of each line is maintained at the same level, and manometers record the pressure difference between consecutive ports on the column wall. The air back-pressure is adjusted with the help of a regulator and a purgemeter so that there is only minimum air flow into the column and no liquid flows out of the column

Similarly, five ports (14) for temperature measurement are provided at equal intervals of 304.8 mm, with the first port located 228.6 mm above the distributor plate. The test section expands into a 0.305 m dia. tank (17), which minimizes the liquid entrainment. The overflow of liquid flows down the sloping walls of the top end of the column into the bottom of the disengagement section, where a drain (16) is provided for the outflow. An automatic tank drain is provided at the bottom end of the calming section (18) to flush out any liquid that may have drained into it. For measuring the axial and radial temperature profiles, copper-constantan thermocouple probes are designed with details given later in Figs. 3.9A and 3.9B. These probes can be inserted at various radial positions in the column and locked in position by a swagelok connector arrangement.

This column is programmed by a computer (23) (HP310), which also

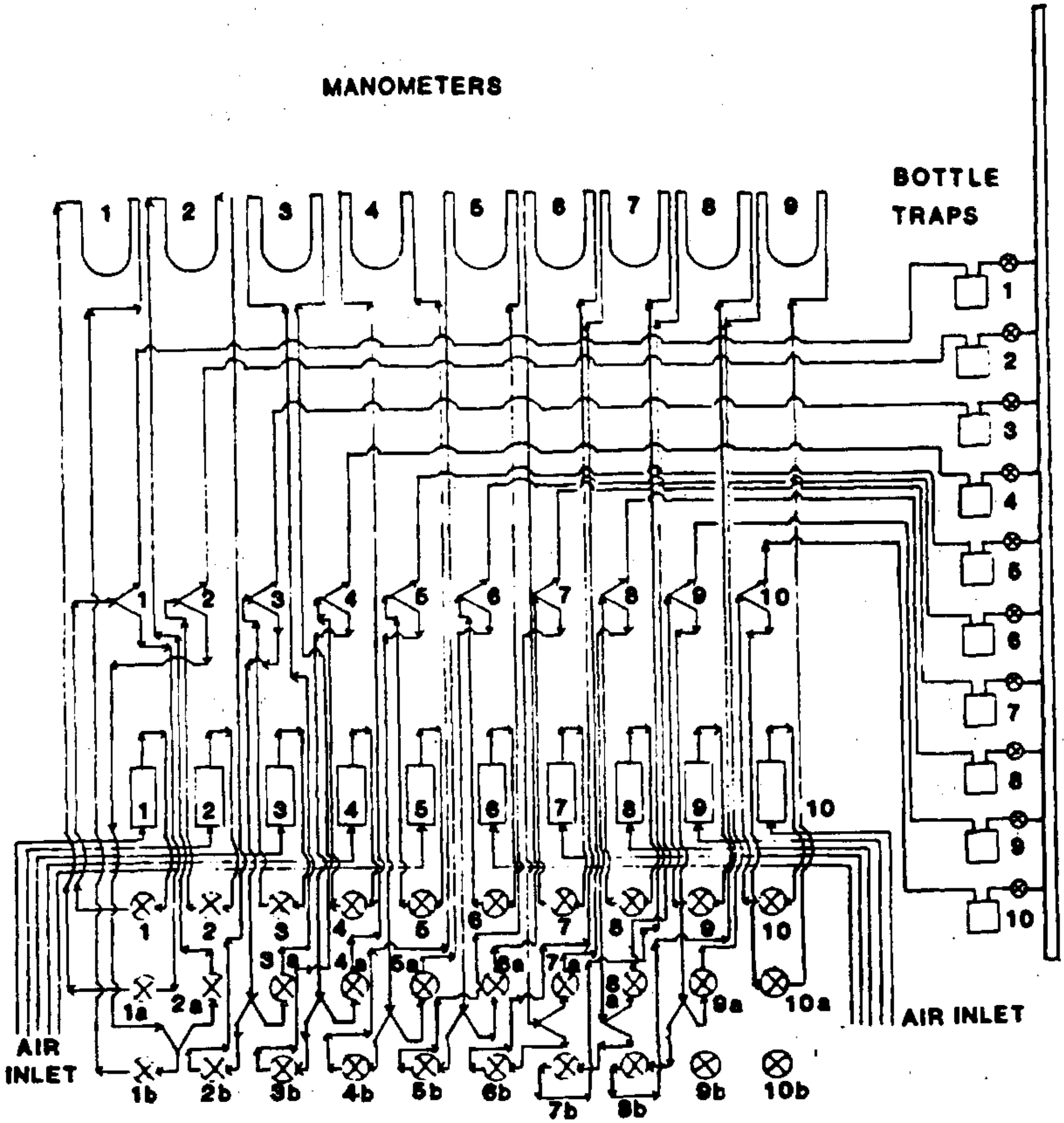

Fig. 3.3. Schematic of the pressure measurement and control systems.

converts the measured voltages to corresponding temperatures with the help of appropriate software. The system has dual flexible drive (25) and allows the computer either to read data stored on the disk or to write data on a disk with the help of an HP4620A keyboard (24). Finally, the processed data are displayed on an HP35731A monochrome video (26) and/or recorded on an HP2225A ThinkJet printer (27). The system also includes an HP7440A eight-pen graphics plotter (28).

3.1.1 Heat Transfer Internals and Thermocouple Probes

3.1.1.a Single-Tubes

The design details of the single-tube heat transfer probe is shown in Fig. 3.4. Basically it consists of three sections - top, middle, and bottom - put together with two Delrin connectors, 50 mm long. The Teflon bottom section is 305 mm long and has a conical end taper to enable smooth liquid flow around it. A threaded connector connects the bottom section to the middle brass section. Inside the brass rod a Calrod heater (305 mm) is inserted, and this middle section is connected to the stainless steel tube top section by another threaded connector. An O-ring seal is provided between the connector and steel tube to prevent liquid seepage from the column into the tube. The Calrod heater is energized by a dc power source.

Surface temperature of the probe brass section is measured by seven strategically located copper-constantan thermocouples. Their orientation and location on the surface are detailed in a of Fig. 3.4A. Thermocouples 9 and 10, and 8 and 11, are provided to measure the end heat loss to the connectors. A clamp for axially locating the probe in the column and to damp out its vibratory motion is fabricated, and its design is shown in Fig. 3.4B. The clamp consists of three arms at an angular separation of 120^{o}. The three arms are attached to a central ring clamp (1), which fits tightly on the probe surface with the help of a screw (2). The two arms (3, 4) have threaded Teflon rounded caps (5) to provide a soft and adequate grip at the inner column surface (6). The third arm (7) can thus

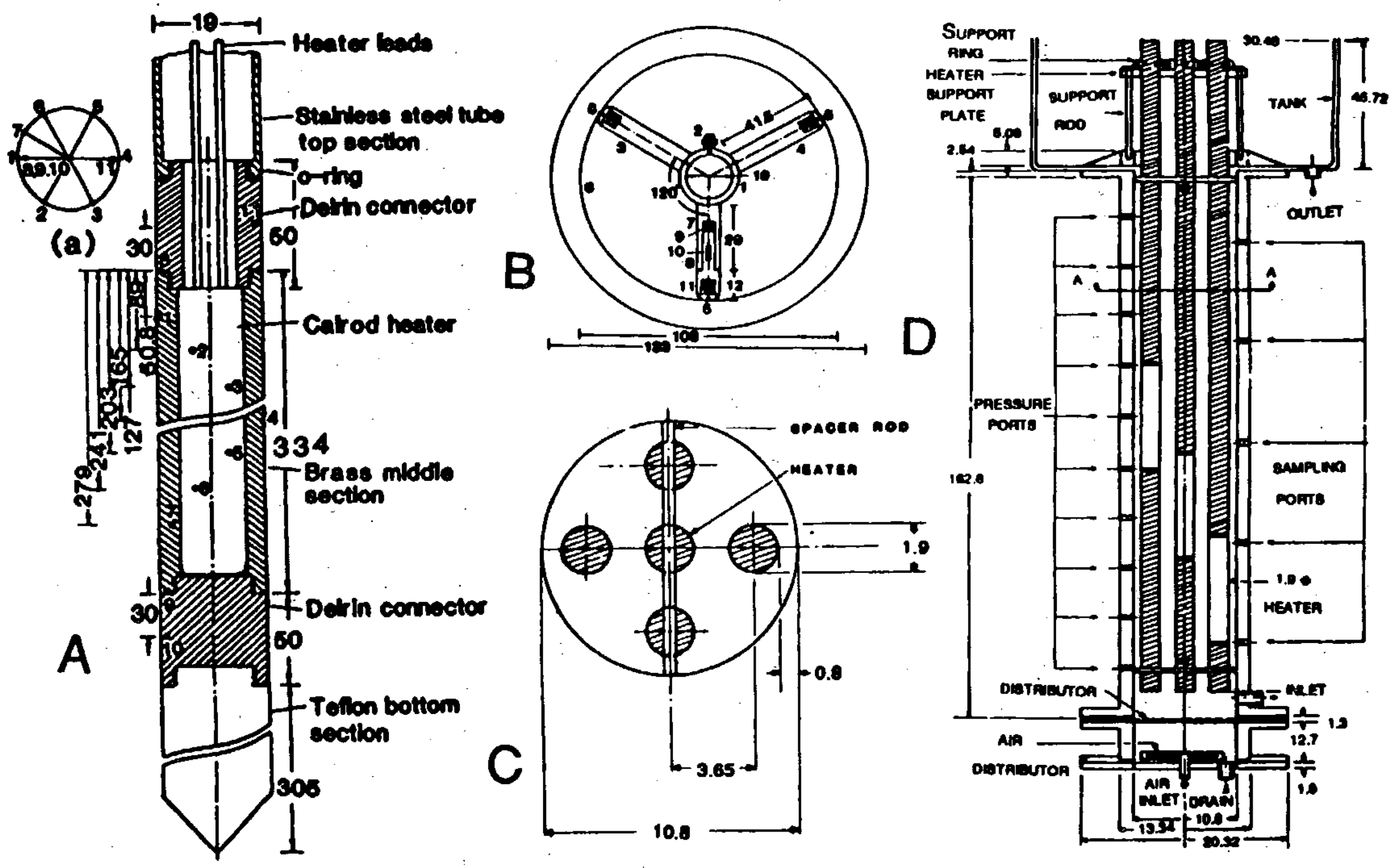

Fig. 3.4. Design details of the heat transfer probe (A), mounting clamp (B), orientation of the five-tube bundle (C), and bubble column with the tube-bundle.

be moved in and out against the spring (9). The three-arm locating clamp will therefore hold the probe rigidly along the column axis. Three such clamps are used along the probe length, and these have successfully avoided and completely damped any possible vibration of the probe in the column.

All the thermocouples for temperature measurement are brought to a Hewlett-Packard 3497A data acquisition control unit with thermocouple compensation, (22) as shown in Fig. 3.1, and also later in Fig. 3.11.

The design details of 31.8 mm and 50.8 mm diameter single heat transfer probes are given in Figs. 3.5 and 3.6 respectively.

3.1.1.b Five-Tube Bundle

A heat transfer probe bundle comprising of five 19 mm outer diameter and 188 cm long Plexiglas tubes in a square arrangement with a pitch of 36.5 mm is also used in the present measurements. Figures 3.4C, D show the probe bundle details. Each of the five tubes is provided with a 0.34 m long brass section containing a 0.305 m long Calrod heater.

3.1.1.c Seven-Tube Bundle

A heat transfer probe comprising of a 0.34 m long heated test section, and 1.0 and 0.819 m long stainless steel end sections, and six other stainless dummy tubes of 19 mm diameter constitute the 7-tube bundle. The design details of the heat transfer probe is the same as given in Fig. 3.4A and it is located vertically along the column axis. The tubes are arranged on an equilateral triangular pitch of 36.5 mm and the bundle is put together by two specially designed clamps, each provided with a telescopic arm, Fig. 3.7. The plan view of the tube bundle arrangement is shown in Fig. 3.7.

