NASA Technical Memorandum 85807

NASA-TM-85807 19840017577

Reynolds Number Effects on Pressure Loss and Turbulence Characteristics of Four Tube-Bundle Heat Exchangers

William B. Igoe and Garl L. Gentry, Jr.
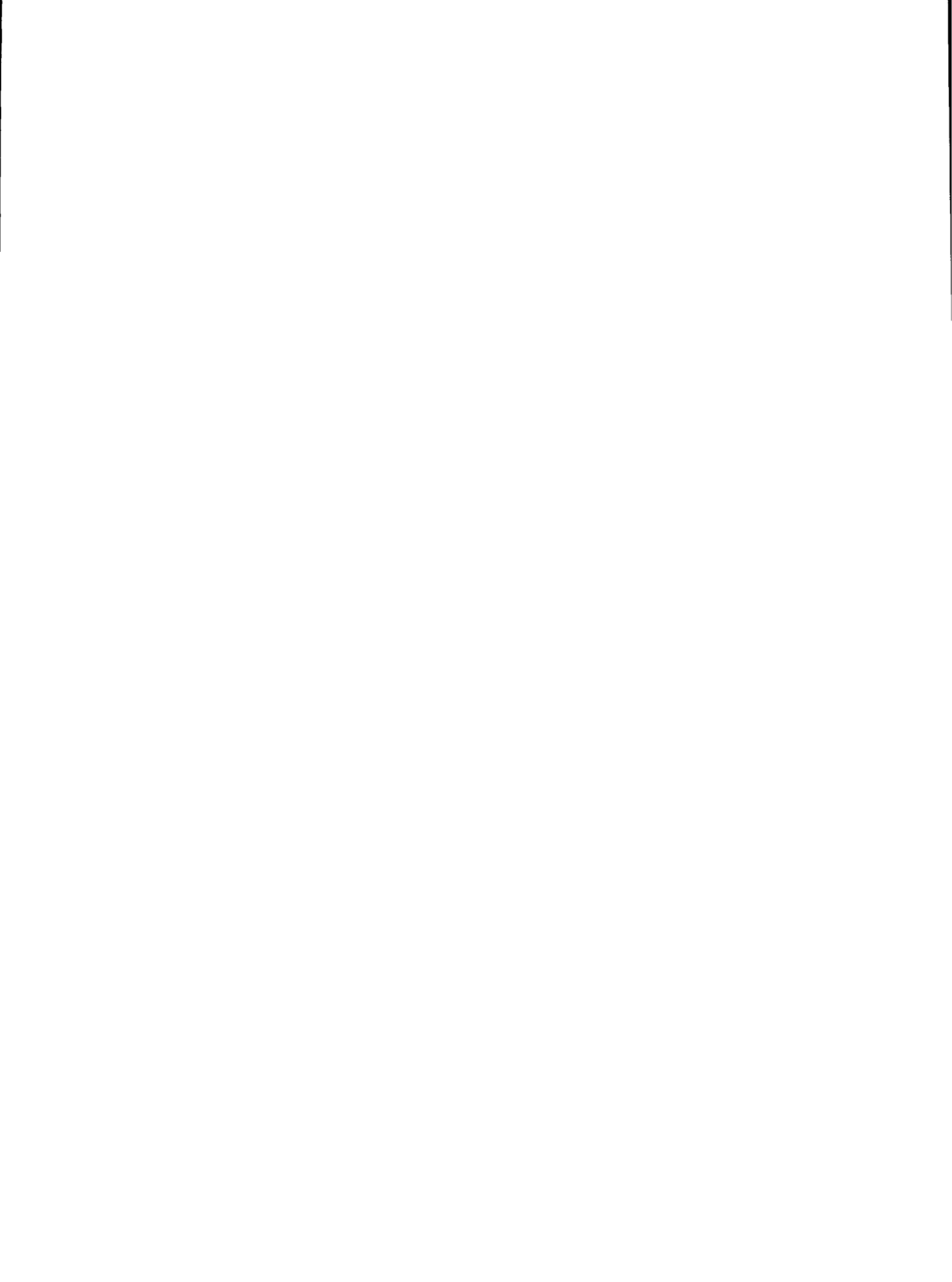
JUNE 1984

NASA

Reynolds Number Effects on Pressure Loss and Turbulence Characteristics of Four Tube-Bundle Heat Exchangers

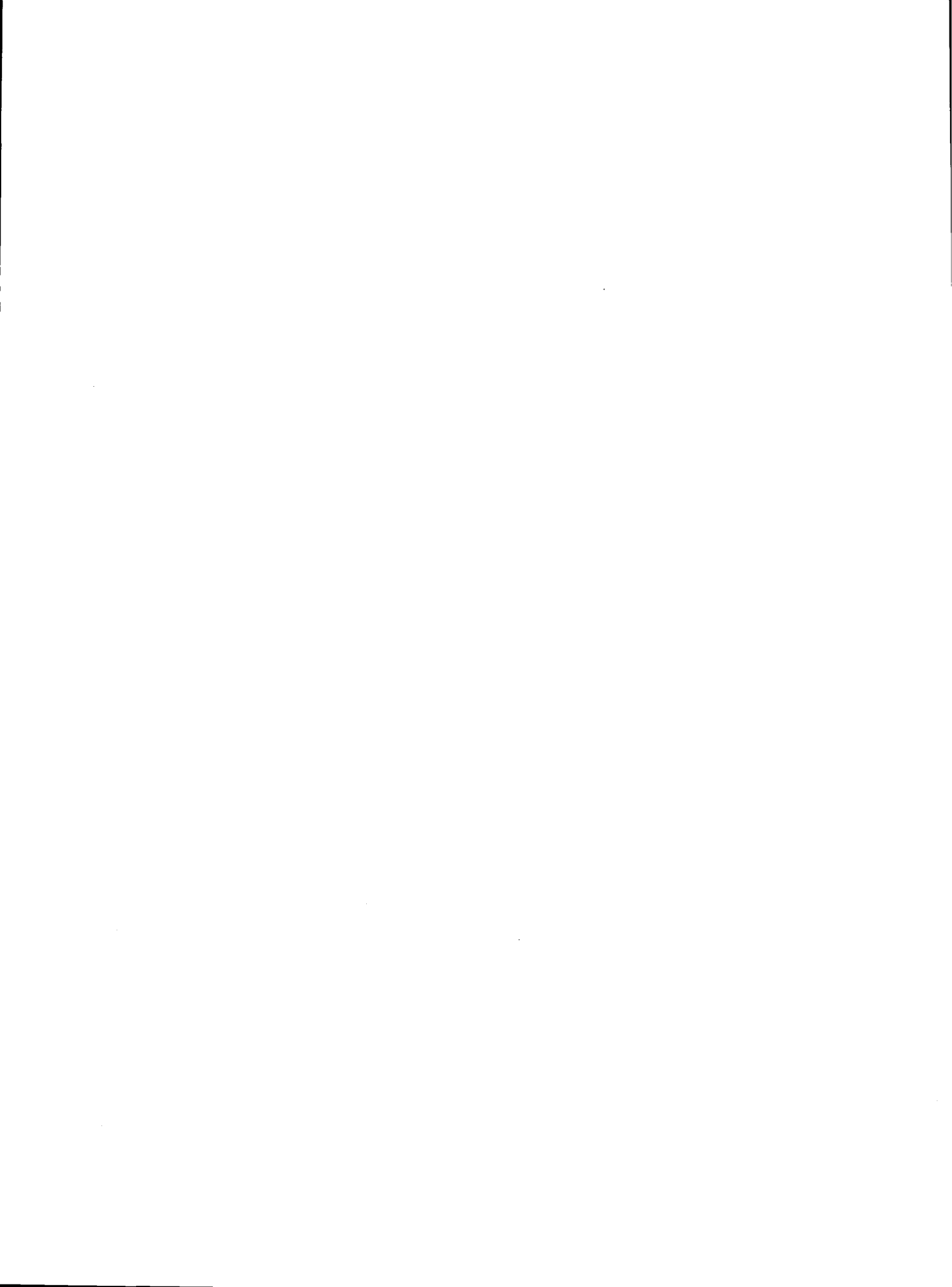William B. Igoe and Garl L. Gentry, Jr.
Langley Research Center
Hampton, Virginia

SUMMARY

The aerodynamic characteristics of pressure loss and turbulence on four tube-bundle configurations representing heat-exchanger geometries with nominally the same heat capacity were measured as a function of Reynolds number from about 4000 to 400 000 based on tube hydraulic diameter. Two elliptical- and two round-tube configurations were tested. All four configurations had plate fins.

The results indicate an apparent aerodynamic advantage of the elliptical-tube shape compared with the round-tube shape both for pressure loss and turbulence characteristics. For all four configurations, the pressure loss coefficient decreased with increasing Reynolds number at low Reynolds numbers. At high Reynolds numbers, the same trend persisted for the elliptical-tube configurations but was reversed for the round-tube configurations.

INTRODUCTION

The adoption of cryogenic operation has made it possible to obtain high Reynolds number test conditions at transonic speeds in conventional closed-circuit, fan-driven, continuous-flow wind tunnels (as indicated, for example, in refs. 1 to 4). Cryogenic operation in nitrogen with liquid nitrogen injected directly into the circuit for cooling in these tunnels has been shown to increase the maximum test Reynolds number by about 5 to 7 times that available at ambient temperatures for the same stagnation pressure and Mach number conditions (ref. 1).

The overall consumption of energy in cryogenic tunnels is high, primarily because of the energy required to produce the liquid nitrogen which is used for cooling (ref. 2). If a conventional chilled-water heat exchanger was used for cooling in the ambient temperature mode of operation instead of liquid nitrogen injection, it has been estimated that the consumption of energy in this mode would be reduced by an order of magnitude. In addition to the advantages in energy consumption, the benefits of using a conventional heat exchanger for cooling also include the capability to use air as well as nitrogen as the test gas in the ambient temperature mode.

The Reynolds number range over which a cryogenic wind tunnel operates in the cryogenic mode is generally well above that for which a heat exchanger would be needed for cooling in the ambient temperature mode. The external, or aerodynamic, characteristics of the tube-bundle elements of the heat exchanger such as pressure loss and turbulence generation are functions of Reynolds number as well as other test variables. These aerodynamic characteristics are important to the efficiency and to the flow quality of the wind tunnel and must be determined for all operating conditions. Consequently, in the development of large cryogenic wind tunnels, it may be necessary to determine these characteristics at Reynolds numbers substantially greater than those for which the heat exchangers are designed for heat transfer purposes.

The National Transonic Facility (NTF) at the Langley Research Center is an example of the kind of wind tunnel under discussion here. It is a cryogenic, fan-driven, continuous-flow wind tunnel with a 2.5-m-square test section. In order to test at low and moderate Reynolds numbers in air as well as in nitrogen, the NTF has a

conventional chilled-water heat exchanger in the tunnel circuit (ref. 5). The heat exchanger has a design heat capacity corresponding to about 0.3 MW/m^2 of frontal area.

In order to provide comparative data needed to guide the selection of the heat-exchanger geometry for the NTF, several candidate tube-bundle configurations, each designed for nominally the same heat capacity, were tested for the aerodynamic characteristics of pressure loss and turbulence. None of the heat-transfer characteristics of the heat exchangers were simulated, and all tests were conducted under adiabatic flow conditions. Some results of tests at low Reynolds number are reported in reference 6.

