HEAT TRANSFER INVESTIGATIONS IN A SLURRY BUBBLE COLUMN: QUARTERLY REPORT FOR THE PERIOD OCTOBER-DECEMBER 1987

ILLINOIS UNIV. AT CHICAGO CIRCLE. DEPT.
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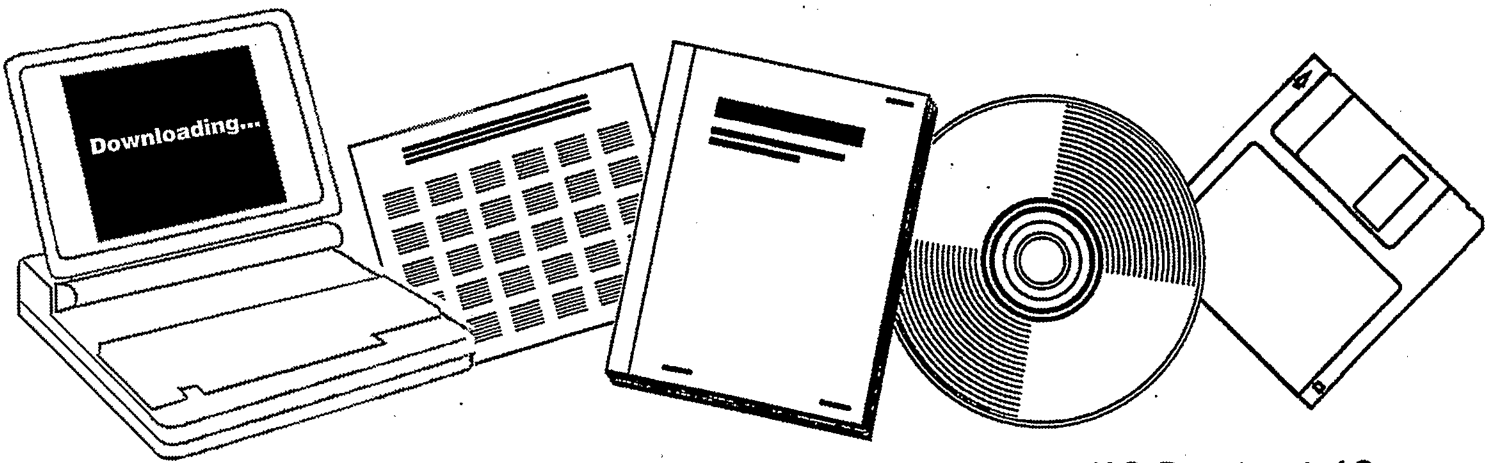

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HEAT TRANSFER INVESTIGATIONS IN A SLURRY BUBBLE COLUMN

Quarterly Report for the Period October-December 1987

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OBJECTIVES

To investigate the heat transfer characteristics in two slurry bubble columns (10.8 and 30.5 cm) as a function of system and operating parameters.

SUMMARY

The small 10.8 cm diameter Plexiglas slurry bubble column has been operated in various modes and in different environments. With minor refinements in instrumentation, it has been used to measure heat transfer coefficients between a heat transfer probe bundle containing five 19 mm outer diameter and 188 cm long Plexiglas tubes and the air-water system. The heat transfer coefficients are reported for the central tube of the bundle which contains a 34 cm long heated brass section as a function of air velocity (0.04 to 0.42 m/s) and for different heat flux values. Data are also obtained as a function of time during which the system tends to move to acquire the steady state. Hydrodynamic condition of the column is also established by taking the gas holdup data, both average and local along the column, as a function of air velocity, water column height, and with and without the probe bundle in the column.

Based on this experience an improved design for the single probe has been developed both for its fabrication as well as for its mounting in the column. The construction and installation of the probe is completed and a bulk of the elaborate heat transfer and hydrodynamic measurements are also completed as a function of operating and system parameters.

The design, fabrication and installation work on the 30.5 cm diameter Corning glass column is continuing and substantial progress is achieved in each phase of the program. It is expected that the column will be ready for initial measurements during the next three-month period.

Solid particles of iron, iron oxide (magnetite) and glass beads are made ready by sieving for work on these columns in the future. FT-300 wax has been bought for eventual use in the big column.

The research journals are being screened to extract the available scientific knowledge pertinent to this program of research.

DESCRIPTION OF TECHNICAL PROGRESS

TASK 2

The 10.8 cm diameter Plexiglas bubble column is used to measure the heat transfer coefficient between the probe bundle containing five tubes and the air-water system. The five commercially prepared chromel - alumel thermocouple probes which were being used for the measurement of air - water mixture temperature in the column have been replaced by the copper - constantan thermocouple probes. These have been designed by us and are fabricated in our workshop. This is considered essential for accurate heat transfer measurement as the heat transfer probe has similar thermocouples. The measurements of heat transfer coefficients are taken on the heat transfer probe bundle containing five 19 mm outer diameter and 188 cm long Plexiglas tubes. Each of the five tubes is provided with a 34 cm long heated brass section. The measurements reported here are confined to only the central tube in the bundle in which the heater section is located 74.6 cm above the distributor plate. The column test section height being 163 cm.

A series of measurements is taken in which heat transfer coefficient is determined as a function of air velocity (0.04 to 0.42 m/s) for a given heat flux i.e., power fed to the electrical heater. Such measurements are conducted for four values (468, 607, 813 and 943W) of the heat flux. At each operating conditions 10-15 minutes are given for the steady state to set in. These measurements revealed that for each value of the heat flux, the heat transfer coefficient between the probe surface and column air - water mixture increases with air velocity initially but tends to achieve a constant value for air velocities greater than about 0.26 m/s. The column temperature steadily rises with time and also with the electrical wattage fed to the heater. The heat transfer coefficients reflect this fact in as much as the values corresponding to 943W are significantly greater than those corresponding to 468W, roughly 25% at 0.35 m/s air velocity. The differences between the values corresponding to 468 and 607W, and between 813 and 943W are relatively smaller (<6%) indicating thereby that the heat transfer coefficient is independent of the value of heat flux as long as the temperature of the column stays constant. We also noticed in the course of these experiments that the steady state is established only after 30 to 40 minutes. We, therefore, plan to explore these features of heat transfer coefficient mentioned above in a more careful series of experiments with a single heat transfer probe in the column.

The heat transfer coefficient between the probe surface and the air - water mixture in the column, h_w; is related the heat flux, Q; the surface area of the brass section of the probe, A; the average temperature of the heated probe surface, T_s; and the average constant bulk temperature of the air - water mixture around the heated section of the probe, T_c; by the following relation

$$Q = h_W A(T_s - T_c) = IV$$

Q is established by the product of constant current, I, supplied to the probe heater and the constant voltage, V, across it. A is computed on the basis that the heater section is a cylinder of uniform diameter (1.9cm) and height (34.0cm). T_S is measured by five thermocouples located on the probe surface at various axial and uniformly staggered angular positions. A typical set of values is given in Table 1 and the value used in the above equation is the arithmetic average of these five values. T_C is obtained by a thermocouple located around the middle of the probe and it can be moved radially in the column. Table 2 lists the temperatures at various radial locations from 0.5 to 45 mm, four such sets are reported taken at different times, and one set of readings is completed in about 2 minutes. These values are graphically represented in Fig 1 and it is to be noted that the constant column temperature, T_C, is reliably obtained when the probe is located around 18 mm from the probe surface. Temperature of the column at various axial positions is also measured at three other locations. The positions of the four thermocouples probes are, 24.7, 55.2, 85.7 and 116.2 cm above the distributor plate. Table 3 reports the column temperatures as registered by these four probes for a given set of operating conditions. The constant uniform temperature of the column is to be noted from these records.