3.1.1.d Radial Thermocouple Probes

The radial temperature profile along the middle of the heated brass section in the column is established by a specially designed thermocouple probe shown

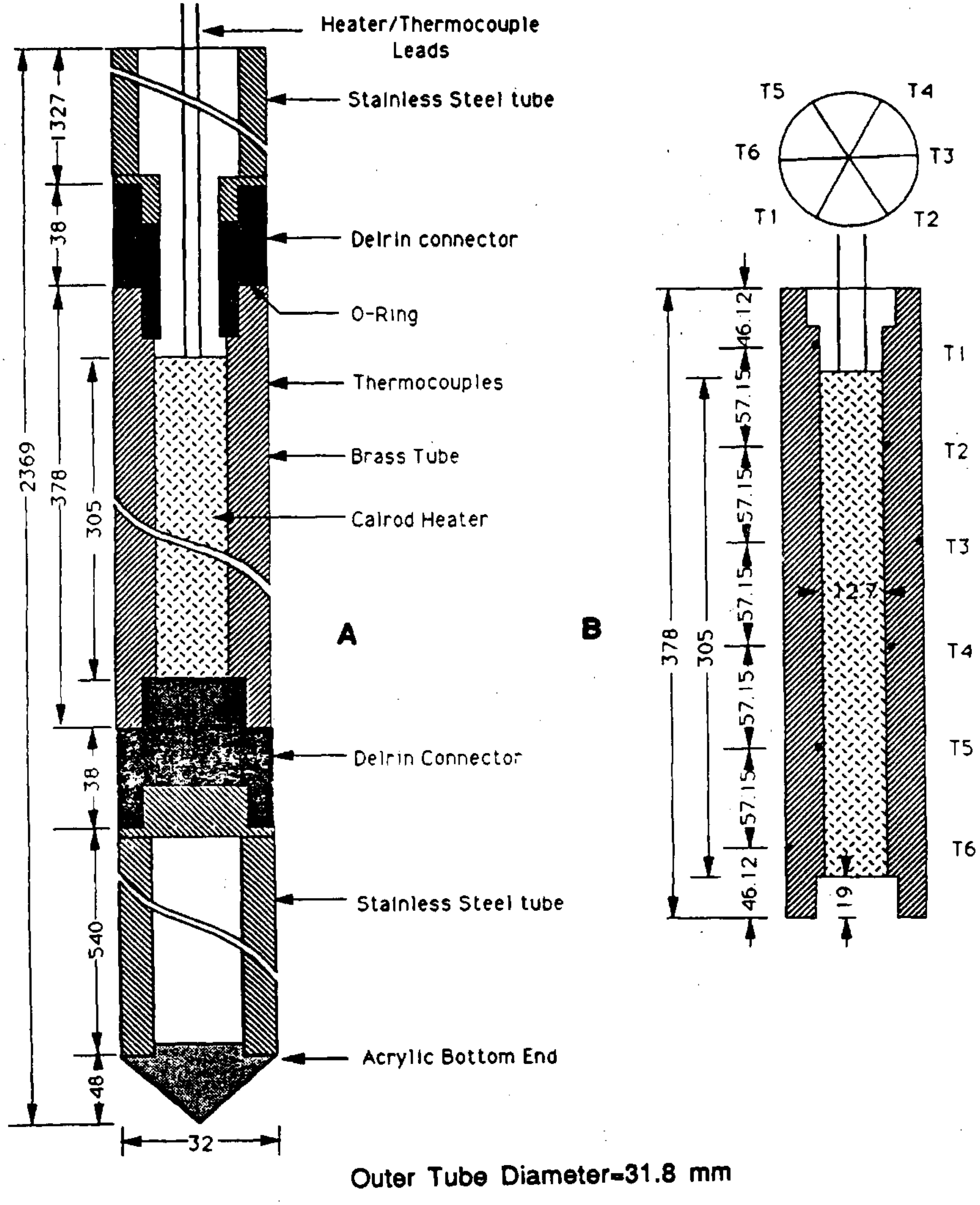

Fig. 3.5. Design details of the 31.8 mm heat transfer probe (A), and of the heated section (B). All dimensions are in mm.

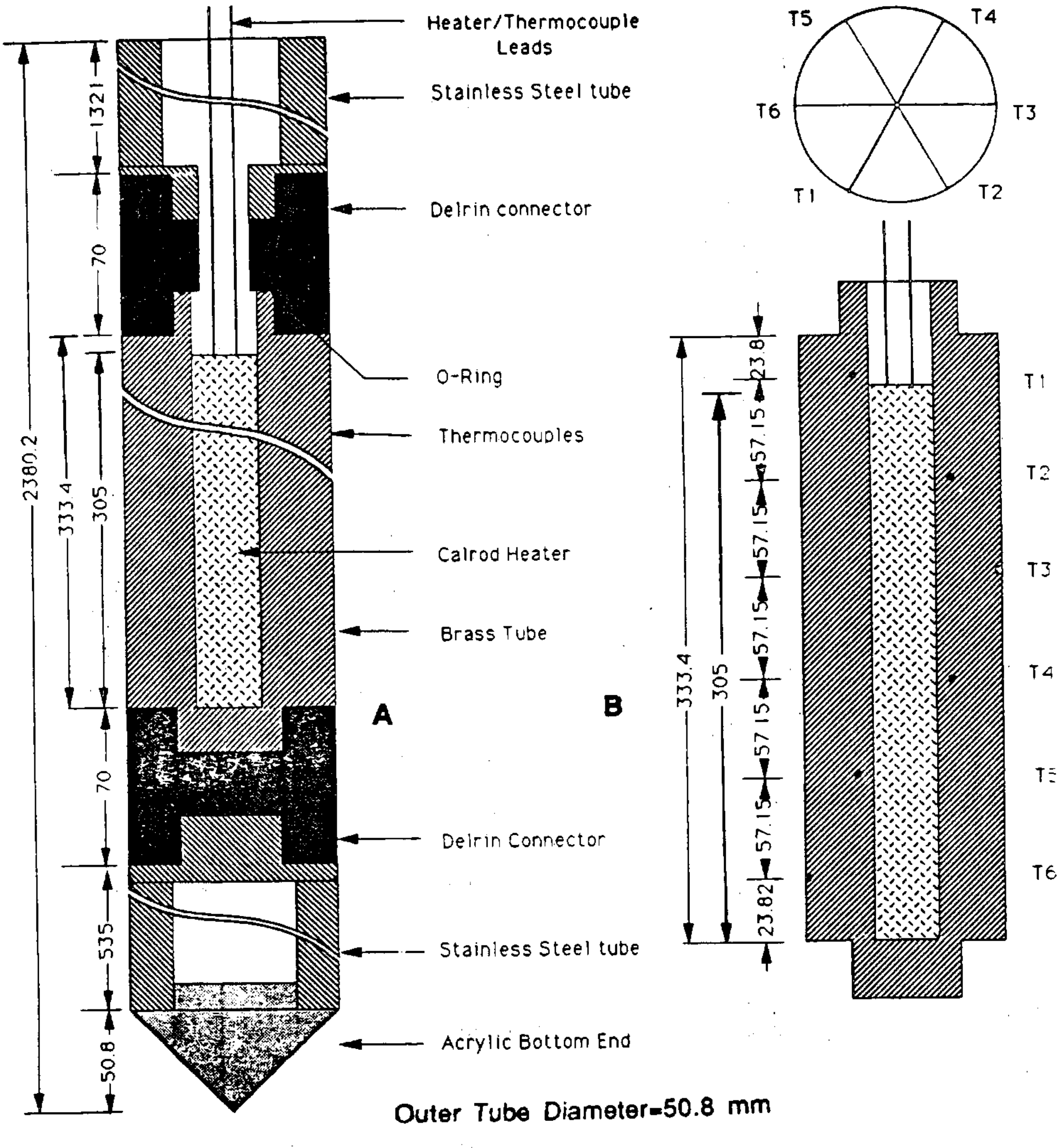

Fig. 3.6. Design details of the 50.8 mm heat transfer probe (A), and of the heated section (B). All dimensions are in mm.

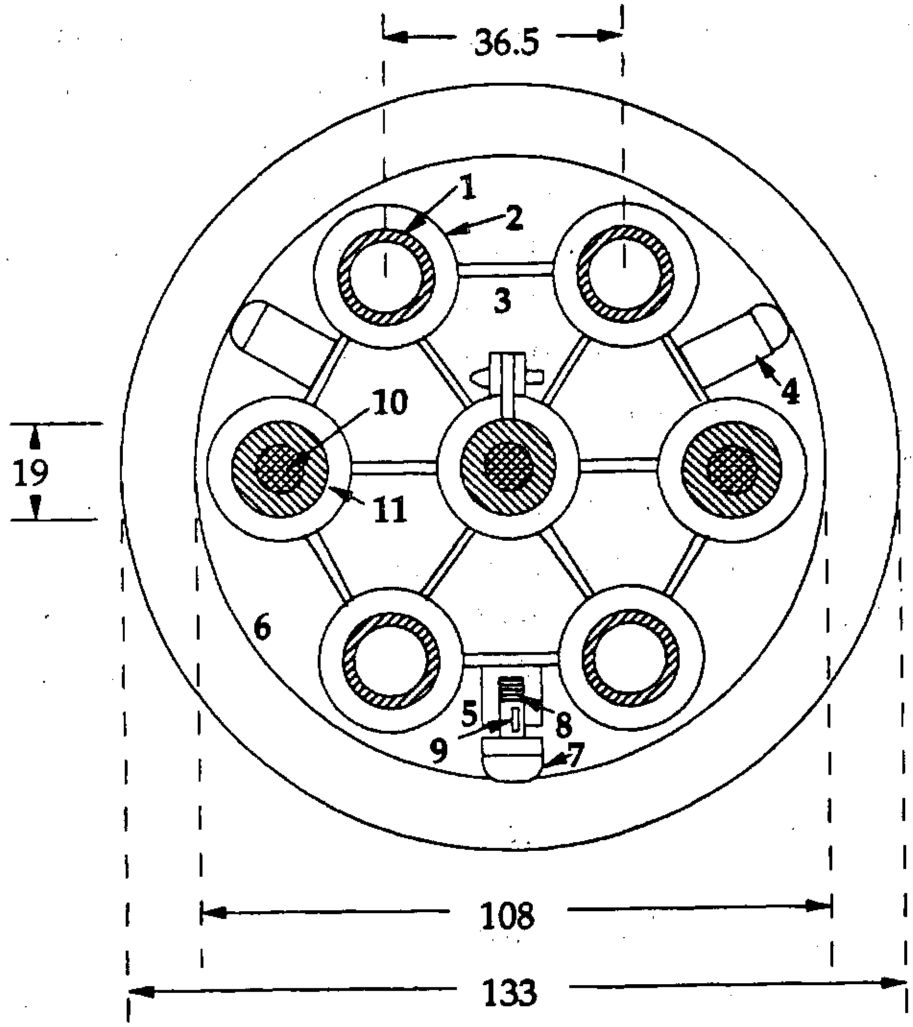

Fig. 3.7. A sectional top view through the center of the probe bundle comprising of seven simulated heat transfer probes arranged in an equilateral triangular configuration. (1) heat transfer probe, (2) ring clamp, (3) spacer plates, (4) locating stud, (5) telescopic locating stud, (6) column surface, (7) Teflon rounded cap, (8) stainless steel spring, (9) locking pin, (10) calrod heater, and (11) brass tube.

in Fig. 3.8. It is made of an Acrylic tube about 12.5 mm in diameter and has six thermocouples cemented at its front face and at different distances from the front face. This probe can be inserted to various radial positions in the column and locked at any particular position by Swagelok connector arrangement. Thermocouple probes are also designed to measure the dispersion temperature along the column height, and are located in the five ports provided at equal intervals of 0.305 m, with the first port located at 0.229 m above the gas distibutor plate. Basically each probe is made of 28 AWG copper-constantan thermocouple with glass braid insulation and is imbedded in a well on the front face of a specially designed Teflon plug with copper cement. The plug is force fitted in a 6 mm dia. stainless steel tube of 1 mm wall thickness and 0.15 m long. The thermocouple wires are passed through the tube and locked in position at the outer end by a PVC shrink tube and cemented together by an epoxy. The probe can be inserted to various radial locations in the column and locked in position by a swagelok connecter. The probe design details are given in Fig. 3.9.

All thermocouple lead wires from both probes are brought to a Hewlett-Packard data acquisition control unit and these details are shown later in Fig. 3.1.1.

3.1.2 Data Acquisition and Analysis System

A calrod heater (1kW) is used to heat the outer brass portion of the heat transfer probe and is energised by a HP6274 A D.C. power source comprising of a master and two slaves, each providing 0-60V and 0-15A with a power regulation of 0.01 percent. This arrangement of auto-series operation is characterized by one-knob control in the master and the amplitude of the slaves output voltage is equal (or proportional) to that of the master. As shown in Fig. 3.10, a voltmeter and an ammeter enable to read accurately the power fed to the heater.

A total of seventeen thermocouples form heat transfer probes designated as A, B, C, D, and E, and radial thermocouples for measuring the bulk column temperature through a thermocouple selector switch, are all brought to a Hewlett Packard 3497A data acquisition/control unit with thermocouple compensation as

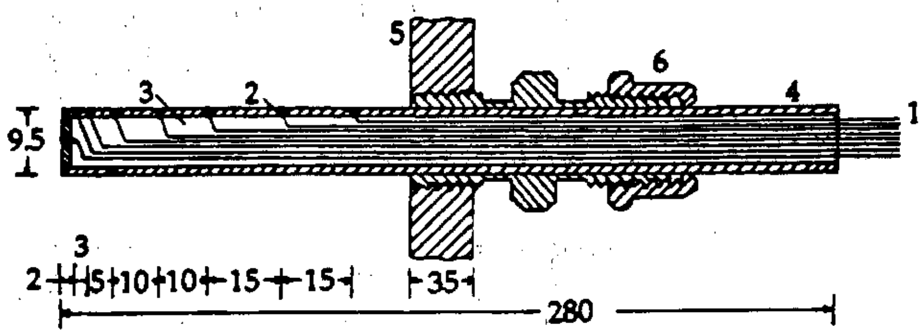

Fig. 3.8. Design details of the radial thermocouple probe. (1) copper-constantan thermocouples, (2) thermocouple well, (3) Silicone rubber, (4) Acrylic tube, (5) column wall, and (6) Swagelock connector. All dimensions are in mm.

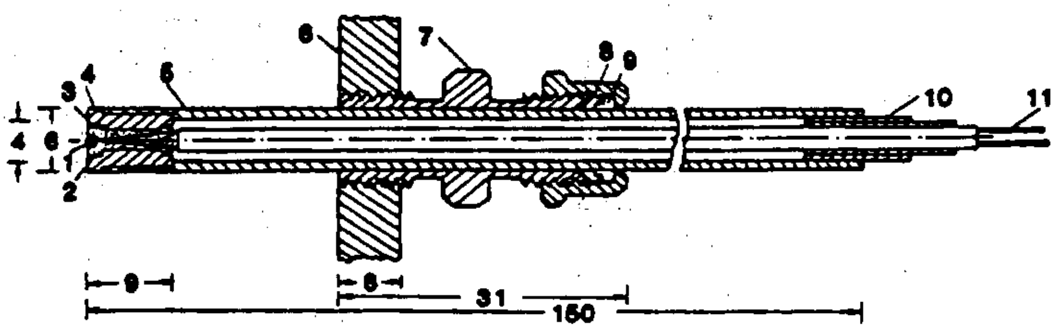

Fig. 3.9 Design details of the thermocouple probe: (1) copper constantan thermocouple, (2) thermocouple wall (3) copper cement, (4) Teflon plug, (5) stainless steel tube, (6) column well, (7) Swagelock connector, (8) front ferrule, (9) back ferrule, (10) shrink tube, (11) thermocouple leads. All dimensions are in mm.