The present tests were conducted in the 20- by 60-cm test section of the Langley 0.3-Meter Transonic Cryogenic Tunnel (TCT) at Reynolds numbers from about 3.8×10^5 to 2.8×10^7 per meter. The free-stream Mach number was varied from about 0.01 to 0.10, the stagnation pressure was varied from about 1.2 to 5.0 atm, and the stagnation temperature was varied from about 100 to 300 K. The Reynolds number based on tube hydraulic diameter varied from approximately 4×10^3 to 4×10^5.

SYMBOLS

a   speed of sound

ℓ length

M   Mach number,   U/a

q   dynamic pressure, $\rho U^2/2$

R   Reynolds number, $\rho U \ell/\mu$

U   free-stream velocity

u'   root-mean-square (rms) turbulent-velocity component in streamwise direction

x,y,z   streamwise coordinate, lateral coordinate parallel to tube axis, and lateral coordinate normal to tube axis, respectively

Δp_t stagnation pressure loss across heat-exchanger tube bundle

μ dynamic viscosity of test gas

ρ mass density of test gas

TEST APPARATUS

The current configuration of the 0.3-m TCT with a 20- by 60-cm test section (fig. 1) is described in reference 7. It is a closed-circuit, fan-driven, pressurized tunnel capable of continuous operation. The test gas is nitrogen, and the method of cooling is by injection of liquid nitrogen into the circuit. This method of cooling, and the consequent exhausting of gaseous nitrogen to the atmosphere to maintain a constant pressure, limits the minimum operating pressure of the tunnel to

about 1.2 atm. At the time of the tests, the maximum pressure limit on the pressure shell was 5.0 atm, although since that time this limit has been raised to 6.0 atm (ref. 7).

The temperature limits of the tunnel range from a low of 77 K (the liquefaction temperature of nitrogen) to about 327 K. This wide range of temperatures permits a wide range of Reynolds numbers to be obtained at low dynamic pressures.

The tube-bundle heat-exchanger models were installed in the 20- by 60-cm test section of the tunnel with the tubes spanning the 20-cm dimension as shown in the photograph of figure 2 and the sketch of figure 3. Normally, the test section is ventilated with longitudinal slots in the top and bottom walls. The side walls are usually solid except when provisions are made for boundary-layer removal. For the present tests, the slotted walls were replaced with solid walls, and no test-section ventilation was used.

MODELS

The cryogenic feature of the 0.3-m TCT allowed high Reynolds number test conditions to be reached without imposing severe loading conditions on the test models. The low dynamic pressures allowed a simplified method of construction for the models of the various tube-bundle heat exchangers.

Since heat transfer was not included in the tests, it was not necessary to construct the tube bundles of actual tube hardware. Consequently, for simplicity, all the models were constructed with thin, flat brass sheets for the plate fins with aluminum washers aligned between the fins to simulate the tubes. The fin spacing, tube diameter, and round or elliptical tube shapes were provided by using washers of appropriate size and shape. The tube bundles were held together by aluminum stud bolts through the centers of the washers. All the materials used were compatible with the cryogenic temperature environment to which they were exposed.

Geometrically, the models were made the same size as the tube bundles they were intended to represent. Streamwise, the full depth of the tube bundle was simulated. Laterally, the number of tubes represented was sufficient to fill the 60-cm dimension of the test section. The length of the tubes spanned the 20-cm dimension of the test section.

Four tube-bundle heat-exchanger models were tested. The configurations of the models are shown in figure 4. All the configurations had in-line tube arrays with plate fins. Two of the configurations (elliptical 1 and 2) had elliptically shaped tubes, and the other two configurations (baseline and six-row) had round tubes. Both of the elliptical-tube configurations and the baseline configuration had four rows of tubes streamwise. The other round-tube configuration had six rows of tubes streamwise. The two configurations designated elliptical 1 and 2 differed only in the size of the tubes.

It was intended that all the tube-bundle heat-exchanger models would represent configurations with substantially the same heat capacity. After the dimensions of the smaller elliptical tube were selected, it was discovered that, from a heat-transfer consideration, this configuration would require a water circulation velocity inside the tube that was higher than was considered desirable. The larger elliptical

tube allowed a lower water velocity. For completely comparable internal flow conditions (same water velocity), the smaller elliptical-tube configuration would therefore have fallen somewhat short (about 75 percent) of the required heat capacity.

INSTRUMENTATION

The instrumentation for the present tests consisted primarily of the instrumentation normally in use at the 0.3-m TCT (refs. 4 and 7). It should be noted that the capacities of the pressure transducers regularly used at the tunnel are sized for the full range of pressures associated with high Mach number (near-sonic) operation at high total pressures. Because of the low speeds of the present tests, in some instances lower capacity, more sensitive pressure transducers were used.

The tunnel free-stream total pressure is normally measured in the settling chamber (downstream of the anti-turbulence screens) with a differential pressure gage referenced to vacuum with a capacity of about 700 kPa. For the present tests, the total pressure was measured with a pitot probe located just upstream of the test section with the same kind of pressure gage installation and capacity.

The free-stream static pressure is normally measured with sidewall static-pressure orifices located near the front of the test section with a pressure gage installation and capacity the same as those used for the total pressure. For the present tests, a more sensitive pressure gage with a capacity of about 3 kPa was connected to the same static-pressure orifices and referenced to free-stream total pressure.

The pressure drop across the tube-bundle heat-exchanger models was obtained from the difference in total pressures measured upstream and downstream of the models. The upstream total pressure was obtained from the free-stream total-pressure pitot tube, and the downstream total pressure was measured with a total-pressure rake. This rake, which is shown in figure 5, is normally used for surveying the wake behind airfoil models in the test section with differential pressure gages referenced to free-stream total pressures; the capacity of these gages is about 140 kPa. For the present tests, the farthest outboard total-pressure tube on the rake was connected to a sensitive differential-pressure gage referenced to free-stream total pressure. The capacity of this gage is about 50 kPa.

For the heat-exchanger models installed in the 0.3-m TCT test section, the distance from the rear face of the tube bundle to the total-pressure-rake tubes was 52.7 cm for the elliptical 1 and 2 configurations, 48.9 cm for the baseline configuration, and 38.7 cm for the six-row configuration. These distances expressed in terms of tube spacing are 13.8, 12.8, and 7.6, respectively. Although the survey rake is normally capable of vertical (z-direction) translation, for this test the rake was fixed at the tunnel centerline. Consequently, the pressure-tube readings on the rake represented single-point measurements. A vertical survey yielding a spatial average would have been preferred, but this was not possible because of hardware limitations. However, flow uniformity measurements of reference 6 for similar tube-bundle configurations at low Reynolds numbers indicate that single-point measurements of total pressure loss, expressed in terms of $\Delta p_t/q$, should not differ from a spatially averaged measurement by more than ± 0.2.

The hot-wire probes consisted of crossed wires of 5-μm, platinum-coated tungsten wire with an effective length-diameter ratio of about 250. The hot wires were operated in the constant temperature mode for turbulence measurements and in the constant

current mode for measurements of temperature spottiness. The output signals from the hot-wire probes were recorded on magnetic tape for off-line analysis, and on-line rms readings were also recorded. Only the rms turbulence data are presented in this report. The tunnel stagnation temperature was measured in the settling chamber with the standard tunnel instrumentation consisting of a platinum resistance thermometer.

RESULTS AND DISCUSSION

The pressure loss characteristics of the various tube-bundle configurations are presented in the form of the difference in stagnation pressures ahead and behind the models Δp_t divided by the free-stream dynamic pressure q. The turbulence characteristics are presented as the rms turbulent-velocity components u', v', and w' divided by the free-stream velocity U. For convenience, the Reynolds numbers are given as unit Reynolds numbers of the flow rather than the Reynolds number based on the hydraulic diameter of the tubes. This is done because the main intention of the tests is to obtain comparative data on the performance of tube bundles of different geometries under the same flow conditions.

Effect of Mach Number

During the tests, it was necessary to vary velocity as well as temperature and pressure in order to obtain the wide range of Reynolds numbers desired. The small change in Mach number caused by the change in velocity was not expected to have significant effects on the aerodynamics of the various tube bundles.

In order to illustrate this anticipated insensitivity to small changes in Mach number, the pressure loss data $\Delta p_t/q$ as a function of y (the probe position on the rake) are shown in figure 6 for each configuration at a nearly constant Reynolds number over a range of Mach numbers from about 0.05 to 0.10. In figure 6, the Reynolds number for the elliptical 1 configuration is about 25×10^6 per meter; for the other configurations it is about 13×10^6 per meter. Within the normal scatter of the data, the pressure loss is uniform for the several probes over the span of the rake.

The data from figure 6 for the farthest outboard probe of the rake have been replotted as a function of Mach number in figure 7 to show that the pressure loss coefficients do not vary significantly with Mach number. From these results, it has been concluded that varying Reynolds number by varying velocity in this low Mach number range does not introduce any extraneous Mach number effects.

Effect of Reynolds Number

As mentioned earlier, the Reynolds numbers of the tests varied from about 3.8×10^5 to 2.8×10^7 per meter. This wide range was only possible by varying velocity or Mach number as well as pressure and temperature. The Reynolds number range at constant Mach number was somewhat more limited. Pressure loss data for a nearly constant Mach number of about 0.05 are presented in figure 8 for the four tube-bundle configurations. With minor exceptions for the baseline and six-row configurations, once again the pressure loss is uniform over the span of the rake.

The data from figure 8 for the farthest outboard probe on the rake ($y = 11.4$ cm) have been replotted as a function of unit Reynolds number for the four configurations

in figure 9. Data for higher and lower Mach numbers have been included to increase the Reynolds number range.

Within the range of the tests, both the elliptical 1 and 2 configurations show a continuing reduction of pressure loss coefficient with increasing Reynolds number. The two round-tube configurations show a reversal to a rising trend at the higher Reynolds numbers, with the effect being more pronounced for the baseline configuration, which also had the lowest porosity (ratio of projected open area to total area of tube bundle).

The magnitude of the pressure loss coefficient in figure 9 varies from the lowest for the elliptical 1 configuration (which had the highest porosity) to the highest for the baseline configuration (which had the lowest porosity). A comparison of the pressure loss characteristics of the elliptical 2 and six-row configurations, which had nearly the same porosities, shows an apparent aerodynamic advantage for the elliptically shaped tubes.

Turbulence Characteristics

The root-mean-square (rms) longitudinal components of turbulent velocity u'/U measured upstream and downstream of the tube-bundle heat-exchanger models are presented in figure 10. The downstream turbulence varies from lowest to highest roughly in the order elliptical 1, elliptical 2, baseline, and six-row configurations. The high value of turbulence measured for the six-row configuration may be at least partially due to the greater streamwise depth of this tube bundle. The turbulence-measuring station was a fixed distance (54.3 cm) downstream from the front face of all the tube-bundle heat-exchanger models. Consequently, for a tube bundle with greater streamwise depth, the distance from the last row of tubes to the measuring station was less. The streamwise decay of turbulence increases with this distance. Since this distance was less for the six-row configuration than for the others, the turbulence for this configuration had less flow length over which decay could take place. Consequently, the higher level of turbulence indicated for this configuration may not be wholly attributable to the characteristics of the tube bundle itself, but may be at least partially due to less decay of the turbulence.

The distance from the rear face of the tube bundle to the hot wire was 39.1 cm for the elliptical 1 and 2 configurations, 35.3 cm for the baseline configuration, and 25.1 cm for the six-row configuration. In terms of tube spacing, these distances were 10.3, 9.3, and 4.9, respectively. Based on turbulence decay data obtained at low Reynolds numbers for similar tube-bundle configurations (ref. 6), it is estimated that the difference in decay distance (35.3 cm for the baseline configuration compared with 25.1 cm for the six-row configuration) could cause a difference of 20 percent more reduction for the configuration with the greater decay length. Since the streamwise depths of the elliptical 1 and 2 configurations were more nearly equal to the baseline configuration, their decay distances were also more nearly equal (39.1 cm compared with 35.3 cm), and so their turbulence levels may be compared directly.