Experimentally determined values of h_W for various air velocities, and at each value as a function of time are reported in Table 4, and graphically displayed in Fig 2. On the basis of these results it is reasonable to conclude that h_W acquires a constant value after about 30 minutes. This, therefore, is the time which must be allowed to establish steady state in the column before taking the final readings.

The steady state constant h_W values as read from Fig 2 are shown plotted in Fig 3 as a function of air velocity. This characteristic variation will be further investigated in our future work and its consequences will be analysed.

On the small 10.8 cm Plexiglas column work has been continued to obtain hydrodynamic data under varying operating conditions using air - distilled water system. Five initial settled heights, H_S, of the water column have been examined and air velocity is varied in the range 0 to 0.35 m/s. Figure 4 reports the data of expanded water column height, H_e, at various air velocities for each of the five initial settled column heights. In these experiments the air velocity is brought to its maximum value and then decreased in steps when the steady state values of the water column height are recorded. At each air velocity twenty minutes are allowed before the air velocity is decreased though a steady column height is reached in about ten minutes. It will be noticed that the column height consistently increases with air velocity except for the three higher H_s values when in a narrow band of air velocities the rate of increase in column height becomes smaller with increasing H_s. This is different than that observed earlier by us for increasing air velocities when distinct maximum and minimum in H_e values were observed with increase in air velocity for all the three H_s values (91, 95 and 99 cm).

Computed values of average air holdup, $\bar{\epsilon}_g$, are displayed in Fig 5 from the data shown in Fig 4. The $\bar{\epsilon}_g$ values for all the five H_s values are monotonic in nature with increasing air velocity except for the case of H_s = 95 cm, it seems to have a constant value in a narrow air velocity range. No maximum and minimum in $\bar{\epsilon}_g$ values are obtained in sharp contrast with the earlier results for increasing air flow velocity. We also observe in Fig 5 that $\bar{\epsilon}_g$ values are smaller for H_s = 99 cm than for the values corresponding to H_s = 95 cm and even H_s = 91 cm at lower air velocities.

In Fig 6 are shown the values of local air holdup, ϵ_g, computed from the pressure drop data for 15 cm column section along the column height for decreasing air velocity and for the case of H_s = 95 cm, These data are represented by unfilled circles and the broken curve is a smooth plot through them. Also displayed in this figure are the ϵ_g values corresponding to increasing gas velocities as reported in last quarterly progress report. Two sets of experimental data were taken and the vertical lines on the filled circles represent the variations in the data points. The continuous curve is a smooth plot through the data points. The ϵ_g values corresponding to decreasing air velocities exhibit relatively smoother variation with air velocity than that obtained for increasing air velocity where distinct maxima and minima are observed. The intensity of these maxima and minima is much reduced for decreasing air flow velocity.

Next the average air holdup is measured for different water flow rates in the column with the results shown in Fig 7. These experiments are conducted in a different manner. Unlike the previous runs a fixed H_s value is not chosen instead a constant expanded column height of 170.18 cm established by the column design is kept the same for each data point and the air and water supplies to the column are cut off to determine the corresponding H_s value. $\bar{\epsilon}_g$ values computed in this fashion are shown in Fig 7 for increasing and decreasing air velocities for zero water flow velocity. A pronounced maximum and minimum is observed for increasing air velocity while a monotonic smooth variation is found for decreasing air velocity. Three liquid flow velocities of 0.373, 0.570 and 0.892 cm/s are investigated and for each case gas holdup is determined for increasing and decreasing air velocities. No systematic difference in the data points is encountered and the holdup, in general, with liquid flow is smaller for each of the air velocity values in the range investigated than the corresponding holdup values with no liquid circulation for either increasing or decreasing air velocity.

Based on our experience of the heat transfer coefficient measurements between the immersed surface and air - water system, an improved single heat transfer probe has been designed and fabricated. Its design and dimensions are shown in Fig 8. Basically it consists of three sections, top, middle and bottom, put together by two delrin connectors 50 mm long. The Teflon bottom section is 305 mm long and has a conical bottom end to enable a smooth liquid or slurry flow around it. This bottom section is connected to the brass middle section by a threaded connector as shown in the figure. 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 a threaded connector. An O - ring seal is provided between the connector and the steel tube to avoid any sweepage of the liquid from the column into the tube. Three different top and bottom sections are made so that the heater section can be located in different regions of the slurry bubble column.

The surface temperature of the brass section of the probe containing the calrod heater is measured by strategically located seven copper - constantan thermocouples. Their orientation and location on the surface is detailed in the figure. Thermocouples 8 and 10, and 9 and 11 are provided to measure the end heat loss to the connectors. It is known to be small but for accurate heat transfer measurements it must be determined. Thermocouples 8 and 9 are cemented on the end surfaces of the brass section, while thermocouples 10 and 11 are placed rigidly 2 mm below the connector surface and 30 mm away from the brass section by means of technical quality copper cement. The thermocouples 1 to 7 are bonded to the brass surface in milled grooves with technical quality copper cement.

A specially designed clamp for centrally locating the probe in the column and to damp out its vibratory motion is fabricated as shown in Fig 9. 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 soft and good grip at the inner column surface (6). The third arm (7) has a telescopic arrangement

(8) with a spring (9) and a locking pin (10). The front end (11) of this arm (7) can thus be moved in and out against the spring (9). This three - arm locating clamp will thus hold the probe rigidly along the axis of the column. Three such clamps are used along the probe length and these have successfully avoided and completely damped out any vibrations of the probe in the slurry bubble column.

The hydrodynamic and heat transfer measurements have been taken with this single tube in 10.8 cm diameter Plexiglas column. For the air-distilled water system the air holdup has been measured for various water flow velocities (V) as a function of air velocity, U. The column is equipped with a 19.0 mm heat transfer probe. The design of the latter was reported in the last month report. The experimental data for increasing and decreasing gas velocity are shown in Fig 10. The data for zero liquid flow velocity refer to an expanded water column height of 170.18 cm. The procedure of recording the settled or unexpanded water column height is to stop the air flow and let the column height settled to a steady value. The air holdup values are slightly greater for increasing air velocity than for decreasing air velocity for the case when water flow velocity is zero. As the water flow velocity is increased the two sets of values for air holdup tend to merge into each other. The air holdup values are almost insensitive to the value of water flow velocity.

The air holdup values were measured for decreasing air flow velocity and for different liquid flow velocities in the same experimental arrangement after a few days with the results shown in Fig 11. The results of the two figures are only in approximate agreement with each other. It is due to the fact that with the continuous aeration of water, its composition changes by absorbing the impurities present in the compressed air. It is, therefore, concluded that in future a fresh charge of distilled water be used in each run and for each situation the corresponding gas holdup will be measured.

With the heater section located in the middle of the probe, the heat transfer coefficient has been measured for the air - water system as a function of air velocity. Ten different values of the latter have been chosen in the range 3.39 - 35.27 cm/s. A thermocouple probe with six copper - constantan thermocouples located at 0, 2, 5, 10, 15 and 20 mm from its tip is used to establish the radial temperature profile in the column. To scan the temperature distribution, the thermocouple probe is first kept near the heat transfer probe and it is pulled out to measure the temperatures in the annulus farther from the heat transfer probe. These two sets of temperature readings are completed in twenty seconds. Typical temperature profiles for arbitrary air flow rates have been taken. These reveal a fairly constant temperature profile, and the constant water - air column temperature in computing the heat transfer coefficient is the mean of temperatures corresponding to positions 20, 25 and 30 mm from the heat transfer probe surface. The heat transfer surface temperature is recorded by seven thermocouples located at different axial and circumferential positions. The data in each case are taken as a function of time for a period of about fortyfive minutes. During this period the column temperature also rises by several degrees, the magnitude depends upon the air velocity through the column. The steady state heat transfer values for an approximately constant temperature of the column as a function of air velocity are then established from these plots. The corresponding air holdup values are also determined. Graphical representation of these data is in progress.