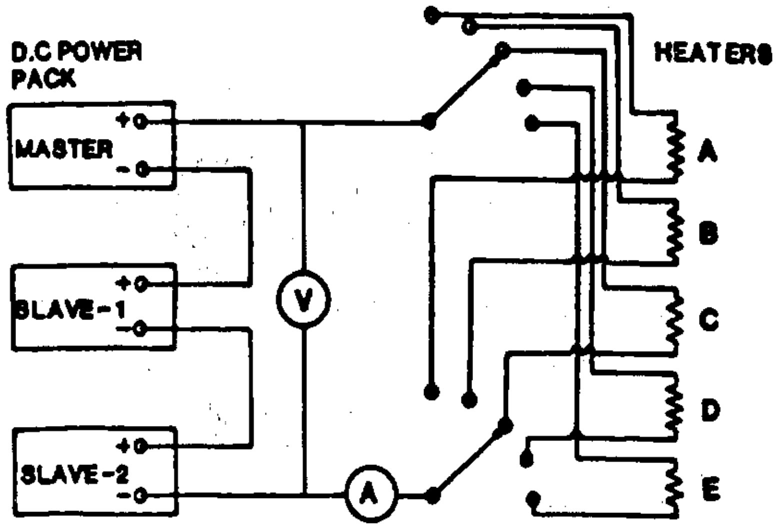

Fig. 3. 10. Schematic of the D. C. power supply system for the heater probes.

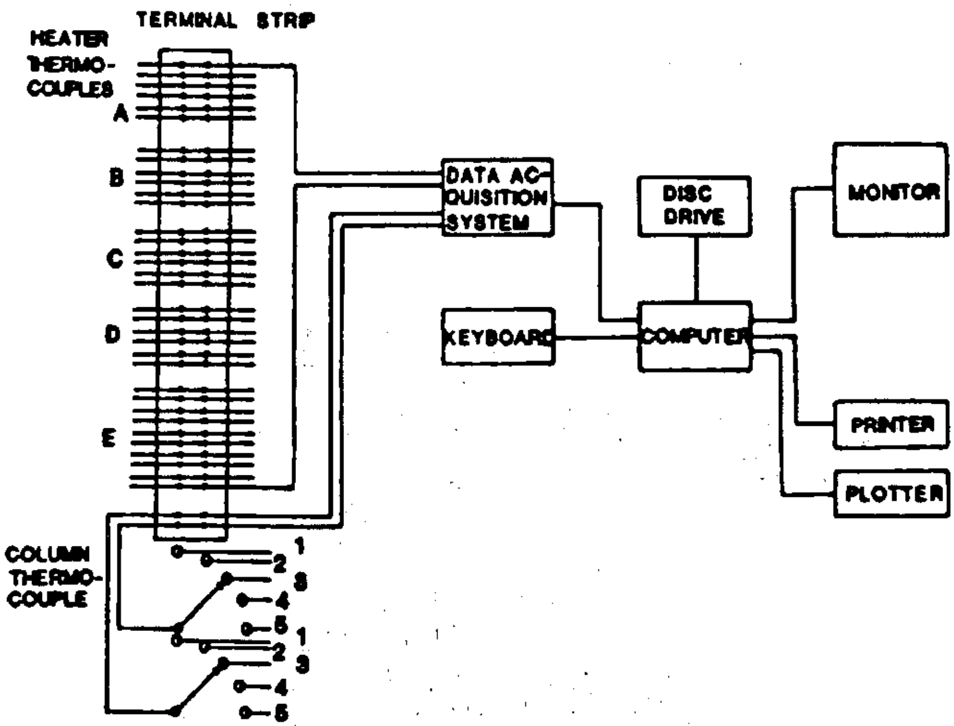

Fig. 3.11. Detailed schematic of the temperature measuring system.

shown in Fig. 3.11. This unit is programmed by a computer (HP310) which also converts the measured voltages to the corresponding temperatures with the help of appropriate software. The system has dual flexible disc drive HP9122D and allows the computer either to read data stored on the disc or to write data on a disc. Finally, the processed data are displayed on a HP 35731A monochrome video and/or recorded on a HP2225A Think Jet printer. The data acquisition system also includes a HP7440A eight-pen graphics plotter.

3.2 Large Bubble Column (0.305 m i. d.)

The schematic of the 0.305 m internal diameter bubble column along with its associated air supply system, pressure and temperature measuring circuits is shown in Fig. 3.12. The air supply loop consists of a two-stage air compressor (1), refrigerator drier (2), filter (3), pressure regulator valve (4), rotameters (5), gas pressure gauge (6), gate valves (7), and one-way valve (8). The pressure measurement system comprises of four trap bottles (17), four purgemeters (18), four liquid manometers (19), pressure sensor (20), pressure monitor (21) and on-off valves (22). The pressure sensor is an Omega PX120-015 GV stainless steel transducer (20) appropriate for the pressure range 0 to 15 psig and capable of handling corrosive media. The output of this transducer is indicated on the pressure monitor (21), an Omega DP-350 digital transducer indicator. A suitable valving arrangement (22) brings this transducer into the desired pressure measuring location. Liquid manometers (19) are also simultaneously exposed for the pressure measurement. The two sets of readings agree with each other within a maximum deviation of 0.2 percent.

Four copper-constantan thermocouple probes are provided along the height of the column in the metal inserts (14). The design details of these thermocouple probes are similar to those given in Figs. 3.15 and 3.16. The output of twenty thermocouples brought to a Hewlett Packard 3552A data acquisition/control unit with thermocouple compensation (23). This unit is programmed by a computer (24), HP310, which also convertgs the measured voltages to the corresponding temperatures with the help of appropriate software. The system has dual flexible disk drives HP9122D (26) and allows the computer either to read data stored on

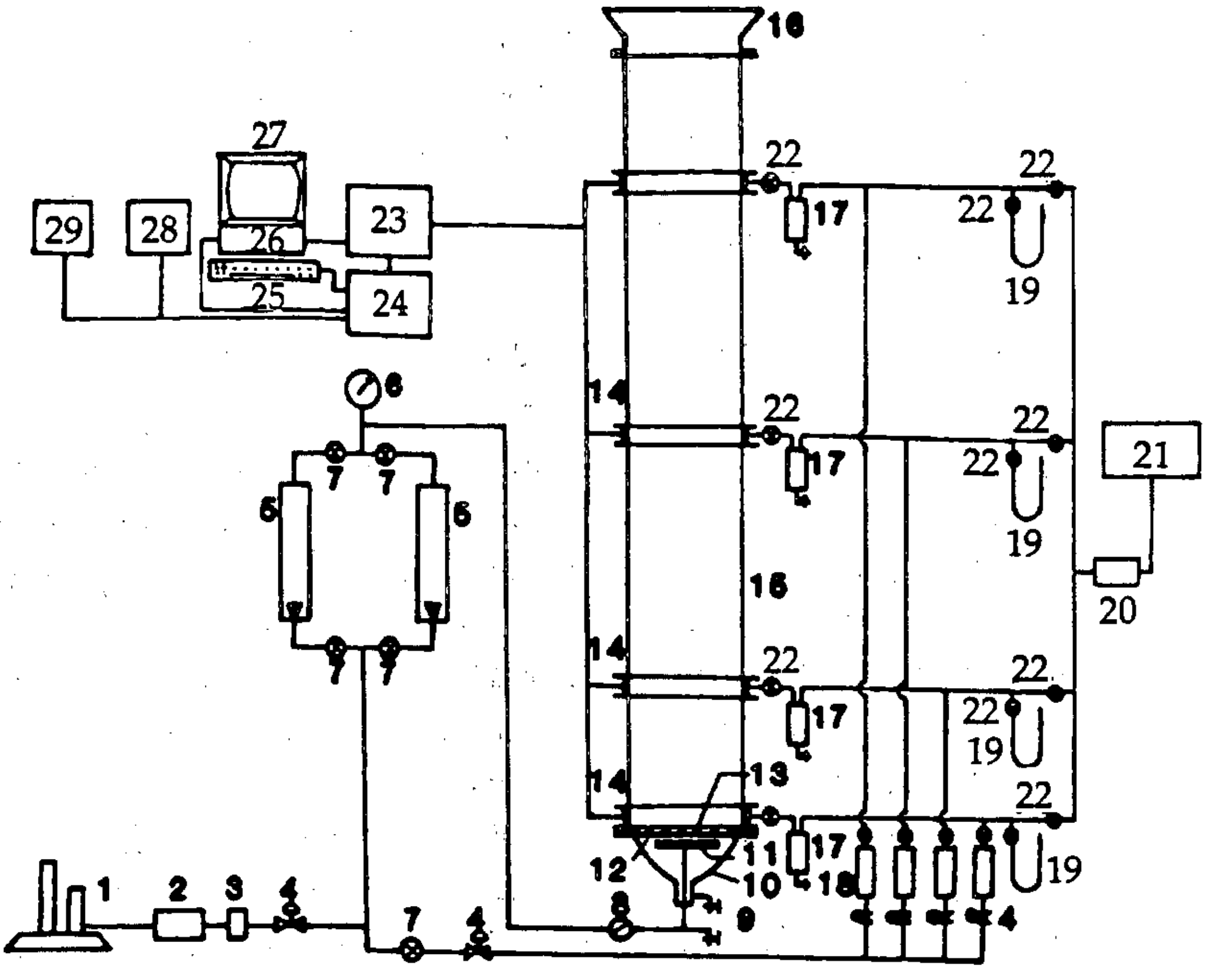

Fig. 3.12. Schematic of the 0.305 m diameter slurry bubble column along with air supply loop, temperature and pressure measuring circuits. (1) air compressor, (2) refrigerator drier, (3) oilscer filter, (4) pressure regulator valve, (5) rotameters, (6) pressure gauge, (7) gate valves, (8) one-way valve, (9) liquid drain, (10) conical section, (11) bubble-cap distributor plate, (12) perforated plate distributor, (13) stainless steel wire cloth, (14) metal inserts, (15) glass column, (16) diverger section, (17) trap bottles, (18) purgemeters, (19) manometers, (20) pressure sensor, (21) pressure monitor, (22) on-off valve, (23) data acquisition system, (24) computer, (25) key-board, (26) disc drive, (27) monitor, (28) printer, and (29) plotter.

the disc or to write data on a disc with the help of an HP46021A keyboard (25). Finally, the processed data are displayed on a HP98786A monochrome video monitor (27) and/or recorded on a HP2225A Think Jet printer (28). The system also includes a HP7440A eight-pen graphics plotter (29).

The slurry column cosists of four glass sections of total height (15), four stainless steel inserts each 75 mm high (14), and the bottom conical section (10). These are assembled together on a specially designed metal structure enabling to work around the column at two different levels. A specially designed clamp system is fabricated to attach the flange at the second metal insert (14) to the support structure. This arrangement absorbs the loads of the bottom column section, glass conical section (10), bubble cap distributor plate (11), perforated plate distributor (12) and the liquid drain adapter along with its accessories at the second metal insert from where the entire bottom column assembly is hanging. Similarly, the rest of the upper column section rests and is supported from a specially designed clamping system attached at the second and third metal inserts from the bottom of the column.

The design details of the bubble cap and perforated plate gas distributors are shown in Fig 3.13A. The bubble cap distributor (9) is 203.2 mm diameter stainless steel plate having sixty-one bubble caps arranged on concentric circles as shown in Fig. 3.13B with an equilateral triangular pitch of 28.6 mm. This plate is held in the cyclindrical section (10) 44.4 mm high and terminating into the support and gas inlet pipe (1) of 12 mm internal diameter. The pipe is introduced into the bottom conical section (8) of the column and is made gas and liquid tight by attaching it to a specially designed stainless steel liquid drain adapter (3) through a Teflon coated nut (2). The adapter (3) also provides a similar air and liquid tight seal to conical glass section by a glange joint (6) using gasket (5) and a soft insert (7). The adapter also has a liquid drain (4) for removing any liquid that might drain into this section through the distributor plate from the main column. The square gas distributor (11) is made from a stainless steel plate of 4 mm thickness and 420 mm to a side and has 0.8 mm orifices in a square arrangement of 9.5 mm pitch as shown in Fig. 3.13C. A stainless steel 200 X 200 wire cloth is mounted over this perforated plate to avoid solids weeping from the column into the distributor section. Six locating pins (14) are provided in the

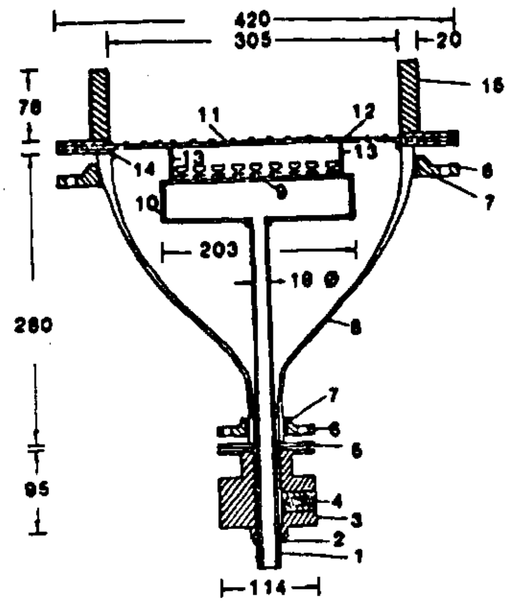

Fig. 3.13A. Design details of the bottom end assembly of the 0.305 m diameter slurry bubble column. (1) gas inlet pipe, (2) Teflon coated nut, (3) liquid drain adapter, (4) liquid drain, (5) gaskets, (6) flanges., (7) soft inserts, (8) conical glass section, (9) bubble cap distributor plate, (10) cylindrical holder, (11) perforated plate distributor, (12) stainless steel wire cloth, (13) spacer studs, (14) locating pins, and (15) metal insert. All dimensions are in mm.