CONCLUDING REMARKS

The aerodynamic characteristics of pressure loss and turbulence on four tube-bundle configurations representing heat-exchanger geometries with nominally the same heat capacity were measured as a function of Reynolds number from about 4000 to

400 000 based on tube hydraulic diameter. Two elliptical- and two round-tube configurations were tested. All four configurations had plate fins.

The results indicate an apparent aerodynamic advantage of the elliptical-tube shape compared with the round-tube shape both for pressure loss and turbulence characteristics. For all four configurations, the pressure loss coefficient decreased with increasing Reynolds number at low Reynolds numbers. At high Reynolds numbers, the same trend persisted for the elliptical-tube configurations but was reversed for the round-tube configurations.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
May 15, 1984

REFERENCES

1. Kilgore, Robert A; Goodyer, Michael J.; Adcock, Jerry B.; and Davenport, Edwin E.: The Cryogenic Wind-Tunnel Concept for High Reynolds Number Testing. NASA TN D-7762, 1974.

2. Polhamus, E. C.; Kilgore, R. A.; Adcock, J. B.; and Ray, E. J.: The Langley Cryogenic High Reynolds Number Wind-Tunnel Program. Astronaut. & Aeronaut., vol. 12, no. 10, Oct. 1974, pp. 30-40.

3. Kilgore, Robert A.; Adcock, Jerry B.; and Ray, Edward J.: Simulation of Flight Test Conditions in the Langley Pilot Transonic Cryogenic Tunnel. NASA TN D-7811, 1974.

4. Kilgore, Robert A.: Design Features and Operational Characteristics of the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TN D-8304, 1976.

5. Howell, Robert R.; and McKinney, Linwood W.: The U.S. 2.5-Meter Cryogenic High Reynolds Number Tunnel. High Reynolds Number Research, Donald D. Baals, ed., NASA CP-2009, 1977, pp. 27-51.

6. Johnson, William G., Jr.; and Igoe, William B.: Aerodynamic Characteristics at Low Reynolds Numbers of Several Heat-Exchanger Configurations for Wind-Tunnel Use. NASA TM-80188, 1979.

7. Ray, Edward J.; Ladson, Charles L.; Adcock, Jerry B.; Lawing, Pierce L.; and Hall, Robert M.: Review of Design and Operational Characteristics of the 0.3-Meter Transonic Cryogenic Tunnel. First International Symposium on Cryogenic Wind Tunnels, Proceedings of the Symposium held in the Department of Aeronautics and Astronautics at the University of Southampton, England, Apr. 3-5, 1979, pp. 28.1 - 28.15.
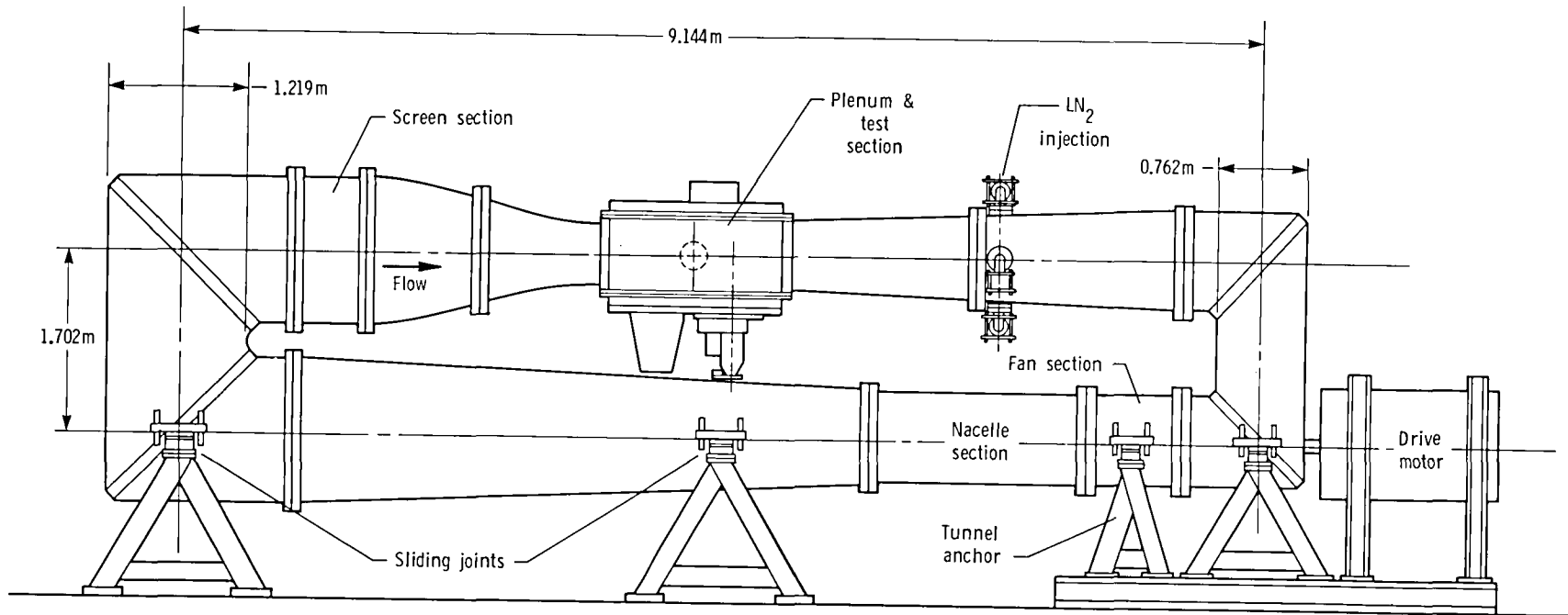
Figure 1.- The Langley 0.3-Meter Transonic Cryogenic Tunnel with 20- by 60-cm test section.