Heat transfer work with a probe bundle comprising of seven simulated heat transfer probes is planned and a special clamp for installing this bundle in the column is designed. The same is shown in Fig 12. Two such clamps will be used and the bundle will have its probes arranged in an equilateral triangular configuration with a center to center pitch of 36.5 mm. The general design of this mounting clamp is somewhat similar to that of the three - arm locating clamp used for a single heat transfer probe and whose description was given in last month report.

TASK 3

The design, fabrication and installation work on the 30.5 cm diameter glass column has continued. During testing of this column it appeared that water leaks at the metal insert and glass column section joint. It is successfully remedied by making fine grooves at the ends of the metal inserts. This provides a tighter grip between the two sections through the Teflon coated gasket. Four ports in each of the four inserts are made to accommodate thermocouple probe, pressure probe, sample withdrawal and fiber optic probe. The last two ports will not be used in the contracted work with the Department of Energy and are temporarily plugged. The four temperature measuring probes have been designed and are under fabrication. The pressure measuring loop consisting of a purgemeter, pressure regulating valve, bottle trap, manometer, pressure sensor and the control valves has been designed, the materials ordered and received, and fabrication is in progress. FT - 300 wax has been ordered. The column heaters for melting and heating the wax, power supply and control system for these heaters is currently being designed. The initial planning for the temperature measuring system and d.c. power supply for the heater probes is in progress.

Three Corning glass sections showed some superficial scratch and therefore the company was requested to replace them. These have arrived though two of these also suffer from the same defect. Plans are being made to replace some of the old glass sections with the new ones. FT300 wax is received. Two of the eleven bags got battered in the transit and company has agreed to replace the material lost. The pressure measurement system for the 0.305 m column is in progress and many components have been fabricated. Four thermocouple probes have been fabricated for measuring the column temperature. The design of the heat transfer probe and associated measurement system is in progress.

Work has continued to prepare solid particles for use in bubble columns to obtain hydrodynamic and heat transfer data in slurry bubble columns. Iron oxide (magnetite) powder has been sieved to produce samples in the range 106-125 µm, 75-106 µm, and 45-75 µm. Similarly glass bead samples have been prepared in the size ranges 125-150 µm, and 75-125 µm. Small samples of smaller size 63-75 µm (125 lb) and smaller than 38 µm (1.0 lb) are also available.

TASK 4

Search through the research journals has been continued to retrieve all the pertinent literature and brief summaries of the main results obtained by different investigators is in progress.

Table 1. Variation of probe surface temperature with air velocity.

Heater Wattage: 621W

Air Velocity m/s	Probe Surface temperature, ^{o}C					
	T_1	T_2	T_3	T_4	T_5	T_s
0.0416	60.80	62.09	61.87	63.08	62.42	61.90
0.104	54.80	55.06	56.07	57.53	56.42	55.97
0.166	58.45	59.70	59.44	60.68	60.20	59.69
0.250	55.17	55.56	55.67	56.87	56.40	55.93
0.333	49.86	50.84	50.64	51.95	51.08	50.87
0.416	47.53	47.71	48.27	49.87	49.27	48.55

Table 2. Variation of column temperature (^{o}C) with radial distance from the central probe surface (diameter 19 mm) in the five tube bundle.

Set No.	Radial distance from the probe surface, mm										
	0.5	2.0	5.0	10	15	20	25	30	35	40	45
1	59.55	59.13	59.13	59.04	59.02	58.92	58.87	58.77	58.62	58.17	58.00
2	59.65	59.41	59.33	59.29	59.24	59.18	59.14	59.01	58.86	58.52	58.44
3	60.10	59.70	59.64	59.64	59.59	59.55	59.44	59.38	59.25	58.98	58.66
4	60.13	59.86	59.86	59.79	59.75	59.71	59.62	59.54	59.37	59.14	58.90

Table 3. Variation of temperature along the column height with air velocity.

Heater Wattage: 621W

Air Velocity m/s	Column Temperature, °C				
	T_6	T_7	T_8	T_9	T(avg)
0.0416	56.58	56.92	55.93	54.91	56.08
0.104	52.19	52.15	51.93	51.73	52.00
0.166	55.93	56.44	55.60	55.43	55.85
0.250	52.63	52.57	52.37	52.15	52.43
0.333	46.99	46.99	46.79	46.60	46.84
0.416	45.11	45.02	44.81	44.53	44.86

Table 4. Variation of heat transfer coefficient (kW/m^{2}K) with time for various air velocities.

Time	Air Velocity, m/s					
s	0.0416	0.104	0.166	0.250	0.336	0.416
2	4.367	6.273	7.054	8.142	7.596	7.770
4	4.437	6.299		7.993	7.254	8.099
6	4.617	6.404	7.750	8.319	7.377	7.730
8	4.625	6.655	7.770	8.056	7.449	8.251
10	4.754	6.458	7.829	8.077	7.810	8.274
12	4.703	6.699	7.711	8.014	7.711	8.207
14	4.746	6.684	7.750	8.035	7.485	8.387
16	4.836	6.848	7.770	8.229	8.142	8.229
18	5.068	7.136	8.035	8.527	7.634	8.077
20	4.930	6.957	7.829	8.504	7.596	8.142
22	5.060	7.021	7.890	8.185	7.731	8.387
24	4.969	7.037	8.120	8.056	7.559	7.993
26	5.060	7.412	7.711	8.480	7.653	8.274
28	5.171	7.540	7.931	8.251	7.395	8.410
30	5.315	7.540	7.972	8.364	7.711	8.341
32	5.198	7.577	8.207	8.251	7.692	8.099
34	5.343	7.503	8.185	8.274	7.615	8.099
36	5.260	7.653	8.319	8.480	7.810	7.951
38	5.380	7.692	8.142	8.797	7.596	8.099
40	5.371	7.711	8.164	8.747	7.596	8.035
42		7.522	7.972	8.480		8.341
44		7.648	8.648	8.319		8.207
46			8.457	8.822		8.551
48			8.457	8.623		8.163
50			8.433	8.797		8.296
52			8.410	8.672		8.120
54			8.164	8.457		8.207
56			8.207	8.772		8.185
58			8.274	8.747		8.341
60			8.797	8.623		8.163