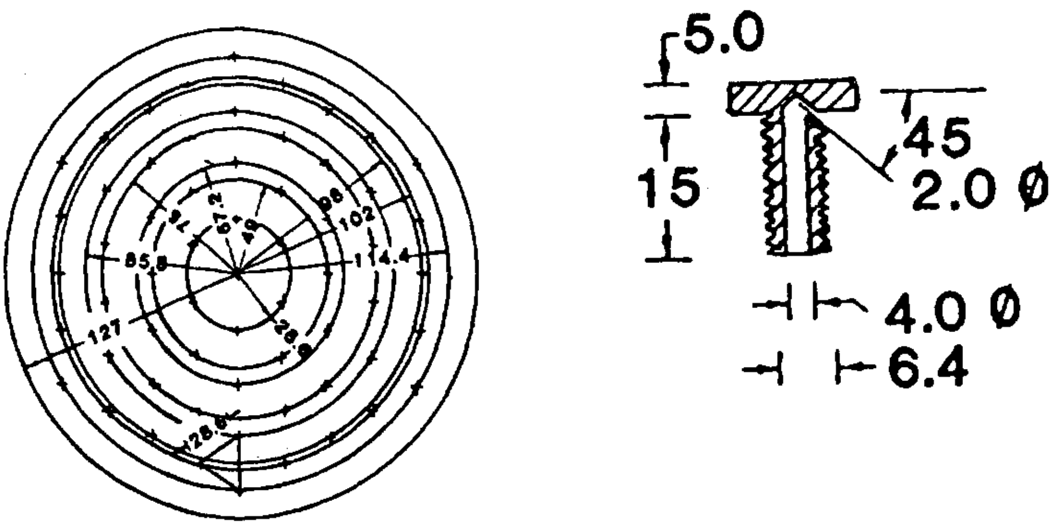

Fig. 3.13B. Arrangement of the bubble-caps on the distributor plate. All dimensions are in mm.

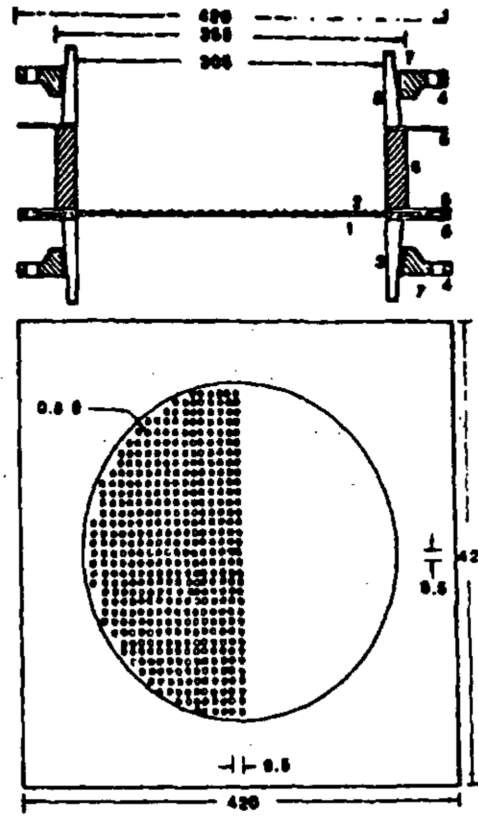

Fig. 3.13C. Design details of the perforated gas distributor plate for the 0.305 m diameter slurry bubble column. (1) perforated distributor, (2) stainless steel wire cloth, (3) bottom conical section, (4) flange, (5) gasket, (6) metal insert., (7) soft inserts, and (8) glass column. All dimensions are in mm.

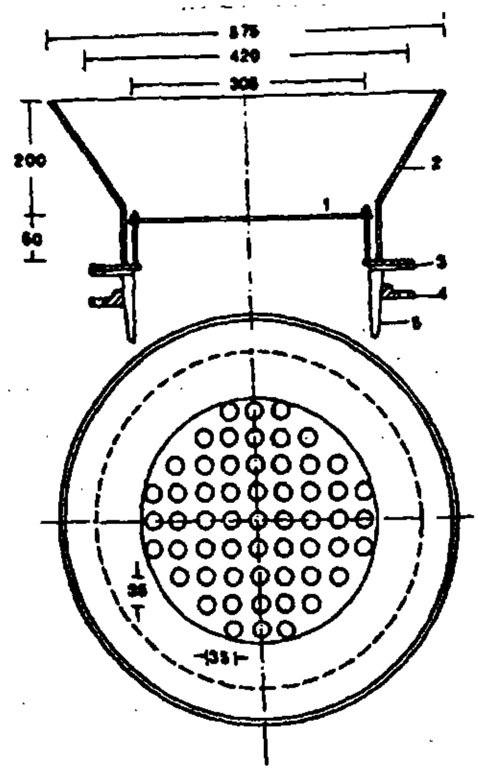

Fig. 3.13D. Design details of the diverger section at the top end of the 0. 305 m diameter slurry bubble column. (1) stainless steel perforated plate, (2) diverger section, (3) gaskets, (4) flange, and (5) glass column. All dimensions are in mm.

distributor plate (11) to ensure its correct positioning in the conical section (8). The perforated plate is held in the right position by three spacer studs (13).

The top end of the column is provided with a diverging section as shown in Fig. 3.13D. The stainless steel plate (1) of 420 mm in diameter and 4 mm thickness is provided as a cover at the top of the column. It has fifty-seven holes of 25.4 mm diameter arranged in a square configuration with a pitch of 35 mm. The conical diverging section has a neck 50 mm tall and a slant height of 150 mm as shown in Fig. 3.13D.

The upper end section of the column terminates into a cylindrical section and its end is closed by a flat stainless steel sheet through a flange joint. A side gas/vapor outlet is connected to a 102 mm diameter metal flexible tube which joins the column to the laboratory main exhaust. The connecting metal pipe has two liquid traps to recover the condensate, one just after the column exit and the second before the main exhaust. This exhaust system became necessary for operating the column at higher temperatures, especially closer to the boiling point of liquids contained in the column.

3.2.1 Heat Transfer Internals and Radial Thermocouple Probes

3.2.1a Single Tube

A cylindrical heat transfer probe, 19 mm in diameter and 3.25 m long, is axially mounted in the column with the help of three specially designed three-arm clamps. Each clamp has one rigid and two telescopic arms. The details are shown in Fig. 3.14A. The heat transfer probe consists of three sections viz., top, middle, and bottom. The middle section contains the heated test brass section, 36.1 cm long, and a calrod heater is installed axially inside this brass section. On either side of this test section are the stainless steel sections attached to the brass section by Teflon connectors. The heater leads are brought out and are connected to a regulated HP6274A D.C. power source comprising of a master and two slaves. The lower end of the probe terminates into a conical stainless steel taper to enable a smooth flow around the probe. On the test surface six thermocoules are

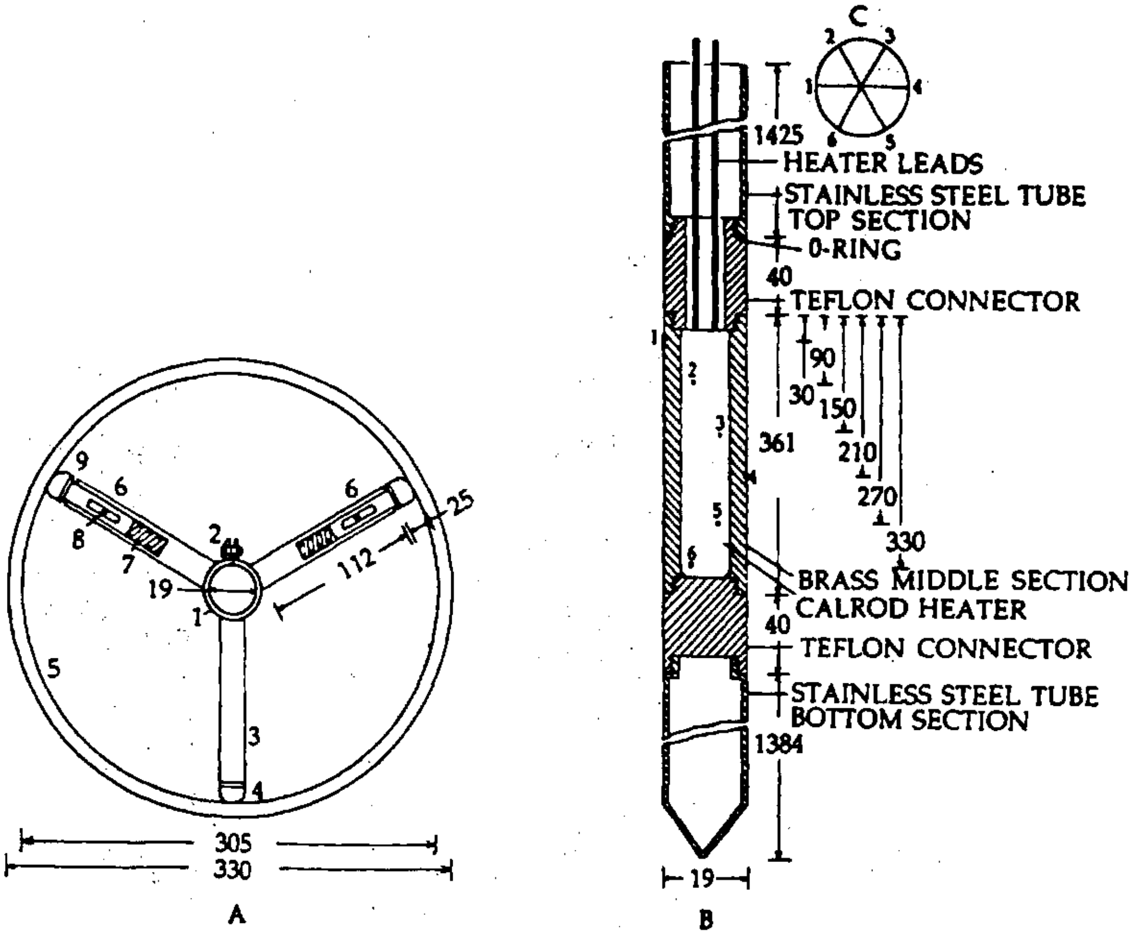

Fig. 3.14. (A) Three-arm locating clamp, (B) single heat transfer probe, (C) orientation of thermocouples for the 0.305 m diameter bubble column. All dimensions are in mm. (A): (1) ring clamp, (2) screw, (3) radial arms, (4) Teflon rounded cap, (5) column surface, (6) telescopic arms (7) spring, (8) locking pin, and (9) front end of the telescopic arm.

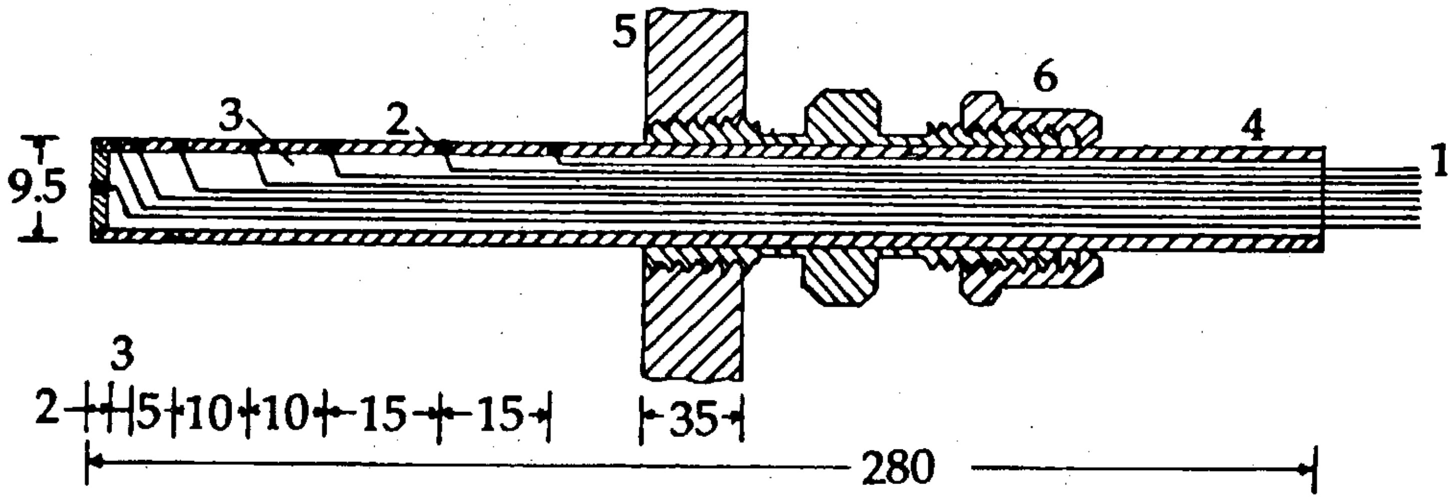

Fig. 3.15. Design details of the radial thermocouple probe. (1) copper-constantan thermocouples, (2) thermocouple well, (3) Silicone rubber, (4) ceramic tube, (5) column wall, and (6) swagelock connector. All dimensions are in mm.