Flow

Heat-exchanger model

Hot-wire support

Wake rake
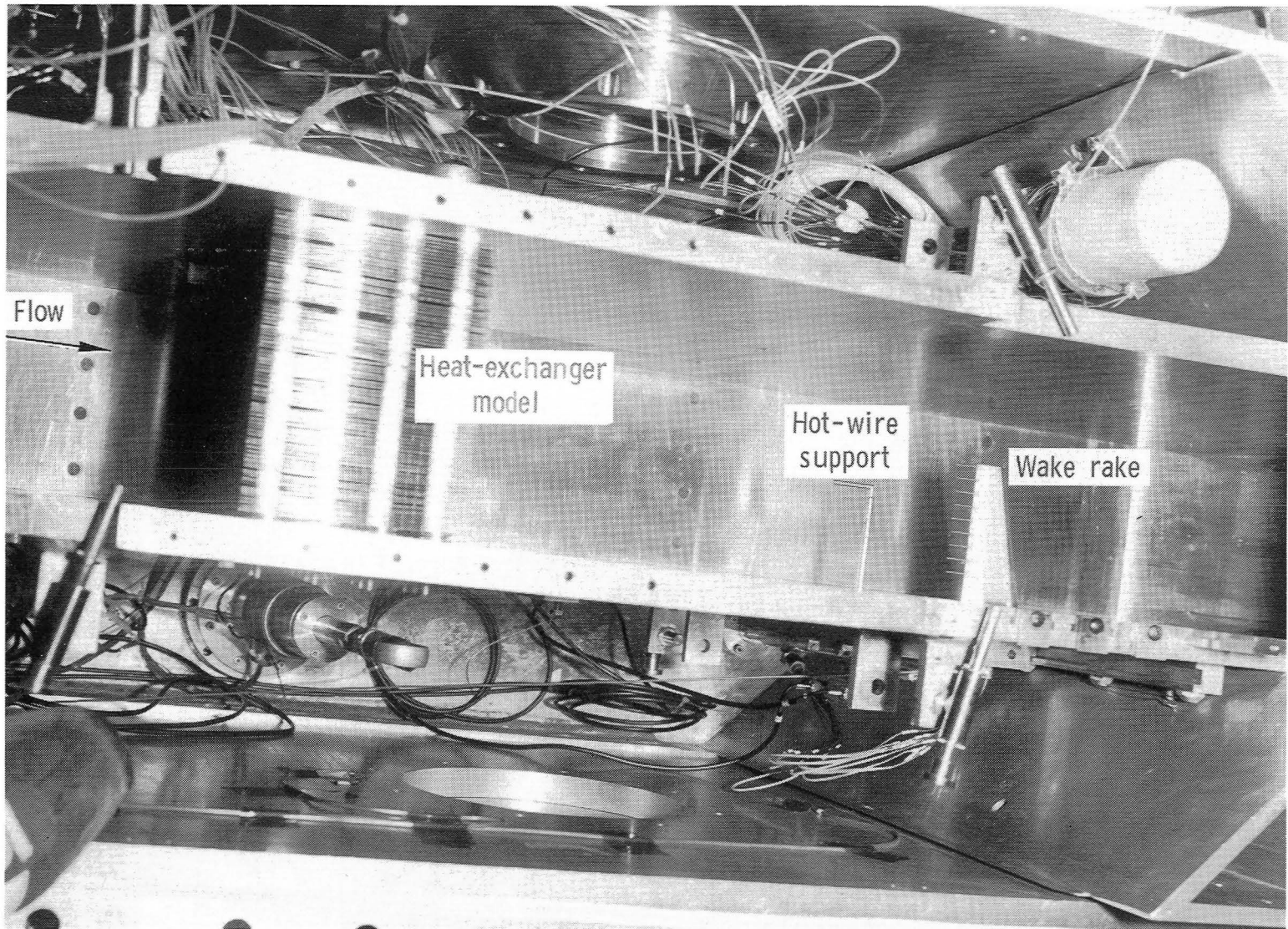
L-77-8237.1

Figure 2.- Tube-bundle heat-exchanger model installed in 20- by 60-cm test section of the Langley 0.3-Meter Transonic Cryogenic Tunnel.
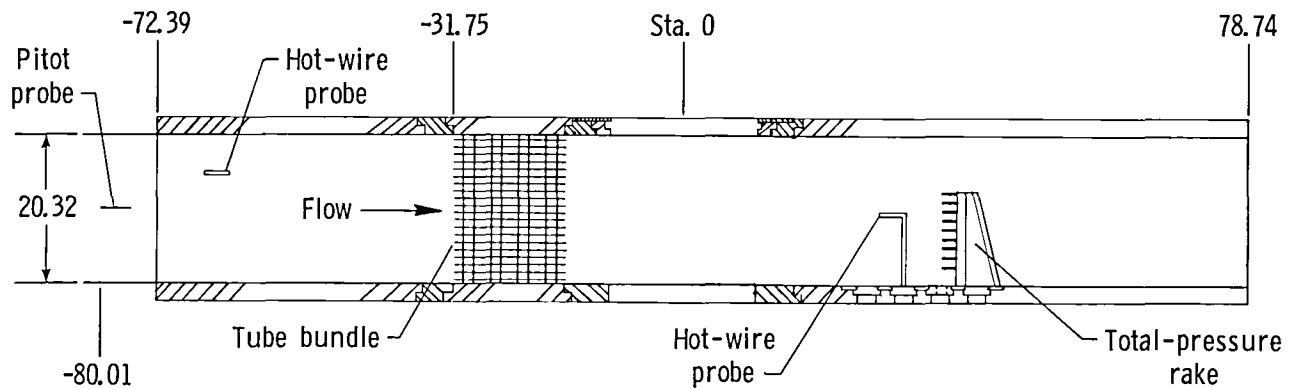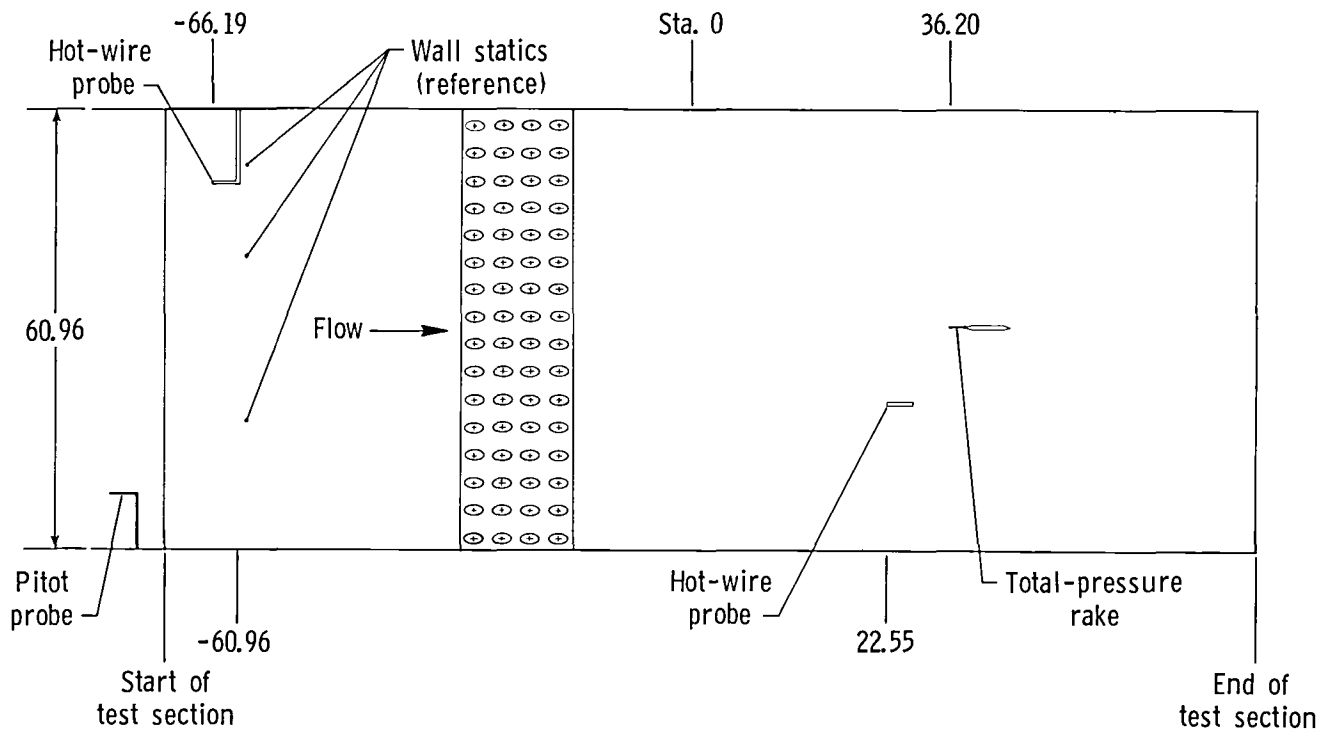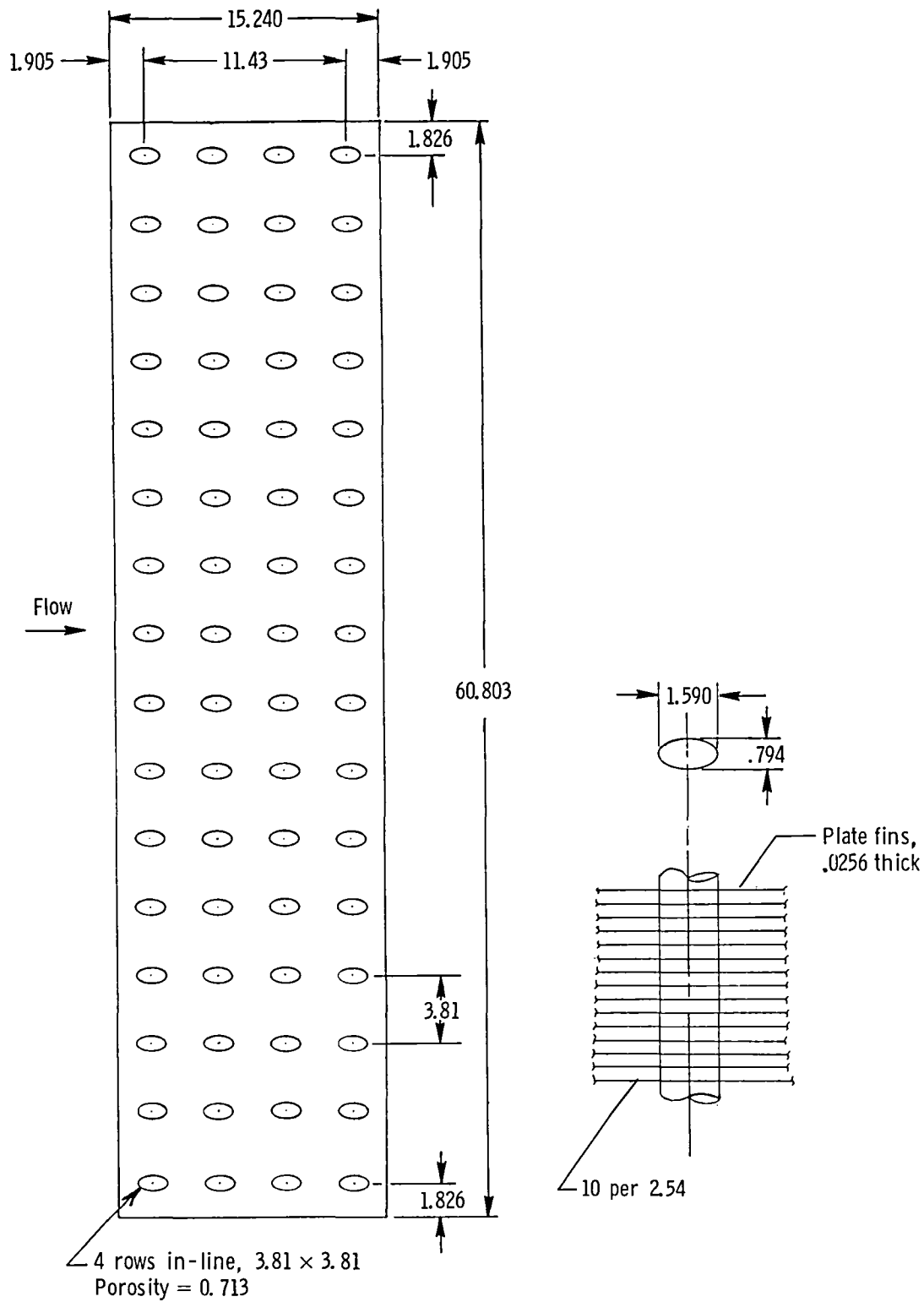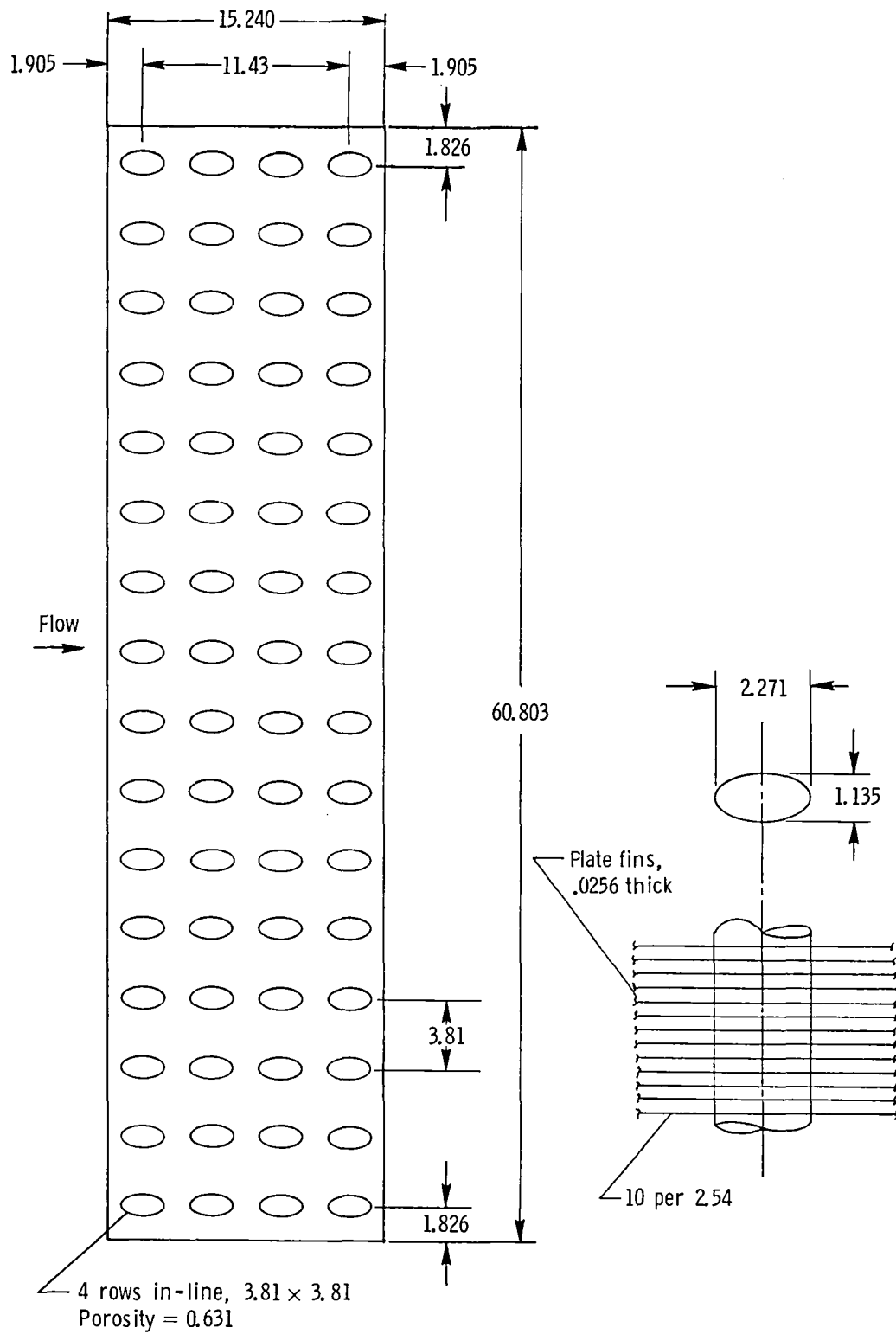
Figure 3.- The 20- by 60-cm test section of Langley 0.3-Meter Transonic Cryogenic Tunnel showing typical tube-bundle heat-exchanger model installation. All dimensions in centimeters.
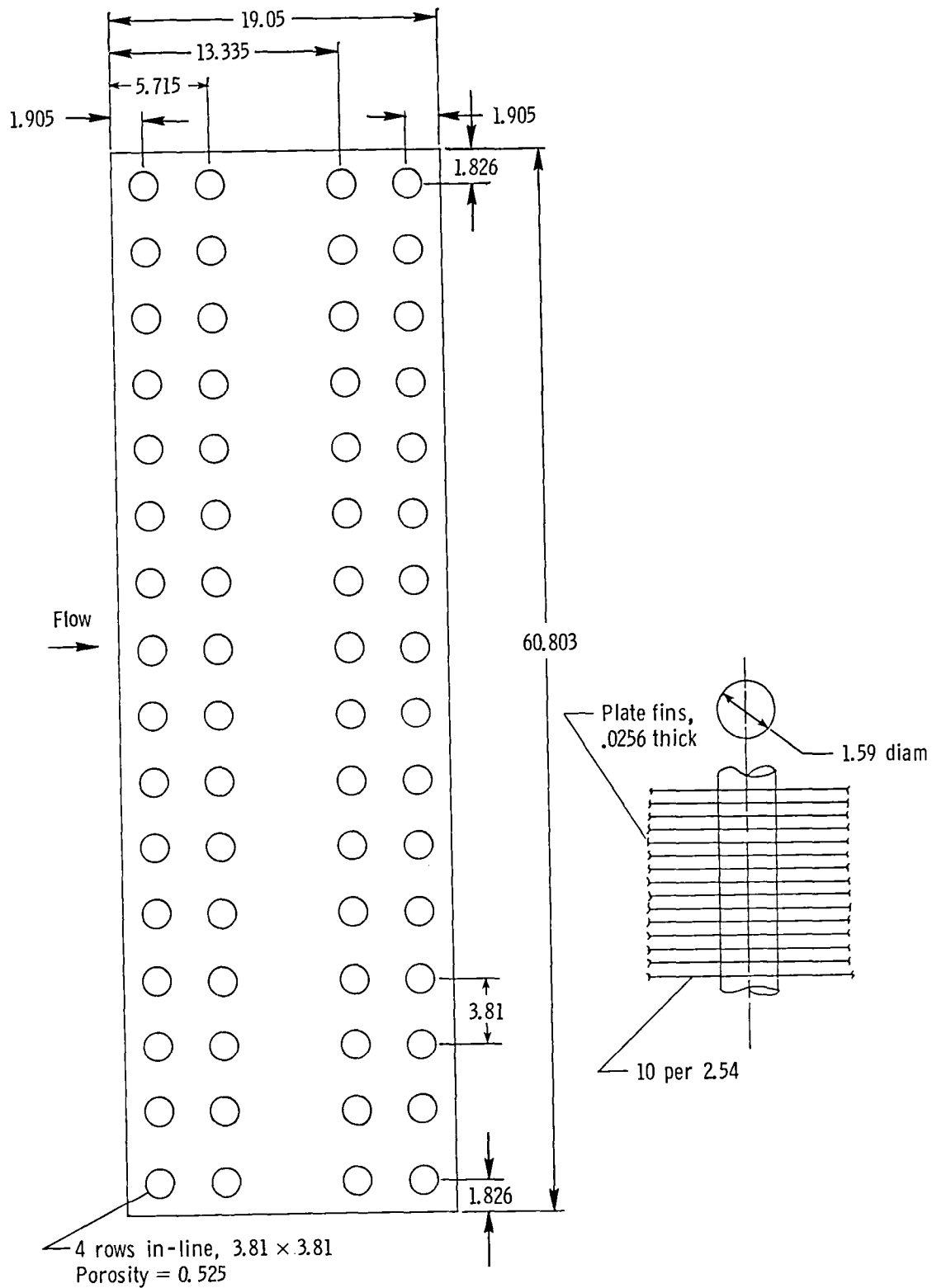
(a) Elliptical 1 configuration.