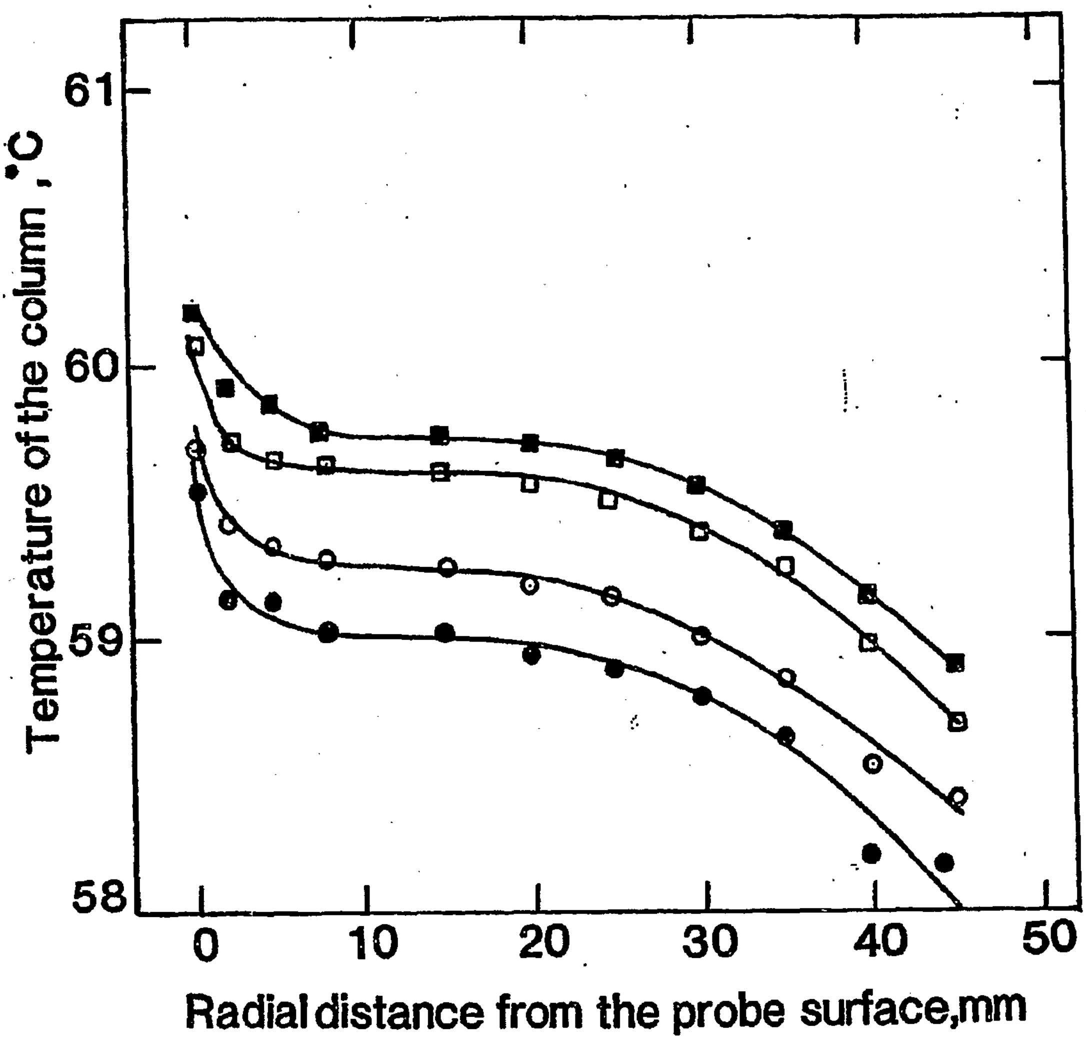

Figure 1: Radial variation of column temperature at four different instants.

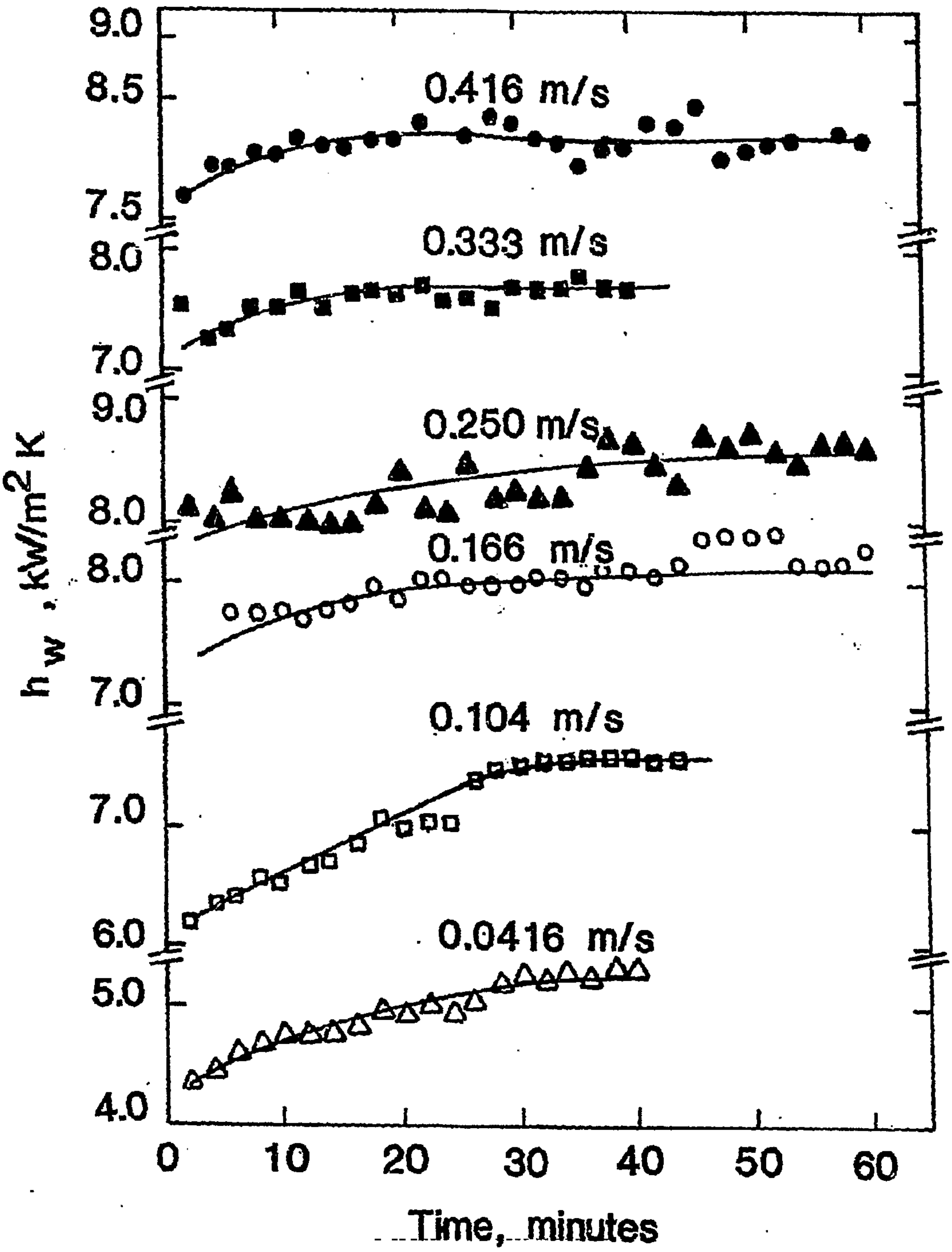

Figure 2: Variation of h_w with time at various air velocities.

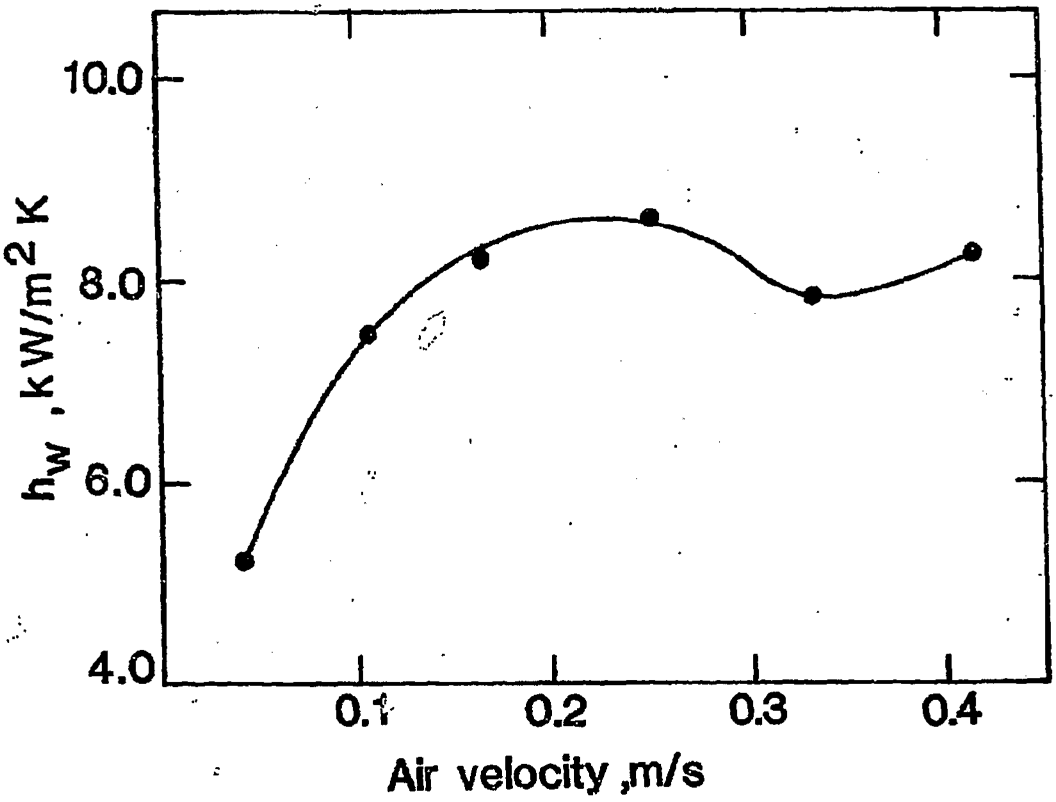

Figure 3: Variation of h_w with air velocity.