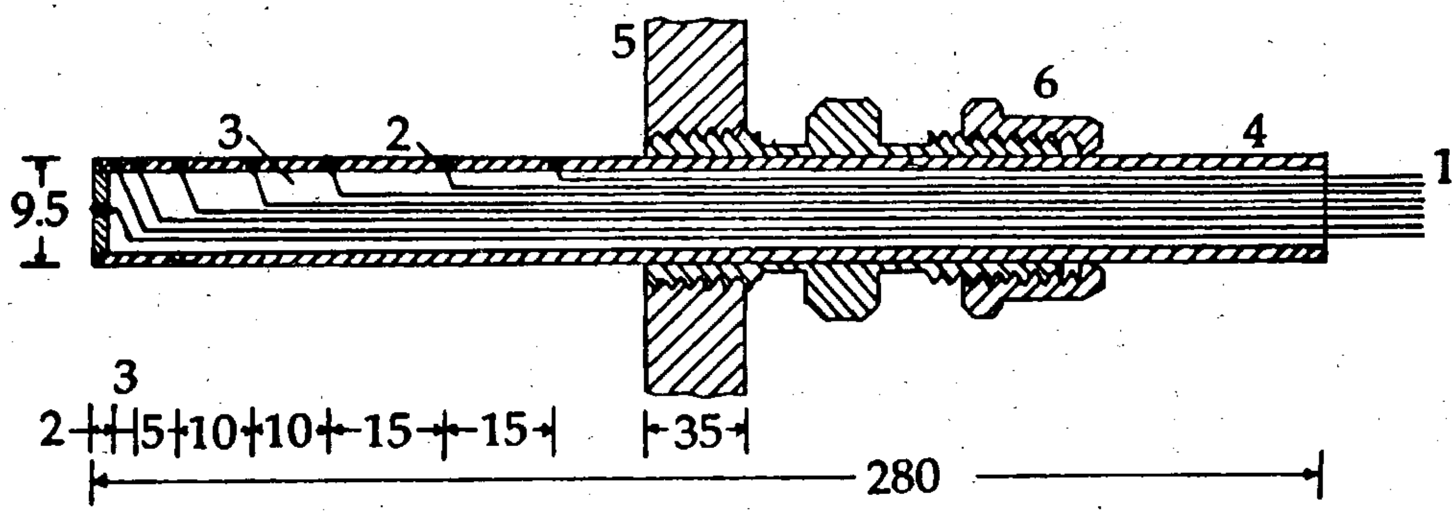

Fig. 3.16. Design details of the radial thermocouple probe. (1) copper-constantan thermocouples, (2) thermocouple well, (3) Silicone rubber, (4) stainless steel, (5) column wall, and (6) swagelok connector. All dimensions are in mm.

connected into milled grooves at various angularly staggered axial positions as shown in Fig. 3.14B. To locate the test section at different axial positions in the column, different stainless steel sections of proper lengths are attached on either end. Three different positions are investigated in this work, referred to as the upper, middle and lower regions of the column. In the upper region, the middle of the heated test section is located 2.188 m above the distributor plate, while its height is 1.605 and 0.523 m for the middle and lower regions respectively.

To obtain the radial temperature profile in the bubble column four thermocouple probes are especially designed as shown in Figs. 3.15, 3.16 and 3.19 a-d. In a typical design these are made from a ceramic tube 9.5 mm in diameter, with eight copper-constantan thermocouples located at 0, 2, 5, 10, 20, 30, 45 and 60 mm from its tip. The length of the probe is 28 cm and is located approximately in the middle of the heated test section and installed in the stainless steel insert with a swagelock connector. It can thus be moved in and out in the column at a given height to obtain the radial temperature profile necessary for the calculation of the heat transfer coefficient between the probe and the dispersion around it. A typical design of single copper-constantan thermocouple probe used to measure column temperature is the same as in Fig. 3.9 except the dimensions are as in Fig. 3.15. These two probes are used to measure column temperatures in conjunction with single, five- and seven-tube bundles.

3.2 l.b Five- and Seven-Tube Bundles

Two tube bundles, containing either five- or seven-tubes and arranged in configurations shown in Figs. 3.17 B, C, are used to simulate the heat transfer surfaces. The heat transfer probes form part of the tubebundle and are marked P1, P2, P3 and P4, are designed similar to the 19 mm heat transfer probe shown in Fig. 3.14B. The heater tubes used to heat the dispersion and maintain it at a given temperature level are shown marked H1, H2, H3 and H4. Each of the heater tubes, houses a single phase 240 V AC, 4kW calrod heater of length 1.22 m. Each tube of the bundles is 19 mm in diameter and 3.25 m in length. The configuration of five-tube bundles is such that the heat transfer probe is located along column axis and the heaters at stratigically chosen locations in the grid.

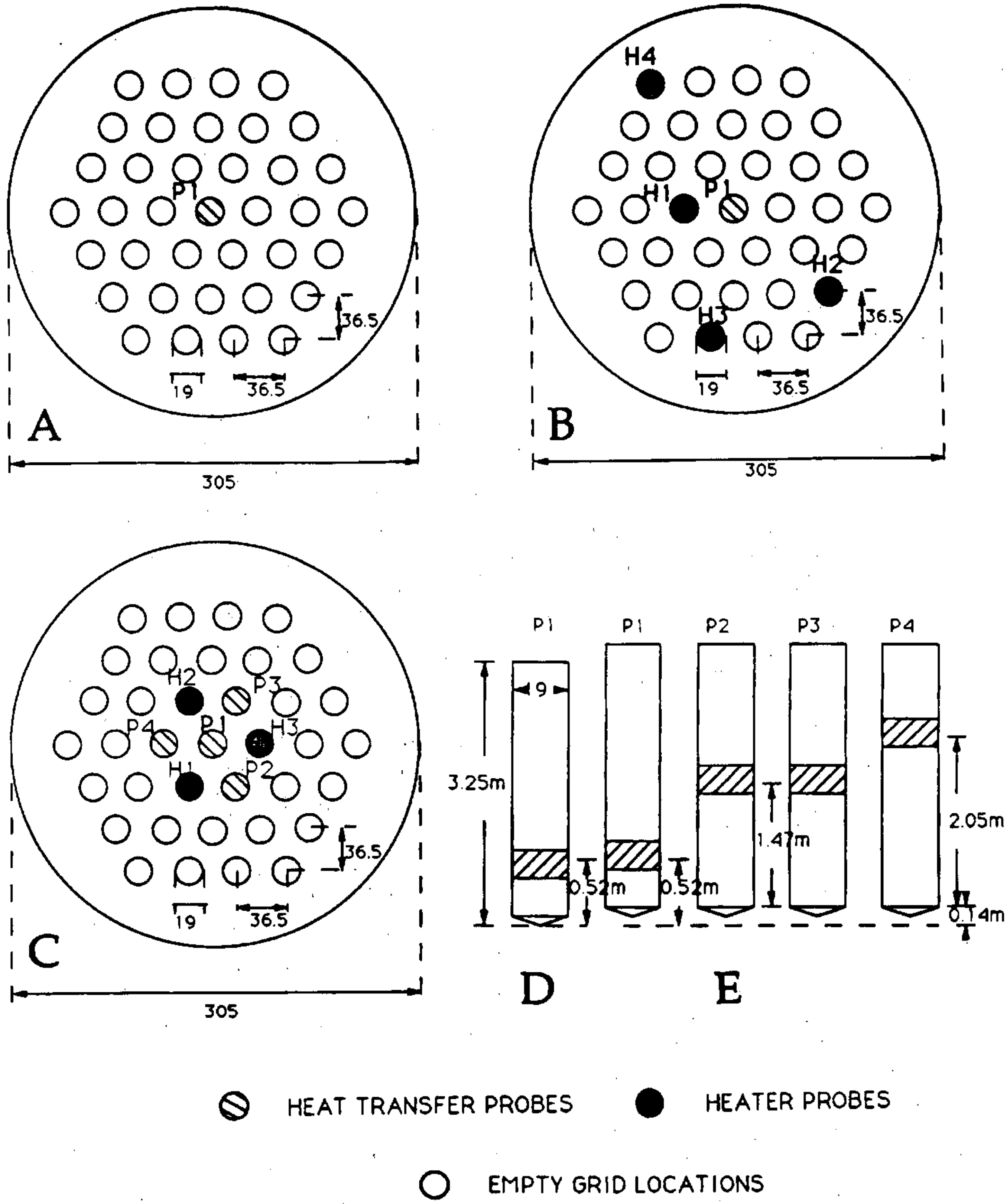

Fig. 3.17. Orientation of heater and heat transfer probes in tube bundles. Single heat transfer probe (A), four heater and single heat transfer probe (B), three heater and four heat transfer probes (C), location of heater section in the single heat transfer probe (D), and location of four heater sections in the four heat transfer probe bundle (E).

The seven-tube bundle has all seven tubes located on the vertices of an equilateral triangle, 36.5 mm to a side. The location of the heat transfer probes (P1 to P4) is shown in Fig. 3.17C and 3.17E.

Each tube bundle can be mounted in the column with the help of two specially designed three-arm clamps. Two arms of each clamp are equipped with telescopic studs and the layout is shown in Fig. 3.17. The clamp can accommodate thrity-seven tubes, located on three equilateral triangles of side lengths 36.5, 73.0 and 109.5 mm from the center.

3.2.1.c Thirty-Seven Tube Bundle

The details of thirty-seven tube bundle are shown in Fig. 3.18A-D. It is equipped with thirty-seven 19 mm tubes which occupy all grids of the mounting clamps shown in Fig. 3.17. Four of these tubes house 4 calrod heaters and will heat the suspension in the slurry bubble column. These tubes can be identified in Fig. 3.18D with white finish at their ends. Four of the tubes are provided with heat transfer test sections about 0.36 m in length. These are also provided with calrod heaters to energize the probes while measuring the heat transfer coefficient. The surface temperature is established by six thermocouples cemented on the surface in milled grooves. The heat transfer coefficents are measured for the test sections located in the four heat transfer probes at different heights and radial positions. These are: test section along the column axis at an elevation of 0.57 m above the distributor plate (heat transfer probe 1); test section at an elevation of 0.57 m but at a radial distance of 36.5 mm (heat transfer probe 2); test section located at an elevation of 1.15 m and at a radial distance of 51.6 mm (heat transfer probe 3), and test section located at an elevation of 1.15m and at a radial distance of 109.5 mm (heat transfer probe 4). A plan view of the locations of heat transfer probes, heater tubes, and of the unheated tubes is shown in Fig. 3.18C.

3.2.1.d Radial Thermocouple Probes

Four ceramic radial thermocouple probes, each equipped with four or five

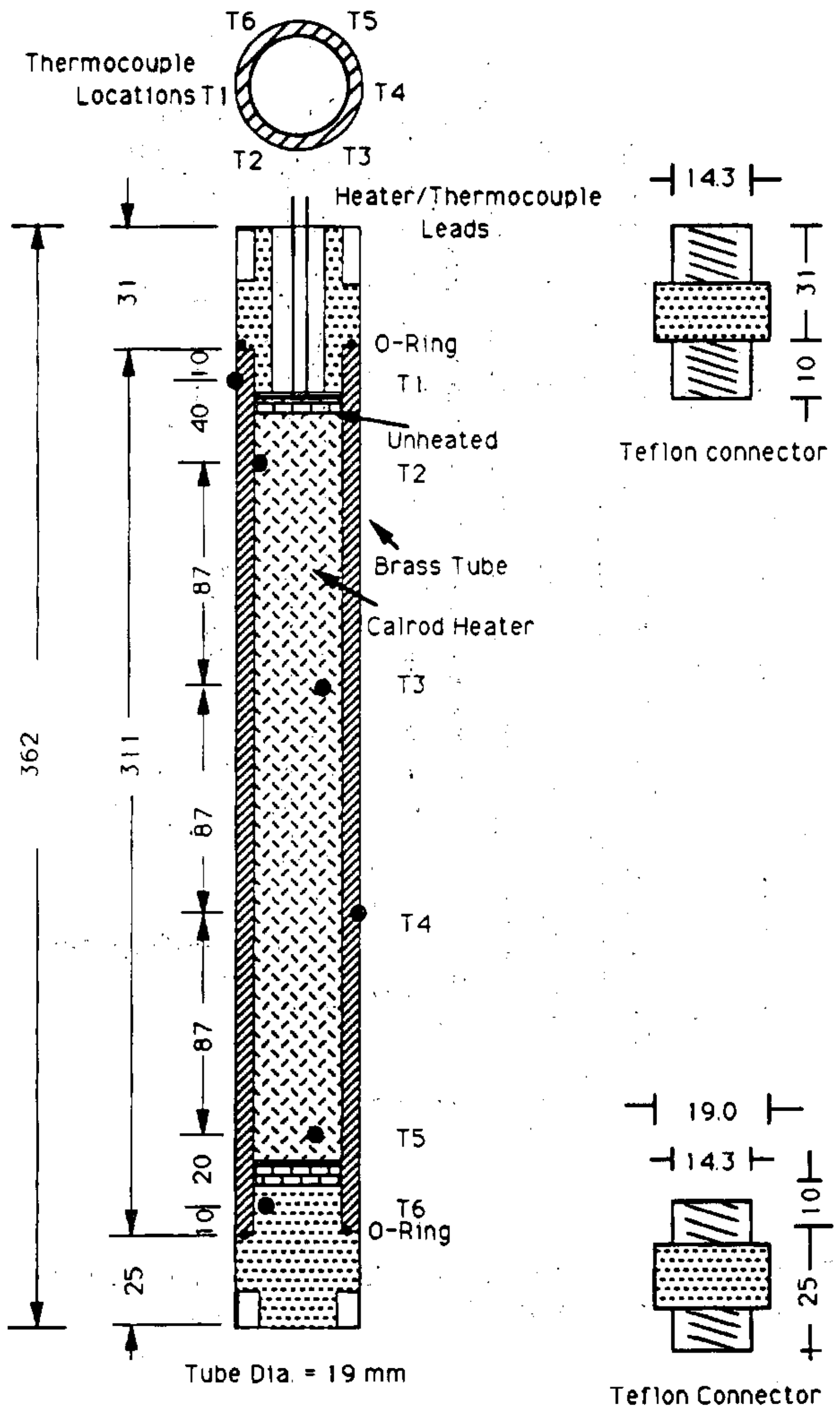

Fig. 3.18A. Design details of the heated section of the heat-transfer probes and thermocouple locations used in the thirty-seven tube bundle.