Figure 4.- Geometry of tube-bundle heat-exchanger models. All dimensions in centimeters.

15.240

1.905

11.43

1.905

1.826

Flow

60.803

3.81

1.826

4 rows in-line, 3.81 × 3.81
Porosity = 0.631

2.271

1.135

Plate fins,
.0256 thick

10 per 2.54

(b) Elliptical 2 configuration.

Figure 4.- Continued.

(c) Baseline configuration.

Figure 4.- Continued.

Flow →

29.210

25.400

1.905

2.461

60.803

55.88

5.08

Plate fins, .0396 thick

1.59 diam

6 per 2.54

6 rows in-line, 5.08 × 5.08
Porosity = 0.623
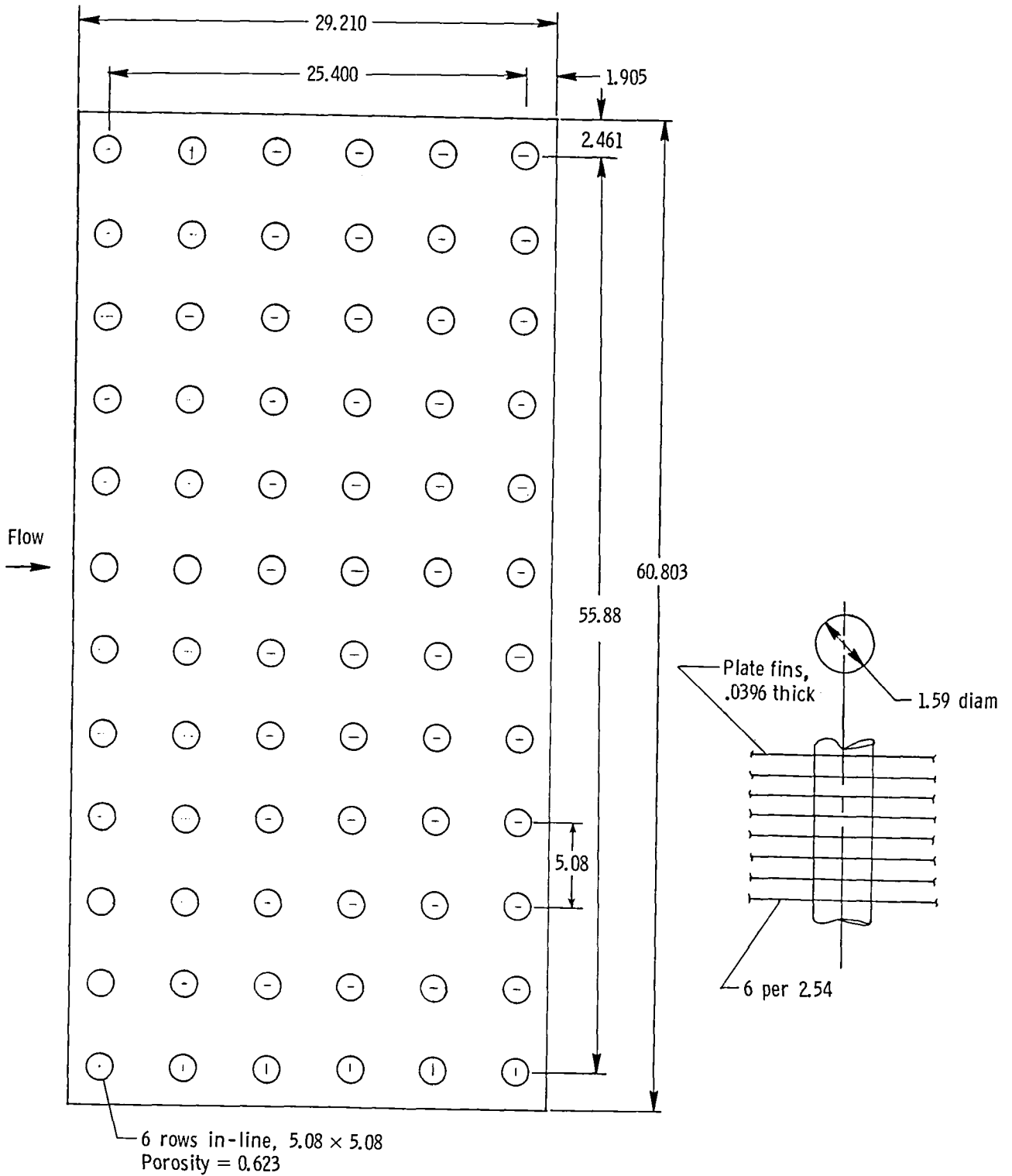
(d) Six-row configuration.