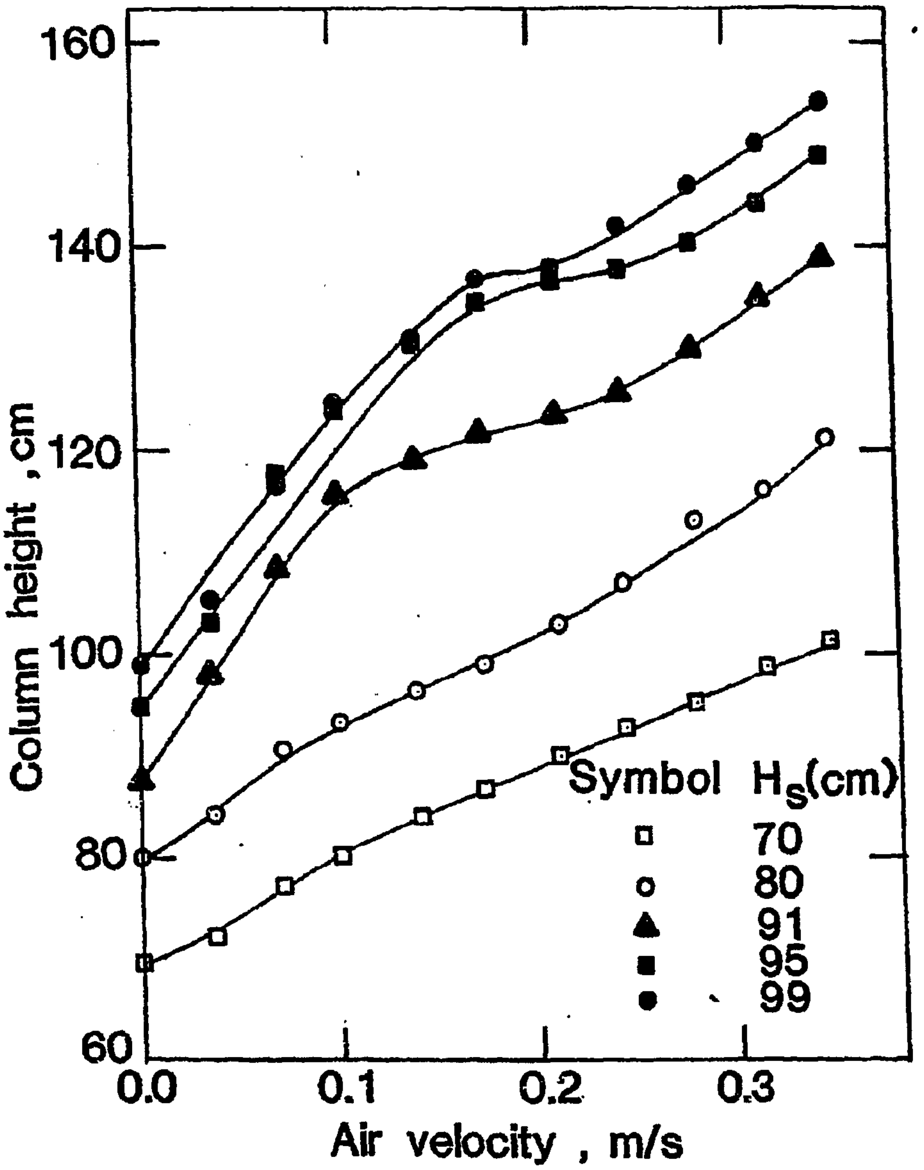

Figure 4. Variation of column height with decreasing air velocity for different settled heights of the distilled water in the column.

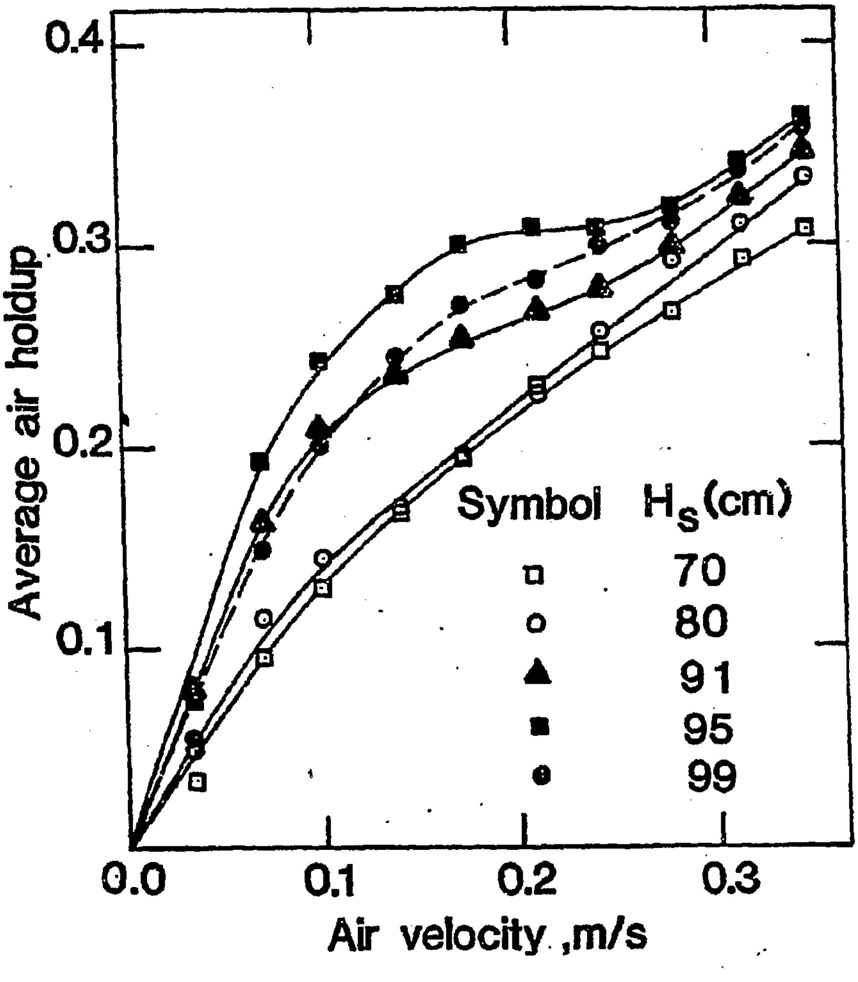

Figure 5. Variation of the average air holdup as a function of decreasing air velocity f
different settled heights of the distilled water in the column.