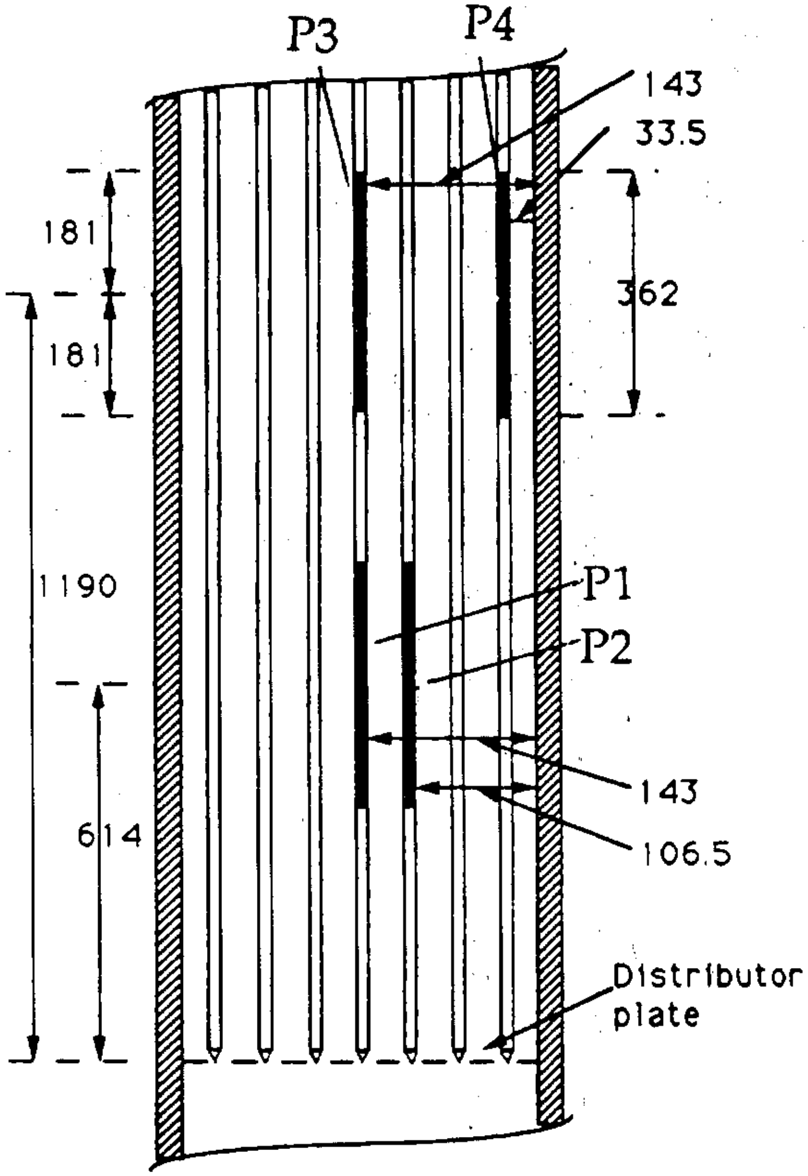

Fig. 3.18B. A sectional view of the tube bundle through plane aa in the figure, 3.18 C. All dimensions are in mm. The figure is not to scale.

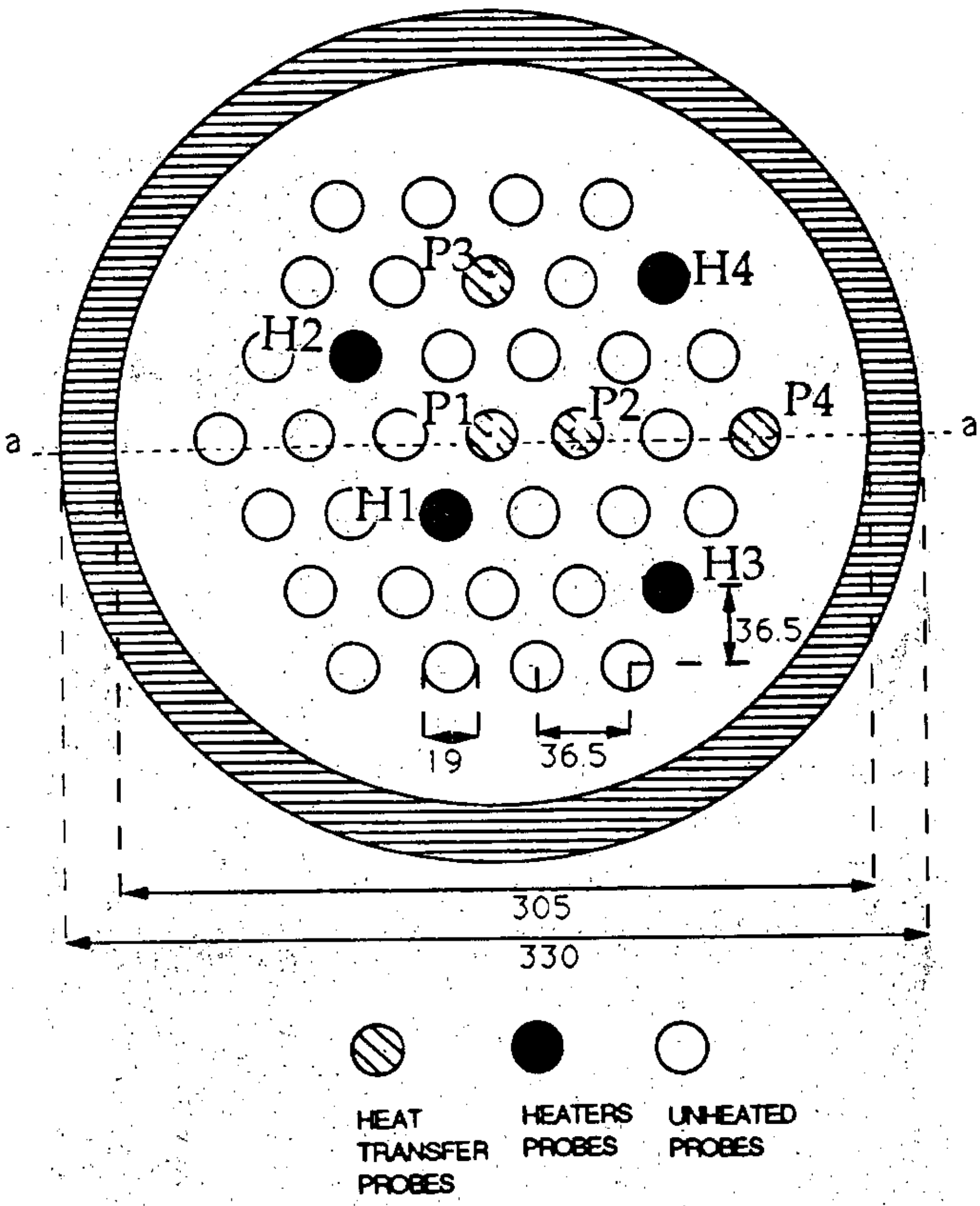

Fig. 3.18C. The plan view of the thirty-seven tube bundle.

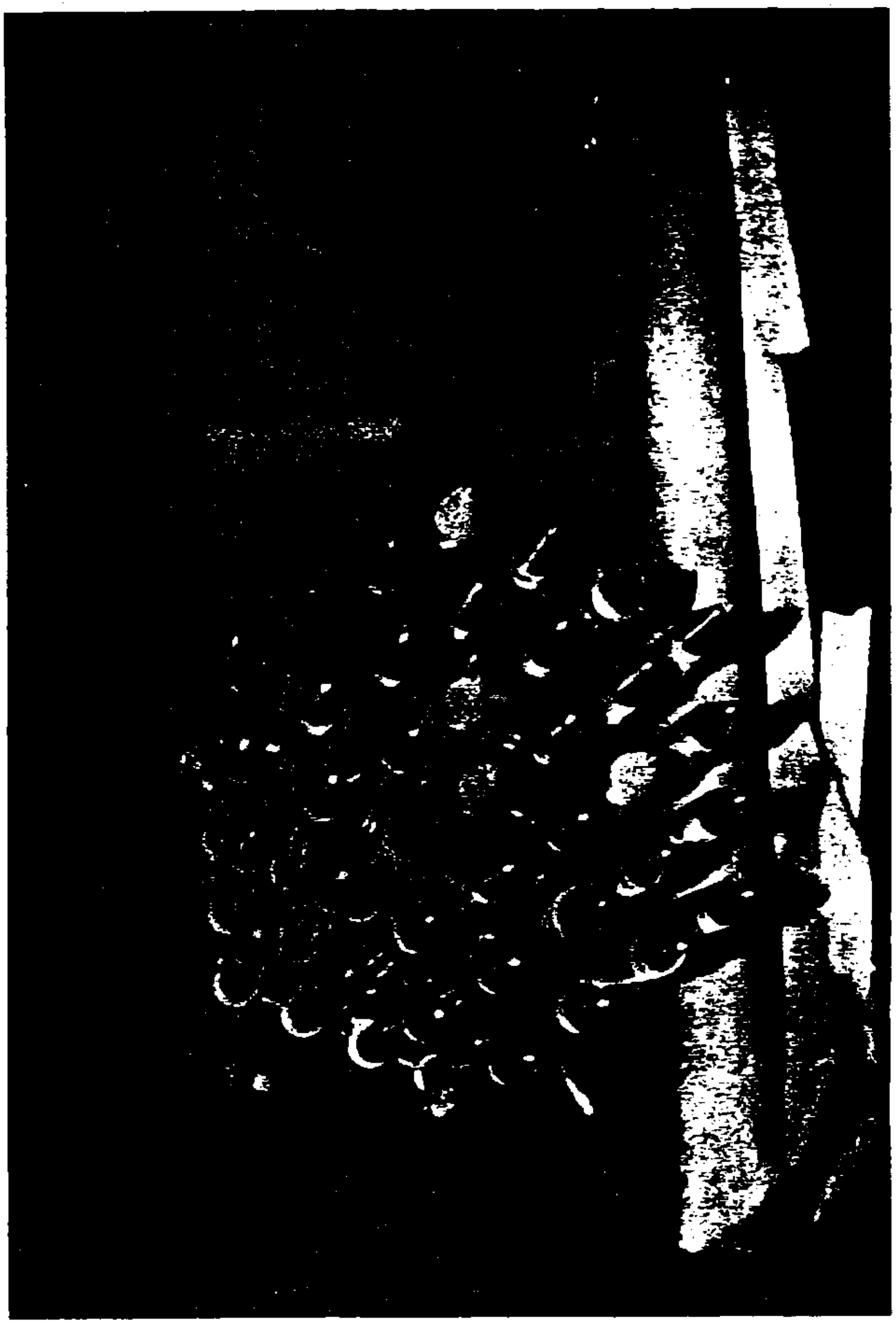

Fig. 3.18D A photographic view of the thirty-seven tube bundle.

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best available copy.

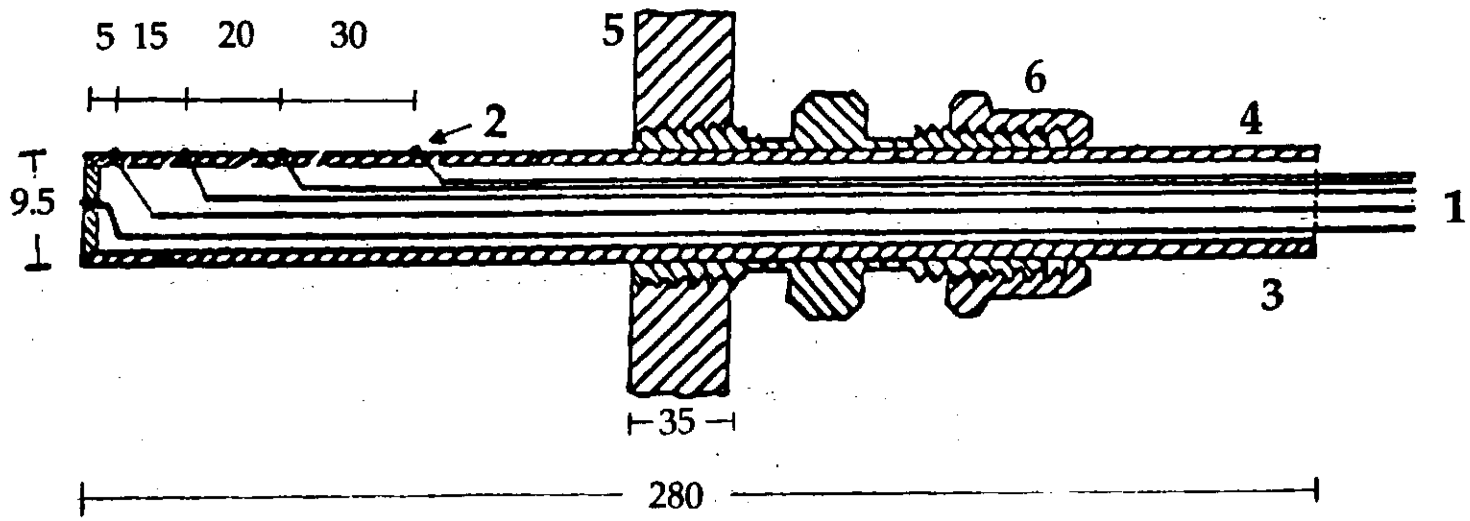

Fig. 3.19A. Design details of the radial thermocouple probe. (1) Copper-Constantan thermocouples, (2) Thermocouple well, (3) Copper cement, (4) Ceramic tube, (5) Column wall, and (6) Swagelok connector. All dimensions are in mm.