Figure 4.- Concluded.
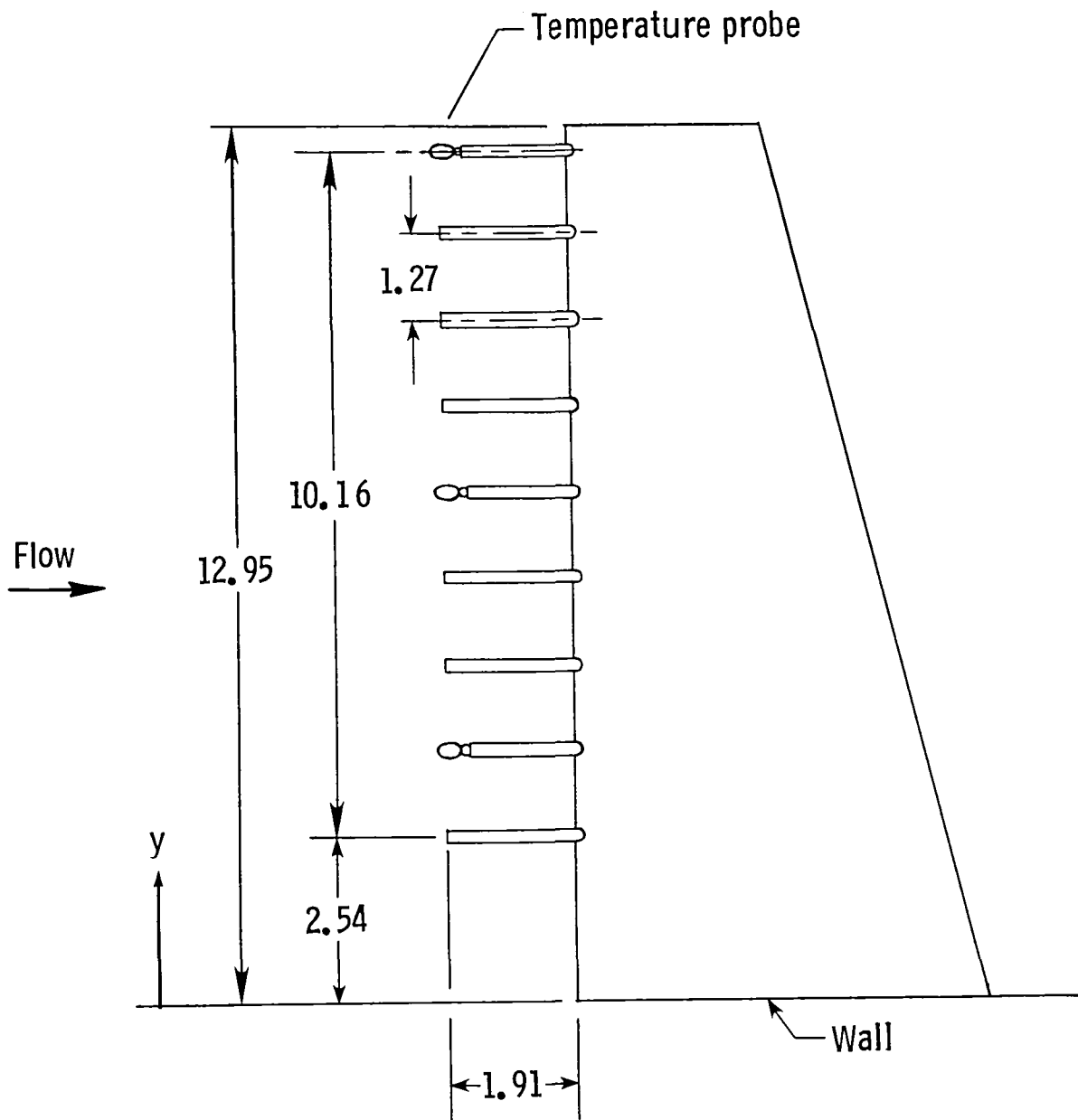
Figure 5.- Rake used to measure downstream total pressure. All dimensions in centimeters.
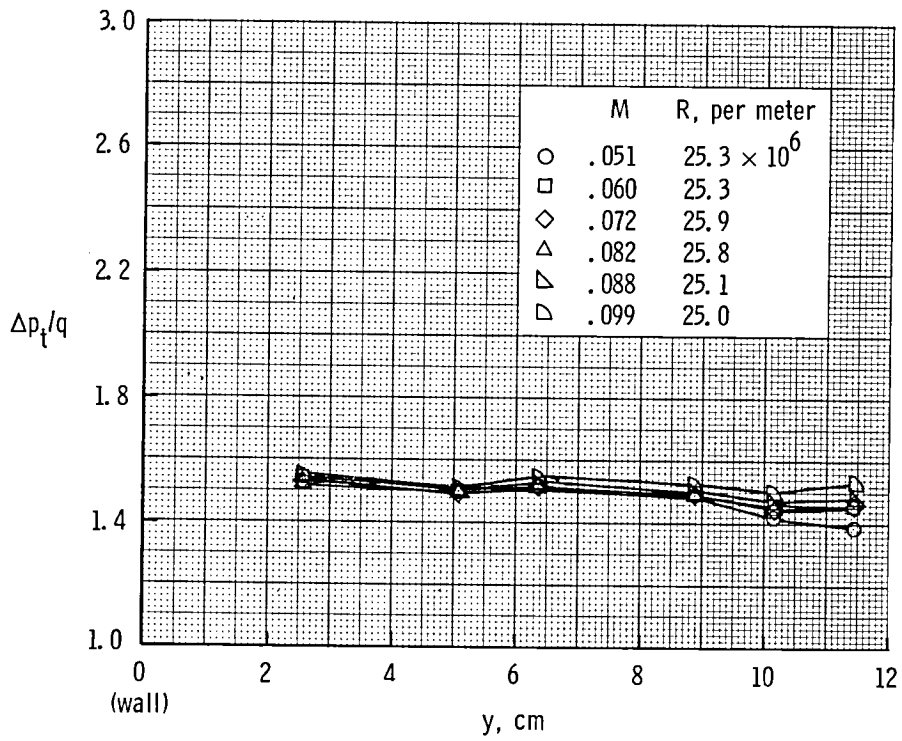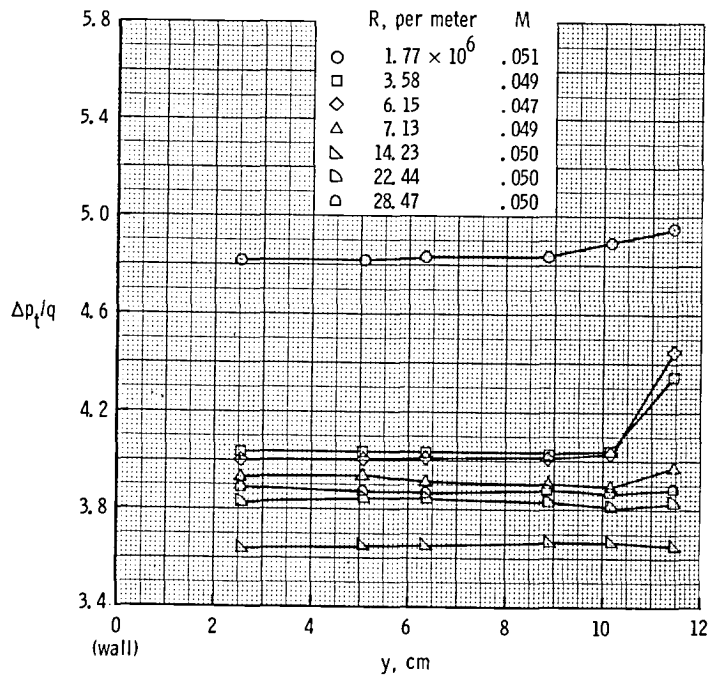
(a) Elliptical 1 configuration.
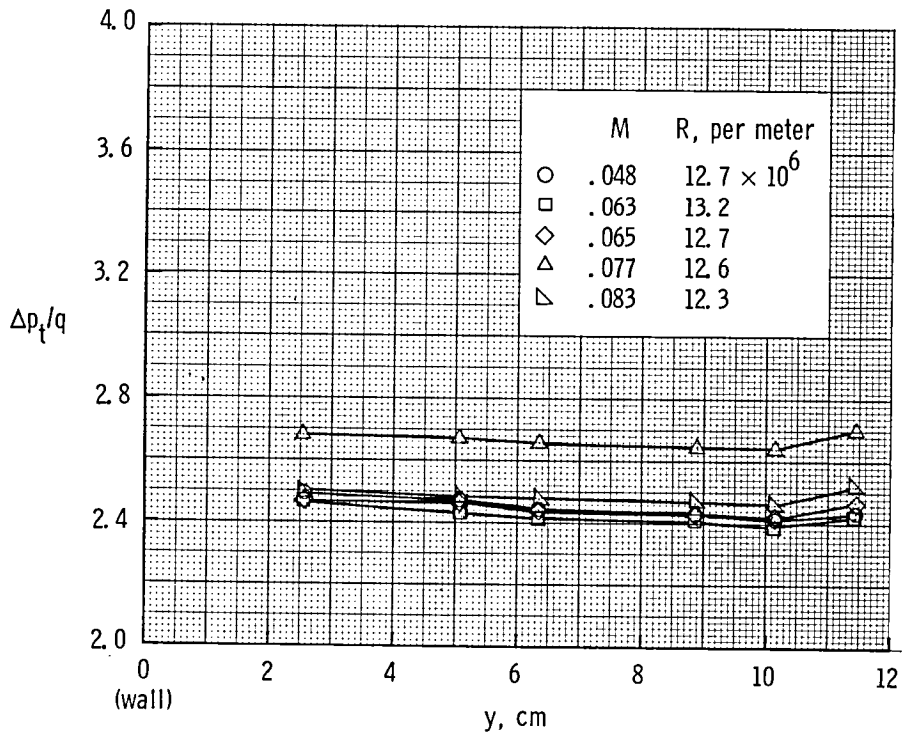
(b) Elliptical 2 configuration.

Figure 6.- Pressure loss coefficient at nearly constant Reynolds number for various Mach numbers.
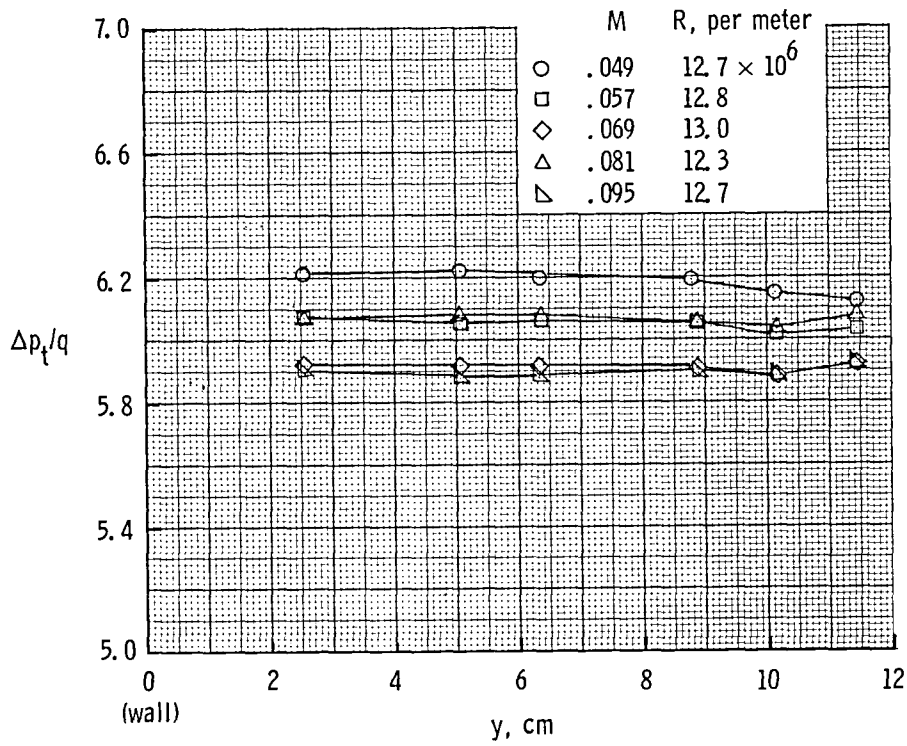
(c) Baseline configuration.
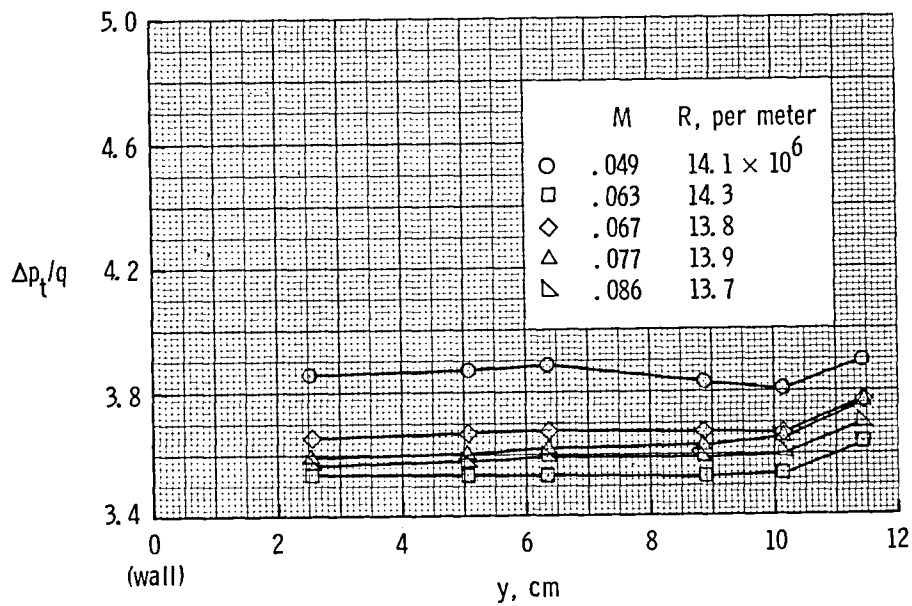
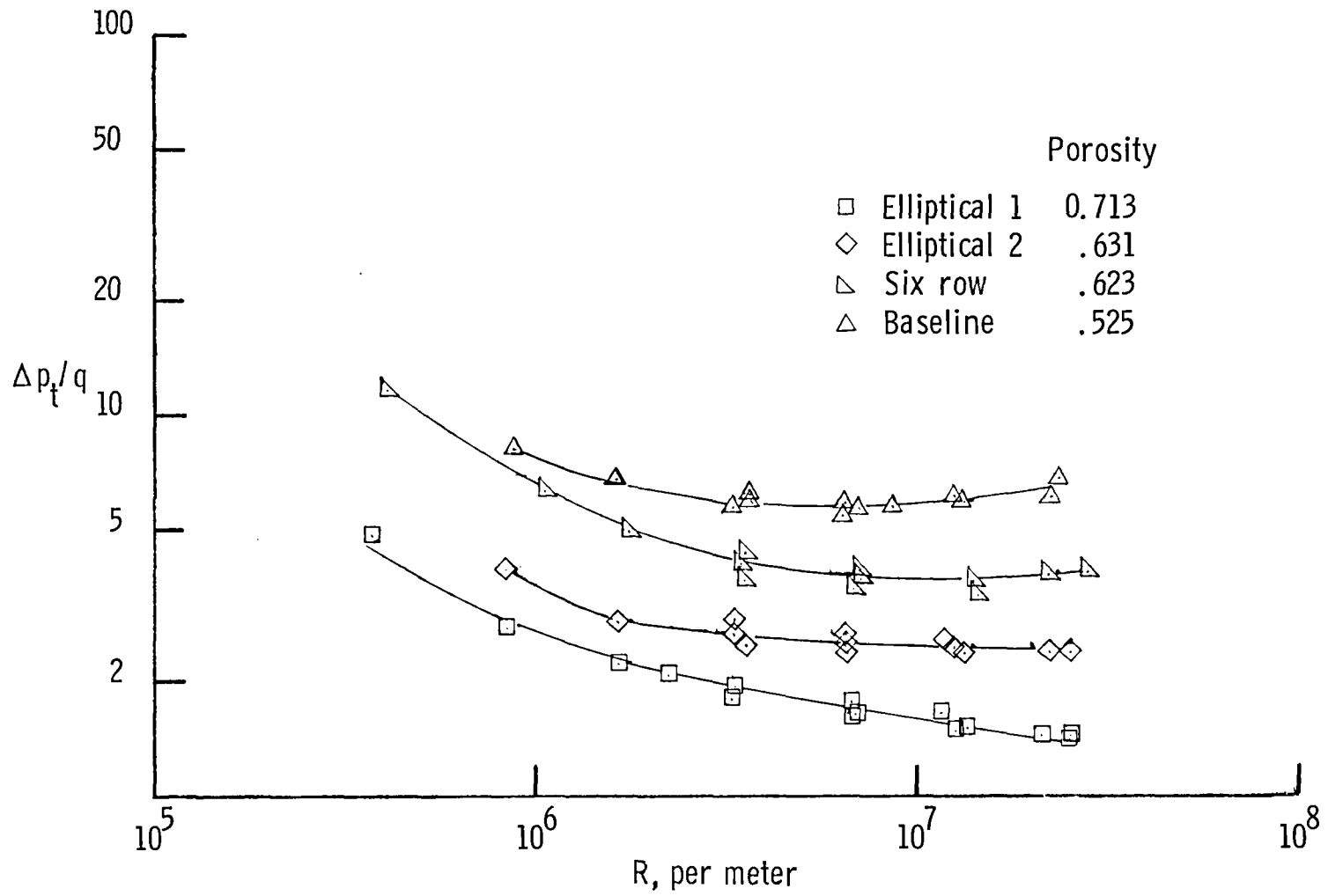(d) Six-row configuration.