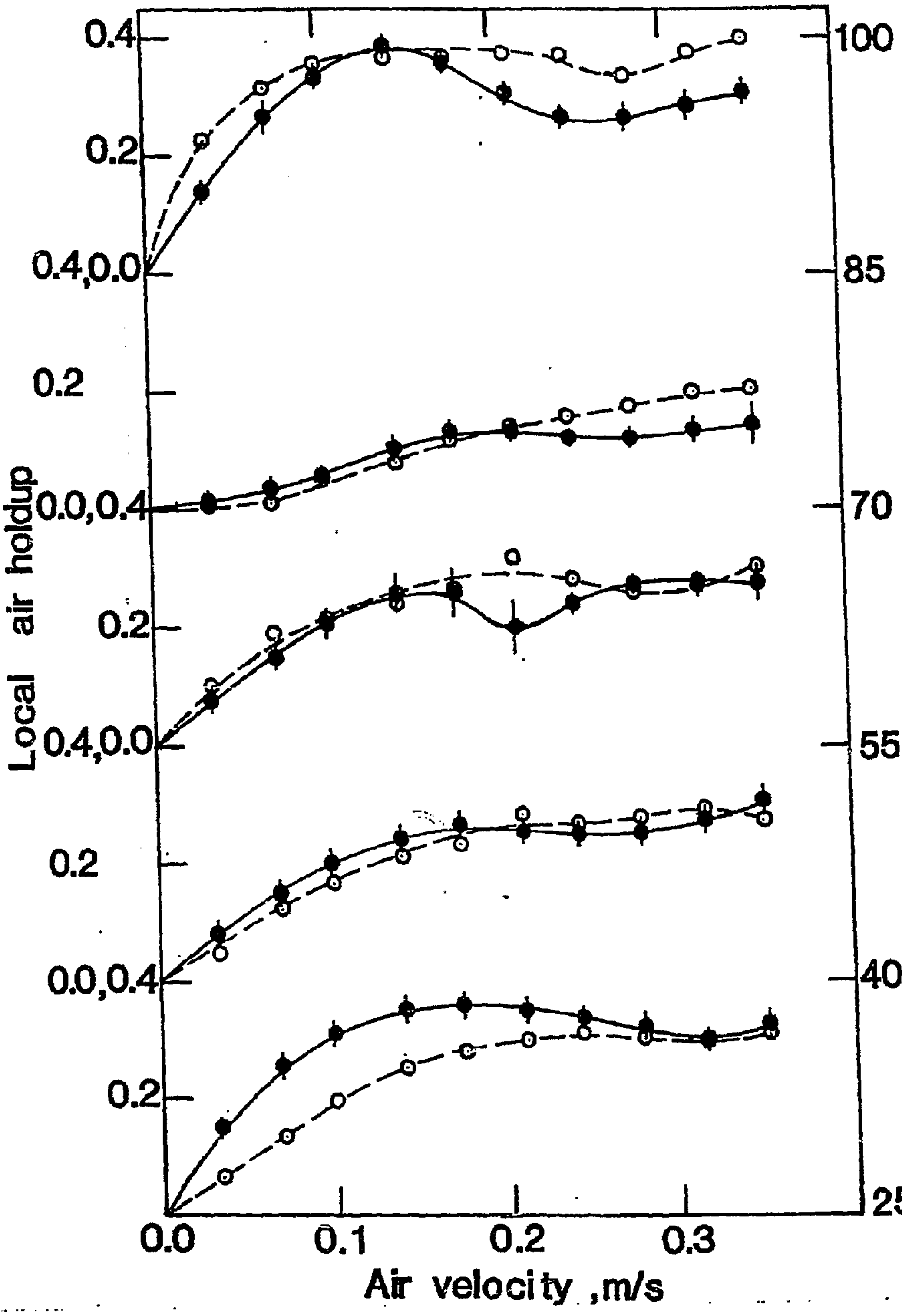

Figure 6. Variation of the local air holdup as a function of increasing (filled circle) and decreasing (unfilled circle) air velocity for the slumped distilled water height of 95 cm in the column.

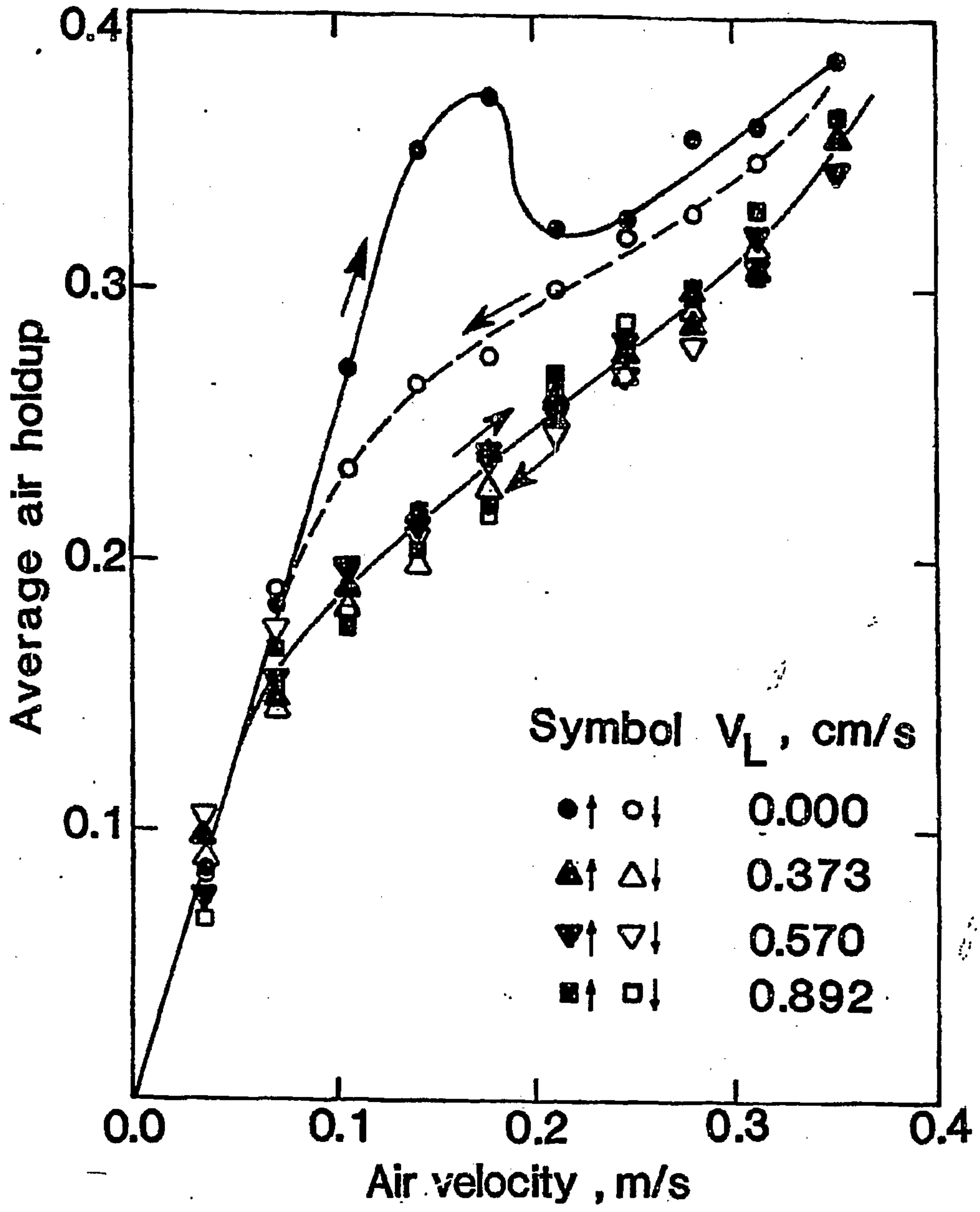

Figure 7. Variation of the average air holdup as a function of decreasing and increasing air velocities at different liquid flow rates.