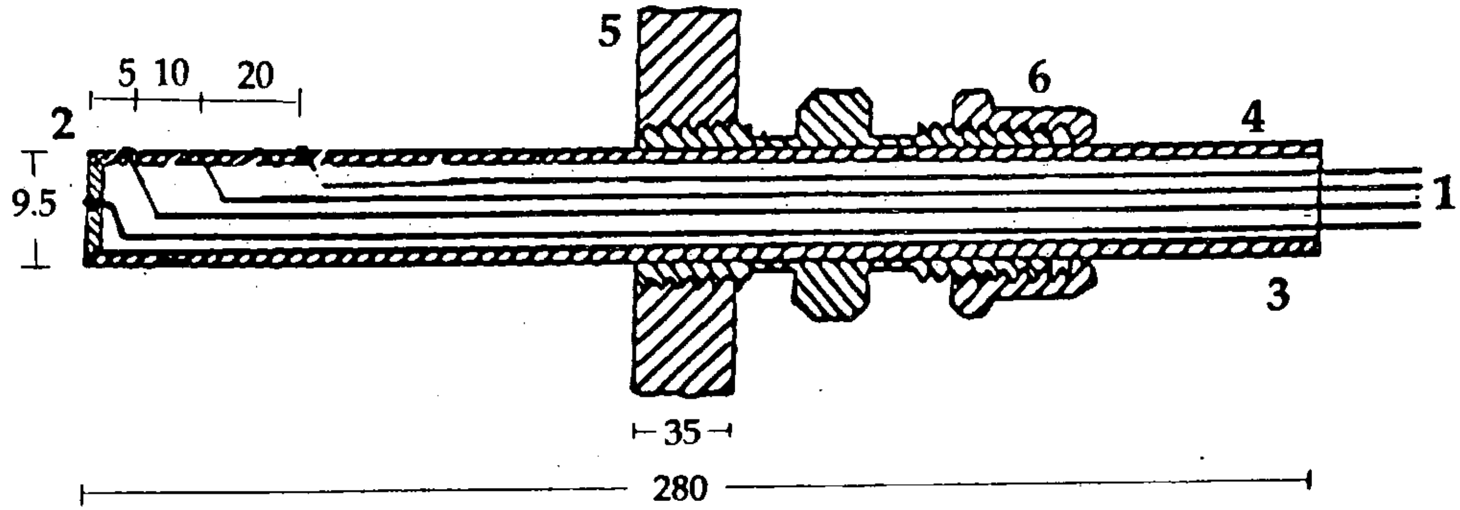

Fig. 3.19B. Design details of the radial thermocouple probe. (1) Copper-Constantan thermocouples, (2) Thermocouple well, (3) Copper cement, (4) Ceramic tube, (5) Column wall, and (6) Swagelok connector. All dimensions are in mm.

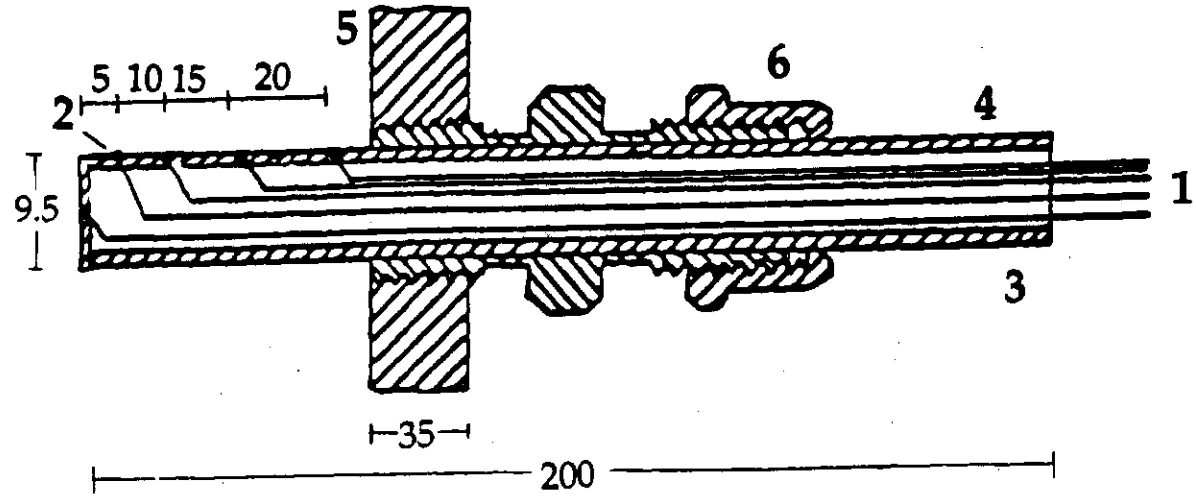

Fig. 3.19C. Design details of the radial thermocouple probe. (1) Copper-Constantan thermocouples, (2) Thermocouple well, (3) Copper cement, (4) Ceramic tube, (5) Column wall, and (6) Swagelok connector. All dimensions are in mm.

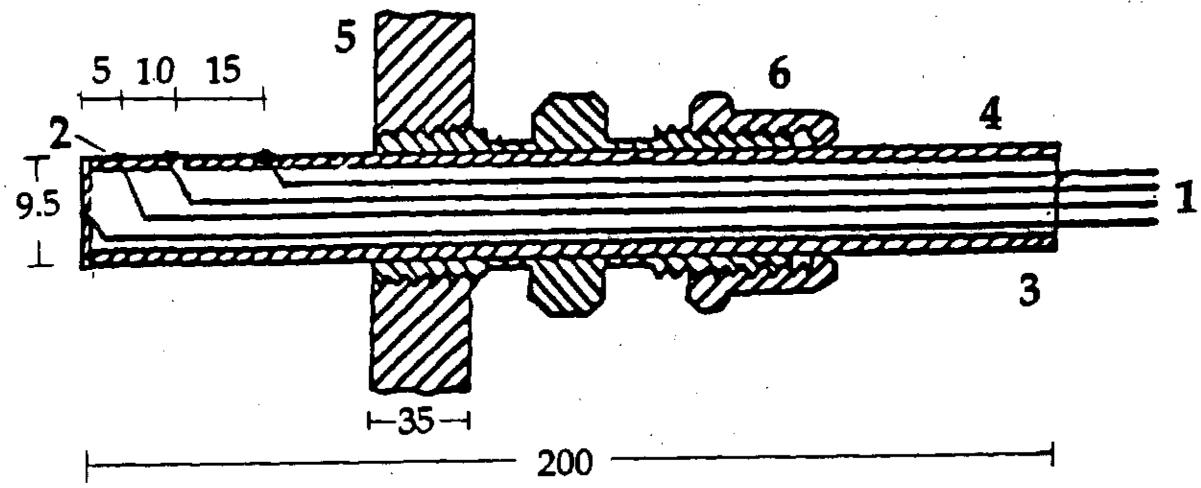

Fig. 3.19D. Design details of the radial thermocouple probe. (1) Copper-Constantan thermocouples, (2) Thermocouple well, (3) Copper cement, (4) Ceramic tube, (5) Column wall, and (6) Swagelok connector. All dimensions are in mm.

thermocouples, have been designed, fabricated and tested successfully to establish the radial temperature profiles essential to compute accurately the heat transfer coefficients. The design details are given in Figs. 3.19 A-D. These probes are used only in conjunction with thirty-seven tube bundle measurements.

3.2.2 Temperature Contollers, Data Acquisition and Processing Systems

The heater probes (H1 to H4) shown in Figs. 3.17 and 3.18 provide the necessary thermal energy to heat the column contents to the desired temperature. These heaters are energized with three Payne Engineering model 18 thyristor power controllers with the zero-fire proportion option, and the temperature is controlled with the help of three Payne engineering model 18A4 thermocouple temperature controllers. The operation involves setting a particular controller to the desired temperature. This in turn energizes the 250V AC/20A receptacle, to which the control heater is connected. A T-type thermocouple is positioned in the column at the point where the temperature is to be maintained constant. This thermocouple is attached to its respective thermocouple connector and it provides the feedback to the Payne control unit. The locations of these heater probes and heat-transfer probes in the tube bundle is indicated in Figs. 3.17 and 3.18. With this arrangement of AC heaters in the slurry bubble column, the gas-liquid or slurry dispersions could be maintained at desired temperature levels up to 523K with an accuracy of $\pm$ 2°C. A schematic of heater probe controllers is presented in Fig. 3.20. The data acquisition unit HP3852A, voltmeter HP44071A, compiler HP98563, monitor HP98786A, dual disc drive HP9122D, keyboard HP46021A, printer HP2225A, and HP color pro-plotter constitute the entire measuring system as shown in Fig. 3.2 1. This system can display, record and plot the data on-line.

3.3 Gas Supply System

The schematic of gas supply system to the 0.108 and 0.305 m diameter slurry bubble columns with its associated air and nitrogen supply and distribution pipe

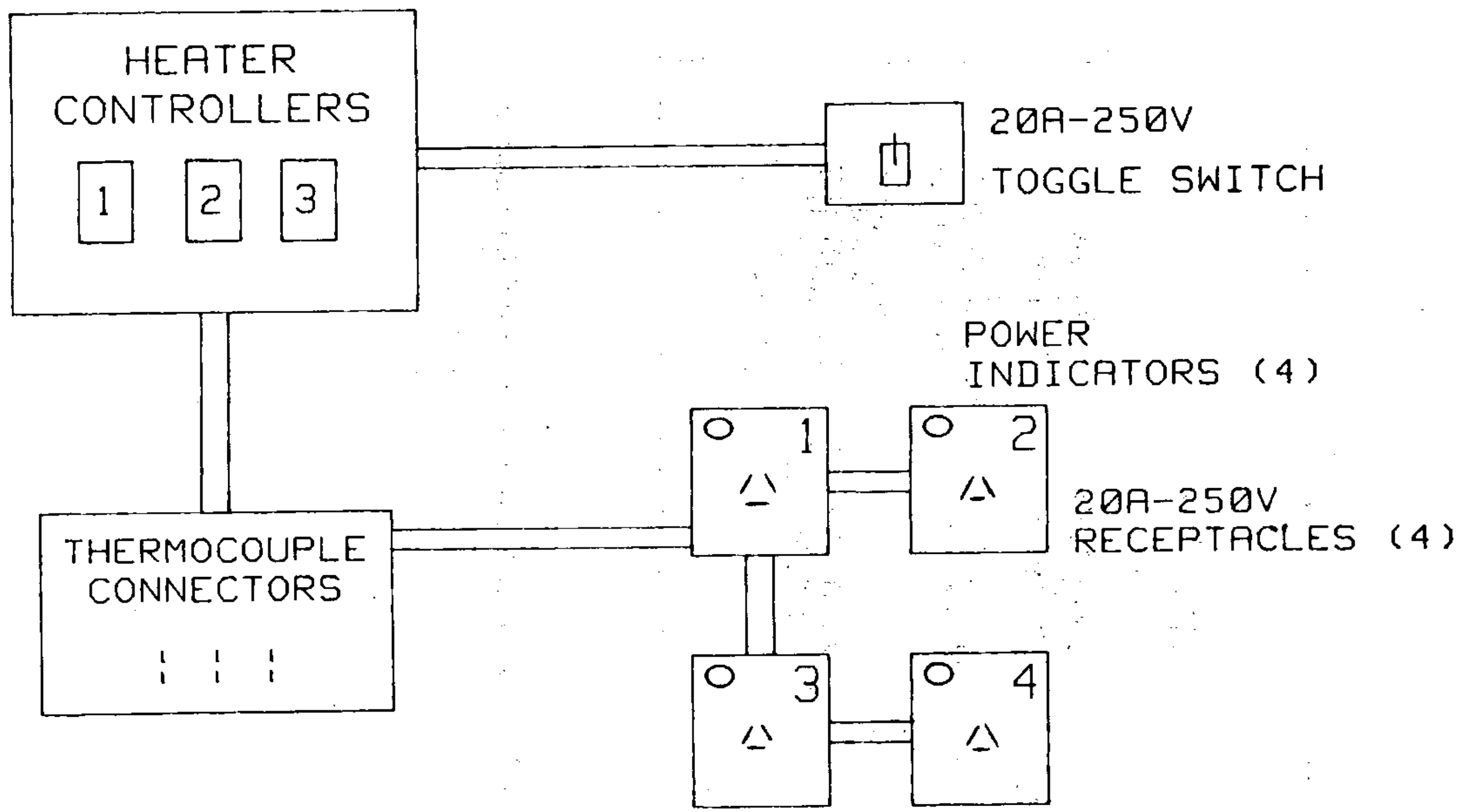

Fig. 3.20. Block diagram of the heater controllers including switches and thermocouple connections.