Figure 6.- Concluded.
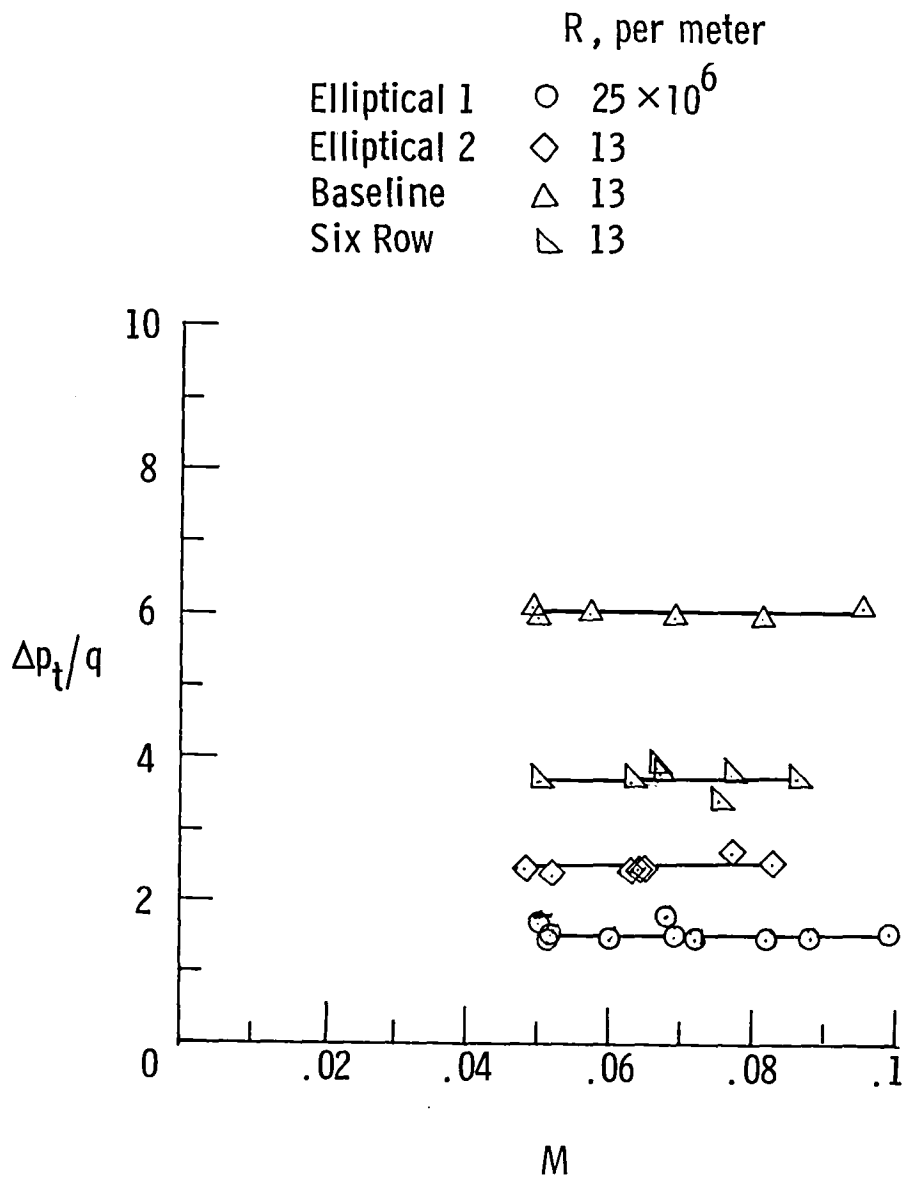
Figure 7.- Pressure loss coefficient as a function of Mach number at constant Reynolds number for y = 11.4 cm.
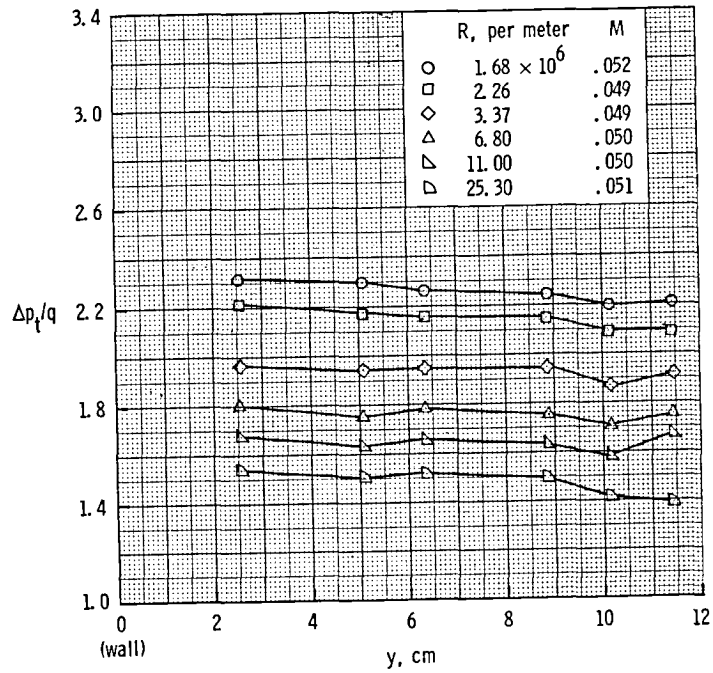
(a) Elliptical 1 configuration.
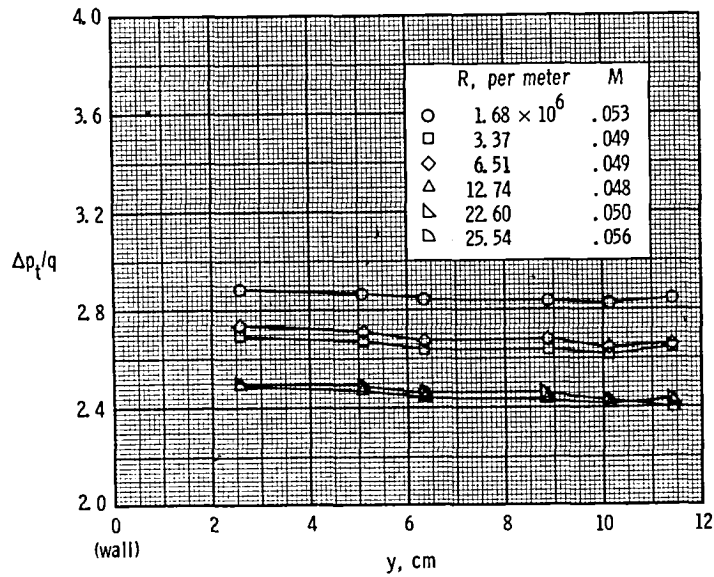
(b) Elliptical 2 configuration.

Figure 8.- Pressure loss coefficient at nearly constant Mach number for various Reynolds numbers.
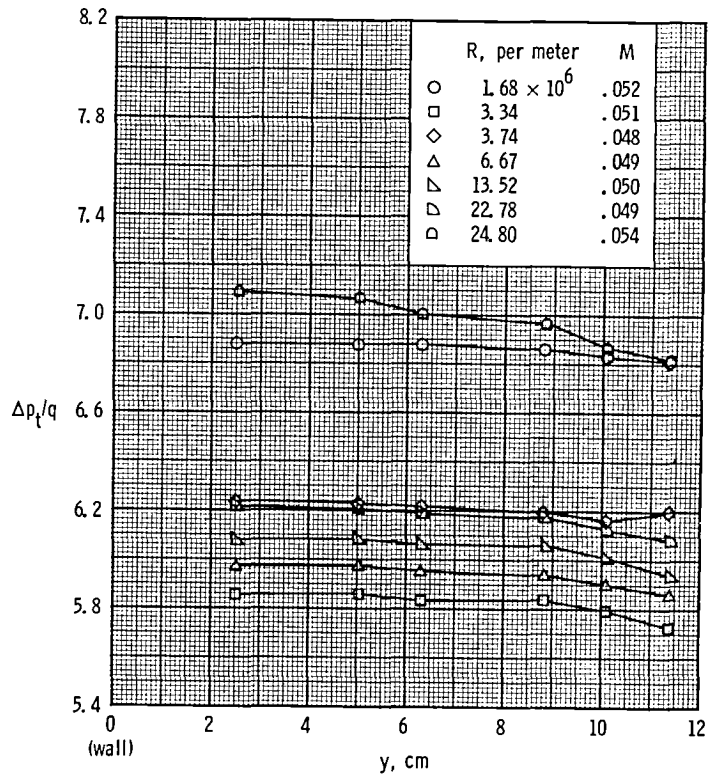
(c) Baseline configuration.