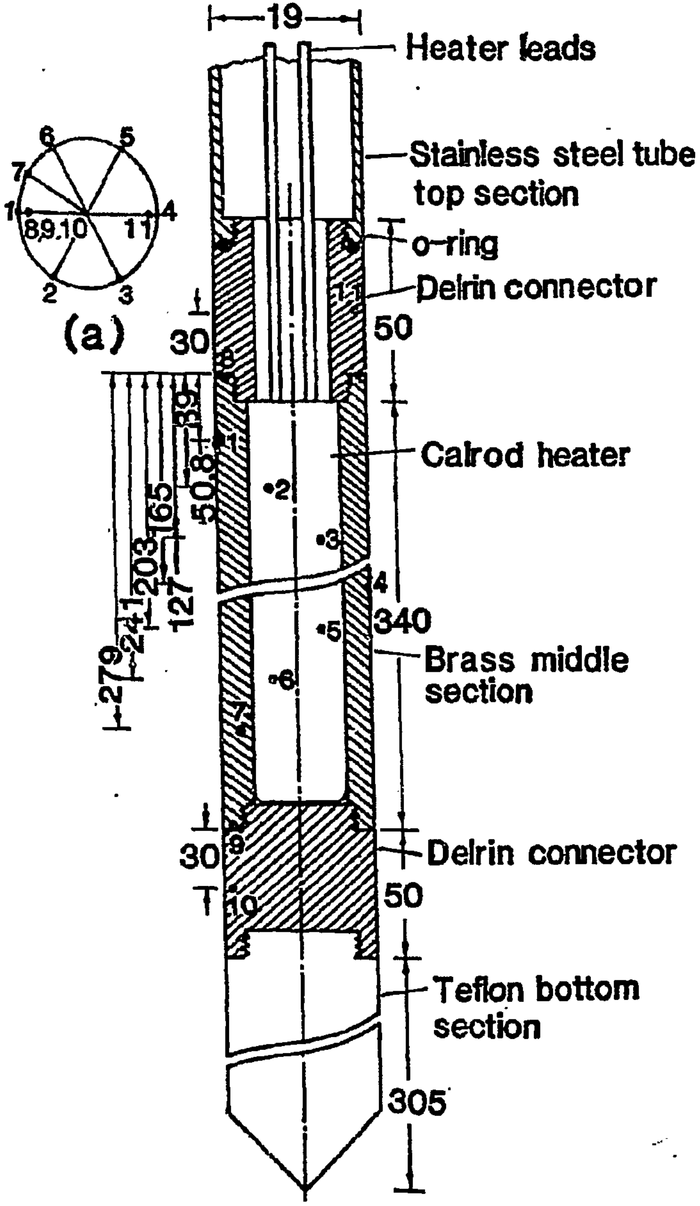

Figure 8. Design and dimensions of the 19.0 mm heat transfer probe assembly. dimensions are in mm. (a) Orientation of thermocouple.

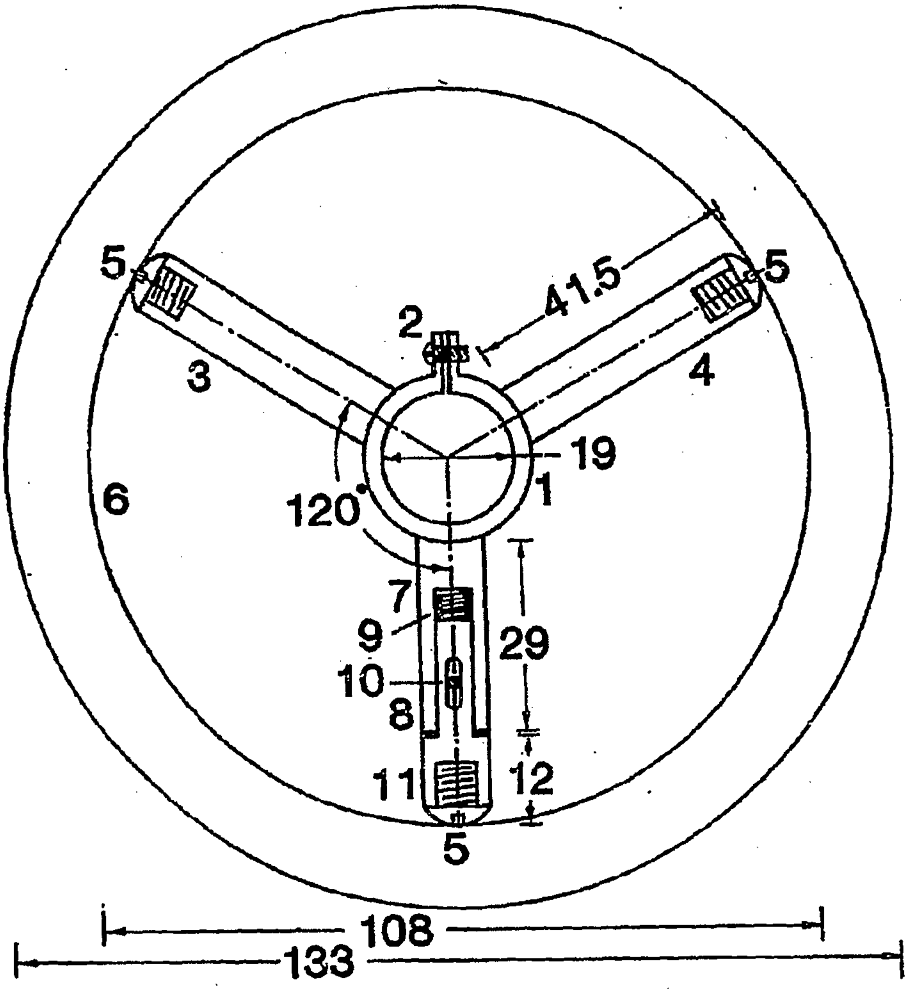

Figure 9. A three - arm locating clamp for the heat transfer probe in the bubble column. All dimensions are in mm. (1) ring clamp, (2) screw, (3, 4) radial arms, (5) Teflon rounded cap, (6) column surface, (7) telescopic arm, (8) telescopic arrangement, (9) spring, (10) locking pin, and (11) front end of the telescopic arm.