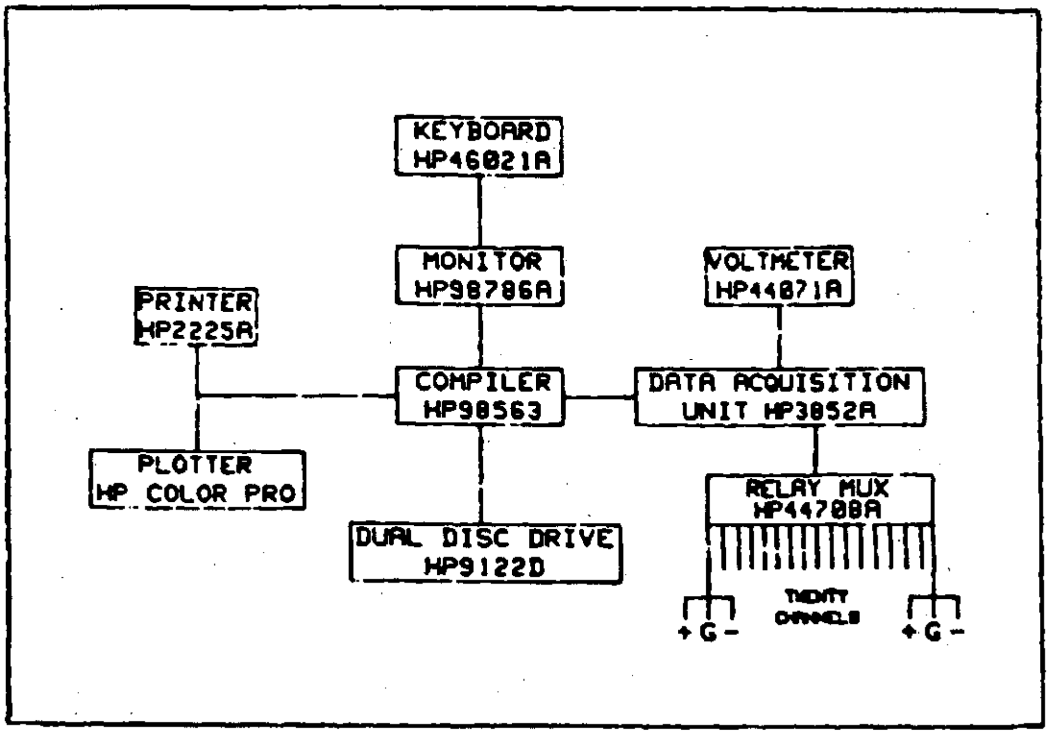

Fig. 3.21. Block assembly representation of the data acquisition and analysis system.

network is shown in Fig. 3.22.

Air is supplied by a 18.65kW, two cylinder, two-stage air-cooled Curtis compressor equipped with a surge tank, a refrigeration dryer, and three filters. To regulate the air flow rate, a pressure regulator, and a bypass line are provided.

Nitrogen gas, extra dry and 99.7% pure, is supplied from a cluster of twelve T-type cylinders, suitably manifolded. Twelve cylinders are connected in double-row manifolds to provide greater on-line storage capacity or higher flow rates than can be obtained from a single cylinder. The nitrogen flow rate is regulated by means of a pressure regulator (Victor Equipment Co., model KU 86126), which has a delivery pressure range of 0 to 200 psi (0 to 1400 kPa).

The column(s) can be switched from air to nitrogen by manipulation of the valves provided for the purpose. Gas flow rate, supplied to the column(s) at 20 PSIG, is measured by a series of rotameters (Fischer-Porter) with volumetric capacities 0.3 - 84.0 m^3/h at standard conditions. The superficial gas velocity is based on unblocked cross-sectional area of the column and at the operating temperature and pressure at the mid-point of the liquid (or slurry) column.

3.4 Powders and Their Properties

3.4.1 Establishment of Particle Size and its Distribution

The equipment employed to establish the particle size distribution consists of an analytical balance, Riffle sampler and a sonic sifter with a complete set of sieves. A quartering method is used to prepare the bed charge. The Riffle sampler divides the material by two series of chutes which discharge material in opposite directions into separate pans. The sonic sifter separates most fine particles of varying sizes, texture and density and automatically duplicates cycle time and duration. This sifting method combines two motions for maximum separation effectiveness and minimum particle attrition. A vertical oscillating column of air moves materials through the sieves while a mechanical pulsing breaks down clustered particles. A diaphragm transmits a 60 Hz oscillation to the air column. A Mettler analytical balance is used for weighing the sieves. The capacity of the balance is 160 g and its standard deviation is ± 0.05 mg. The

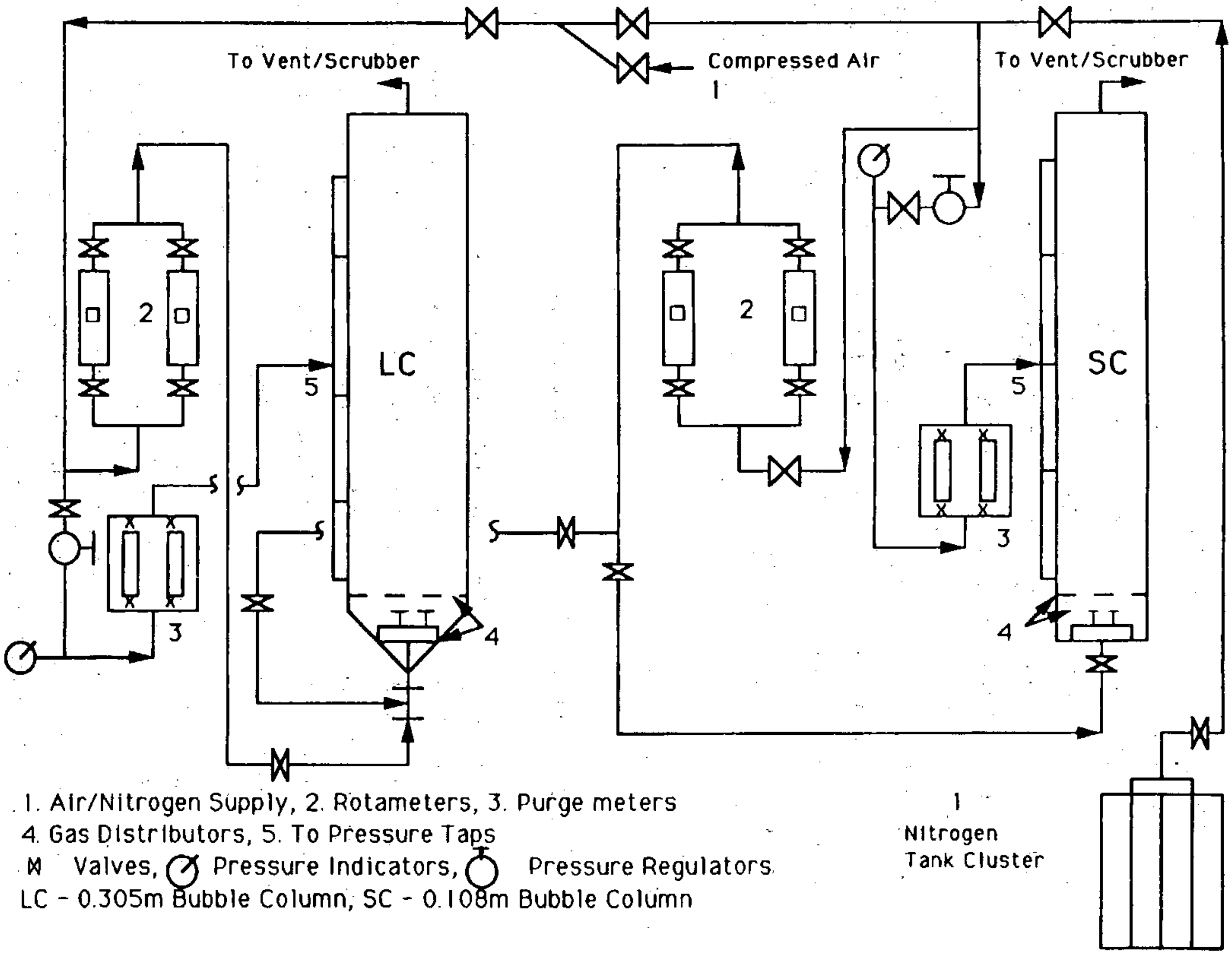

Fig. 3.22. Schematic of gas supply system to the two slurry bubble columns.

Table 3.1. Size distribution of glass beads.

U.S.A. Sieve Number	Avg.size (µm)	Mass Fraction of Solids (-)		
80-100	165.0	0.41952	-	-
100-120	137.5	0.41203	0.2519	-
120-140	115.5	0.16845	0.6339	-
140-170	98.0	-	0.1070	-
170-230	76.5	-	0.0072	0.00337
230-270	58.0	-	-	0.00947
270-325	49.0	-	-	0.84977
325-400	41.5	-	-	0.10196
>400	<38.0	-	-	0.03543
Avg. particle diameter (µm) :		143.3	117.6	50.0

Table 3.2. Size distribution of silica sand.

U.S.A. Sieve Number	Avg.size (µm)	Mass Fraction of Solids (-)
120-140	115.5	0.2231
140-170	98.0	0.1487
170-230	76.5	0.2210
230-270	58.0	0.0696
270-325	49.0	0.0842
325-400	41.5	0.2534
Avg. particle diameter (µm) :		65.0

Table 3.3. Size distribution of red iron oxide.

U.S.A. Sieve Number	Avg.size (µm)	Mass Fraction of Solids (-)		
0.2-0.3	0.25	-	0.02	0.01
0.30-0.71	0.50	0.26	0.03	0.15
0.71-0.80	0.75	0.08	0.01	0.04
0.8-1.0	0.90	0.11	0.04	0.08
1.0-2.0	1.50	0.24	0.10	0.17
2.0-3.0	2.50	0.10	0.10	0.10
3.0-5.0	4.00	0.06	0.20	0.13
5.0-10.0	7.90	0.08	0.45	0.26
>10.0	10.00	0.07	0.05	0.06
Avg. Particle Size(µm) :		1.02	2.38	1.70

knowledge of particle size distribution and mass fraction values is used to establish the mean particle diameter from the following relation:

$$d_p = \left[(x_i / d_{pi})\right]^{-1}$$

3.4.2 Glass Beads

The size distribution of glass beads is given in Table 3.1. The particles are supplied by Ferro Corporation, Jackson, Mississippi - 39208, USA. The glass beads are of high quality with excellent resistance to acids and mild alkalis. The properties of the solids are presented later in Table 3.5.

3.4.3 Silica Sand

The particle size distribution of the silica sand used in our experiments is reported in Table 3.2, and its physical properties in Table 3.5.

3.4.4 Iron Oxide Powders

Copperas Red, used in the present studies in one of the pure Red Iron Oxide available from Pfizer. The formula is $Fe_2 O_3$ (99 + %). Iron oxide wets easily and has excellent suspension properties. It is a chemically stable substance and the particles are spheroid. The physical properties are given in Table 3.5, and size distribution in Table 3.3 for the two powders used in the present investigations.

3.4.5 Magnetite Powders

The magnetite powders used in the present research were black Grade A magnetite containing 90% Fe_3O_4 supplied by the Prince Manufacturing Co., Bowmanstown, Pennsylvania. The physical properties were taken from the technical data sheets supplied by the Company and from the Thermophysical

Properties of Matter, (TPRC) series, Vols. 2 and 5 [49, 50], and these are reported in Table 3.5. The size ranges and average diameters of different powders used in the present investigations are listed in Table 3.4A and 3.4B.

Table 3.4A. Size distribution of magnetite powders.

Size Range (μm)	Avg.size (μm)
0-53	41.4*
45-53	49.0
53-63	58.0
63-75	68.0
75-106	90.5
106-125	115.5
125-150	137.5

* Size Distribution of 35.7 μm Magnetite Powder

U.S.A. Sieve Number	Avg.size (μm)	Mass Fraction of Solids (-)
<38	19.0	0.2206
38-45	41.5	0.1348
45-53	49.0	0.6446
Avg. particle diameter (μm) : 41.4		

Table 3.4B. Size distribution of magnetite powders.

Size range (μm)	Mean size (μm)	Weight fraction (-)		
		A	B	C
< 38	19.0	0.5189	0.3294	0.2310
38-45	41.5	0.1633	0.1243	0.0641
45-63	54.0	0.1977	0.1850	0.1388
63-106	84.5	0.0533	0.1881	0.2908
106-125	115.5	0.0505	0.0756	0.1805
125-150	137.5	0.0162	0.0973	0.0947
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
	d_p (μm):	27.7	36.6	45.5

Table 3.5. Physical properties of solids.

Solid	T(C)	Density kg/m3	Heat capacity J /kg K	Thermal conductivty W/m K
Glass bead	25	2500	671	0.744
	50	2500	687	0.744
	70	2500	705	0.744
Silica sand	25	2560	766	0.328
	50	2560	792	0.328
	70	2560	823	0.328
Red iron oxide	25	5100	648	70.0
	50	5100	677	70.0
	70	5100	701	70.0
Magnetite	25	4900	651	70.0
	50	4900	685	70.0
	100	4900	744	70.0
	200	4900	826	70.0
	300	4900	886	70.0