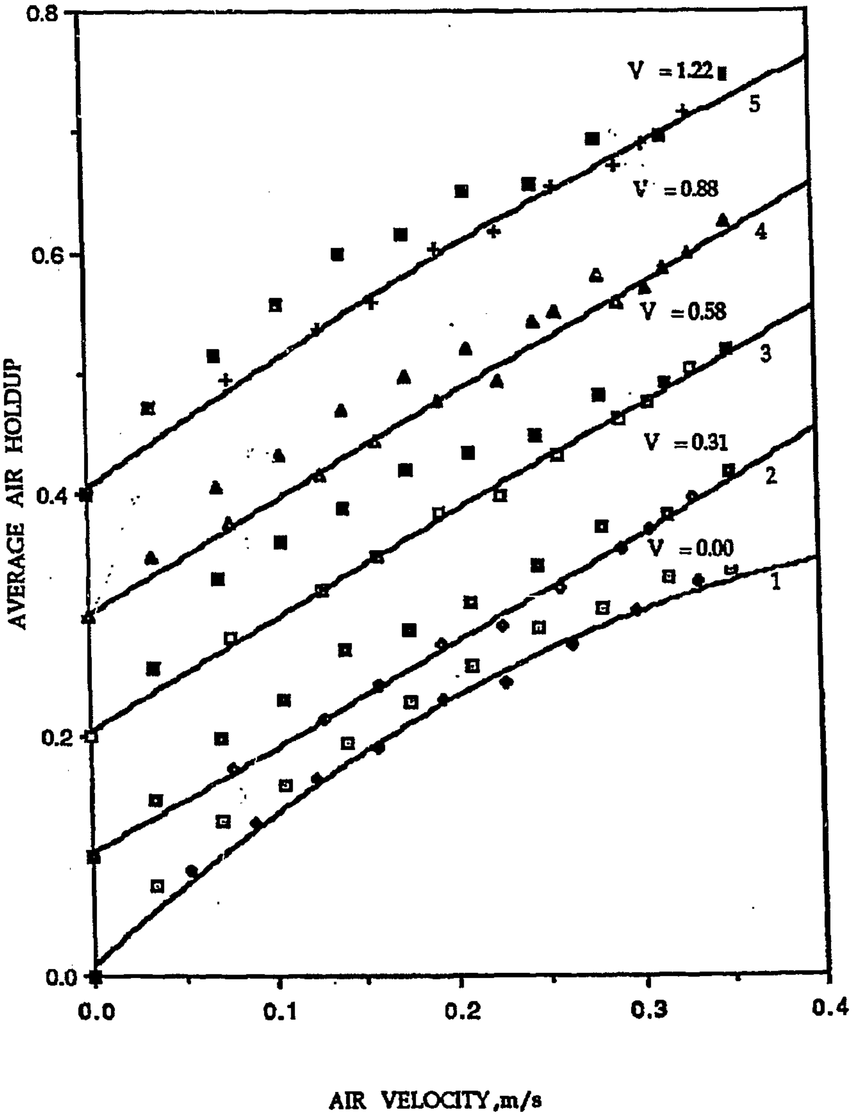

Figure 10. Variation of average air holdup as a function of air velocity for different liquid velocities in the column with single heat transfer probe. Ordinates for curves 2, 3, 4 and 5 are shifted by 0.1, 0.2, 0.3 and 0.4 respectively.

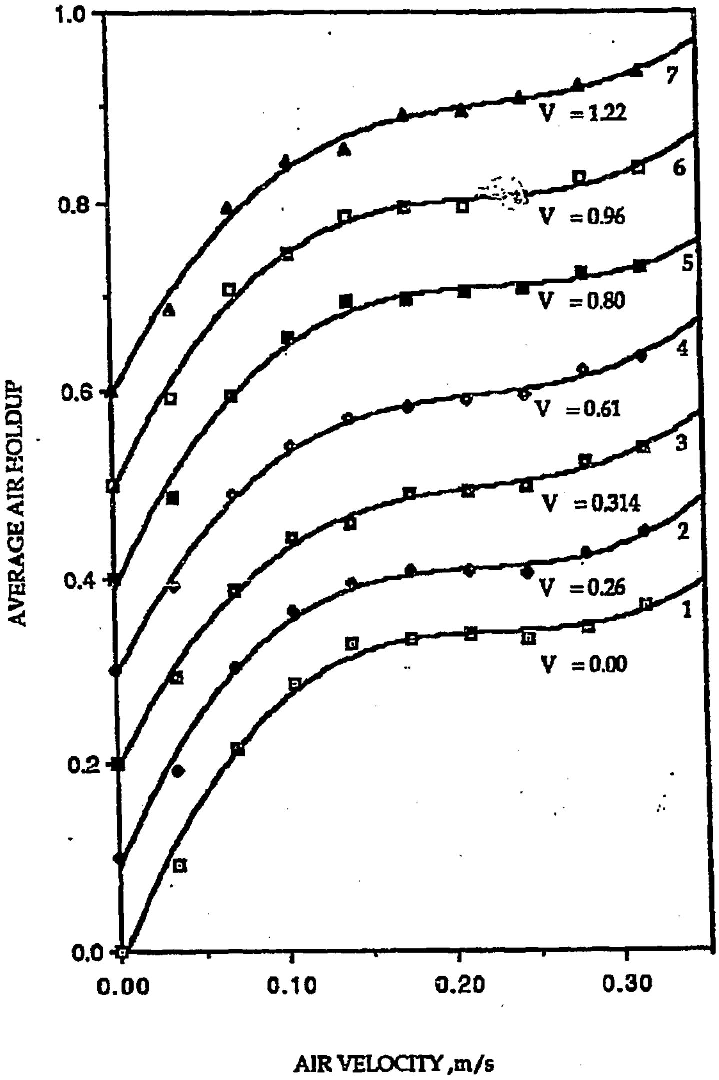

Figure 11. Variation of average air holdup as a function of air velocity for different liquid velocities in the column with single heat transfer probe. Ordinates for curves 2, 3, 4, 5, 6 and 7 are shifted by 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 respectively.

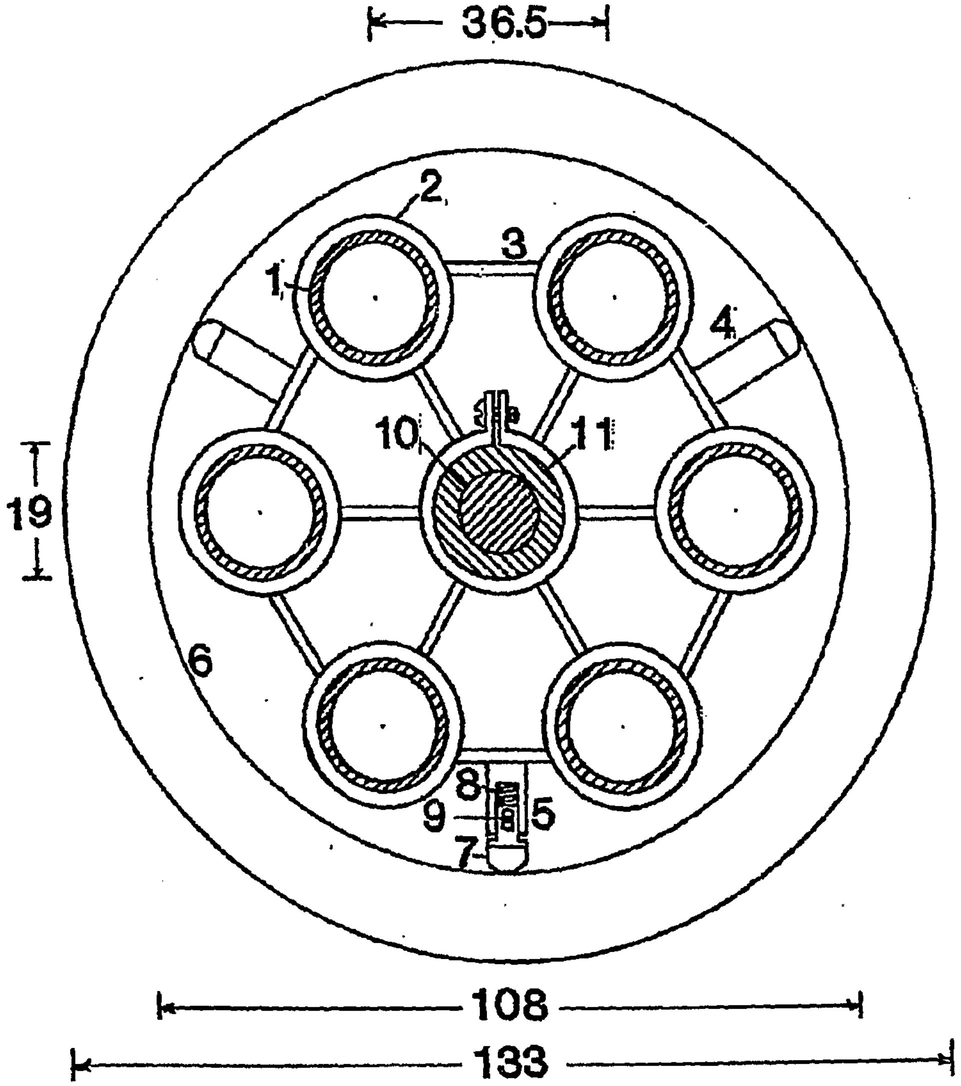

Figure 12. A sectional top view through the center of the probe bundle comprising of seven simulated heat transfer probes arranged in an equilateral triangular configuration. (1) heat transfer probe, (2) ring clamp, (3) spacer plates, (4) locating stud, (5) telescopic locating stud, (6) column surface, (7) Teflon rounded cap, (8) stainless steel spring, (9) locking pin, (10) calrod heater, and (11) brass tube.

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