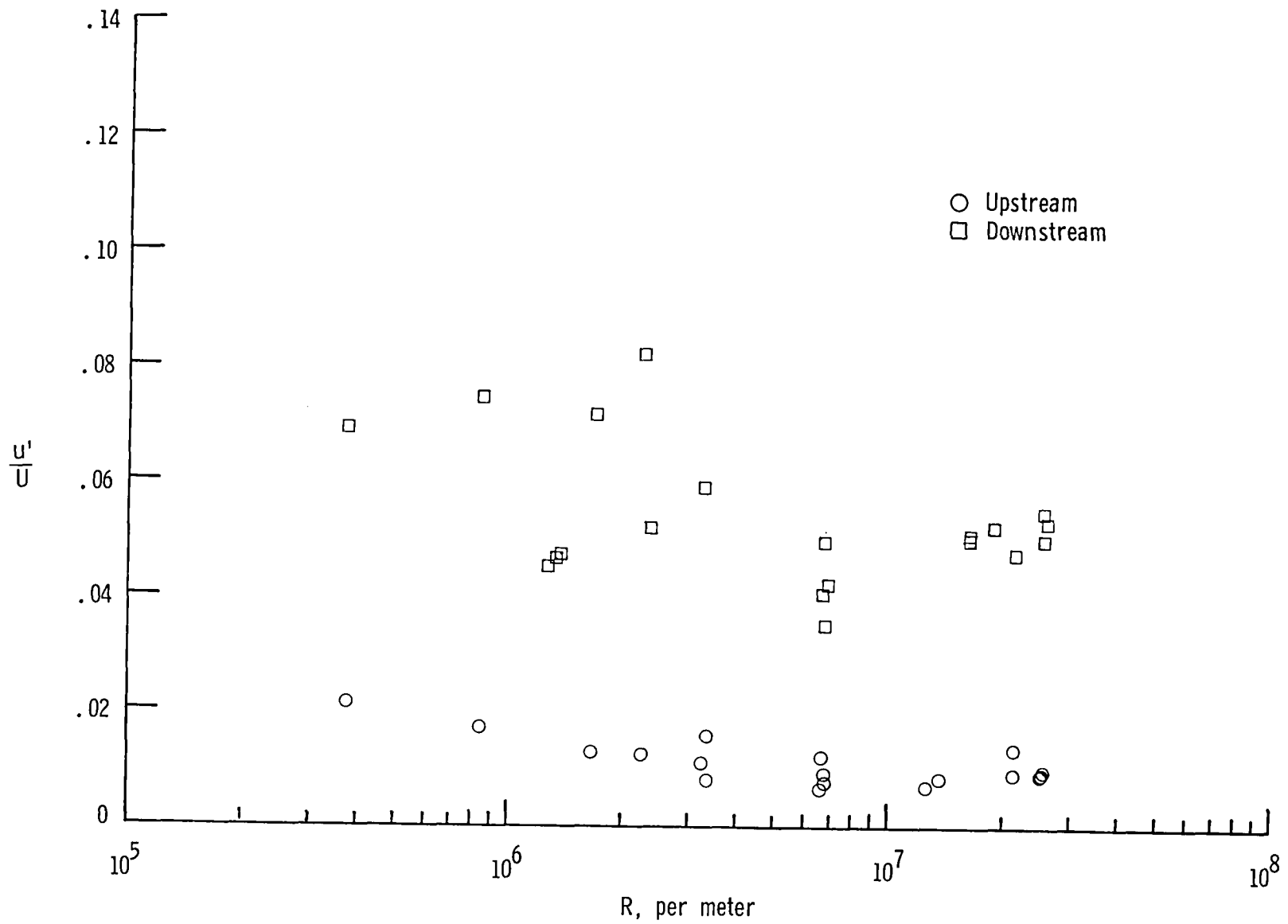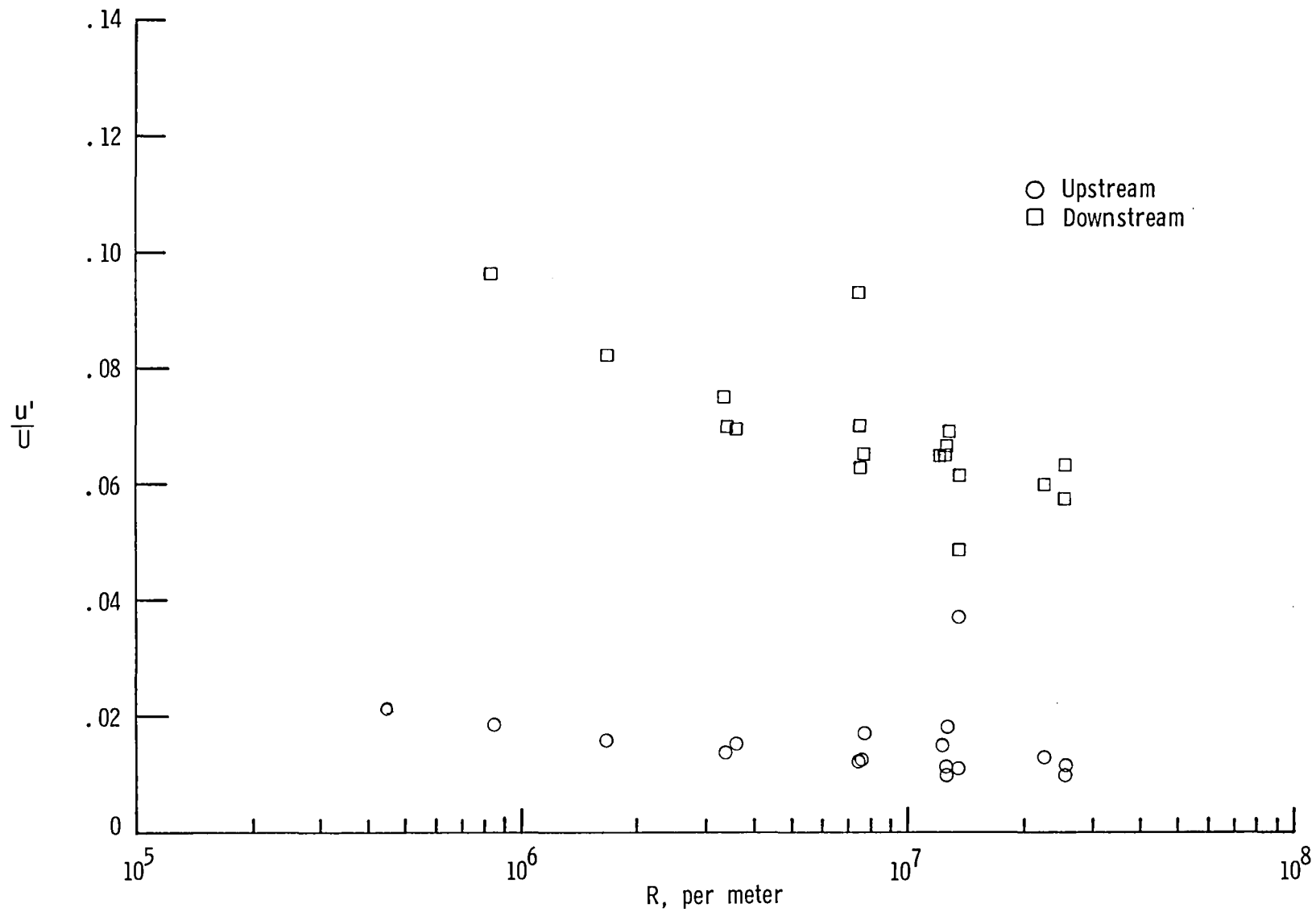(d) Six-row configuration.

Figure 8.- Concluded.

Figure 9.- Pressure loss coefficient as function of unit Reynolds number
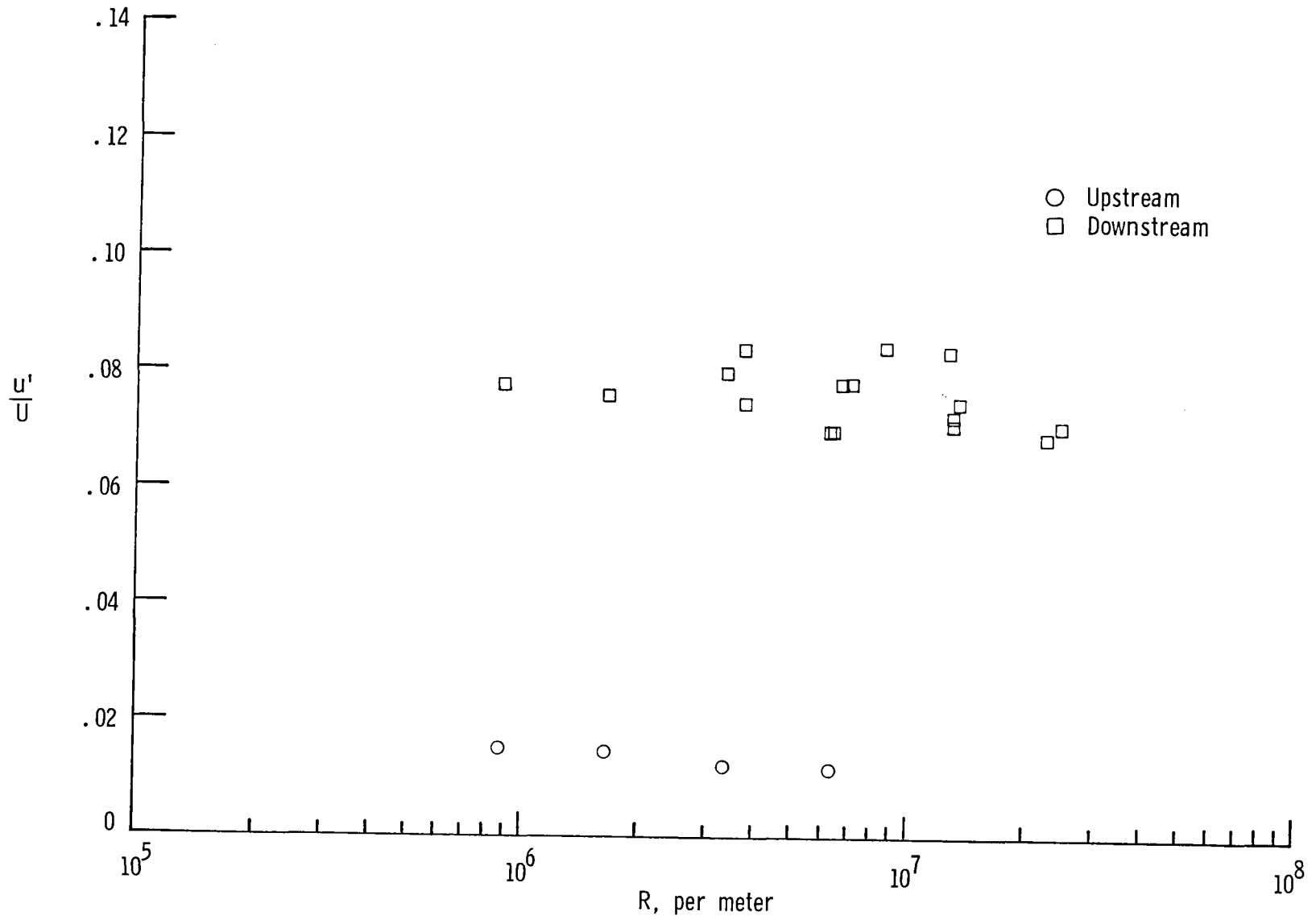for y = 11.4 cm.

(a) Elliptical 1 configuration.

Figure 10.- Longitudinal turbulence characteristics of tube-bundle heat-exchanger models.
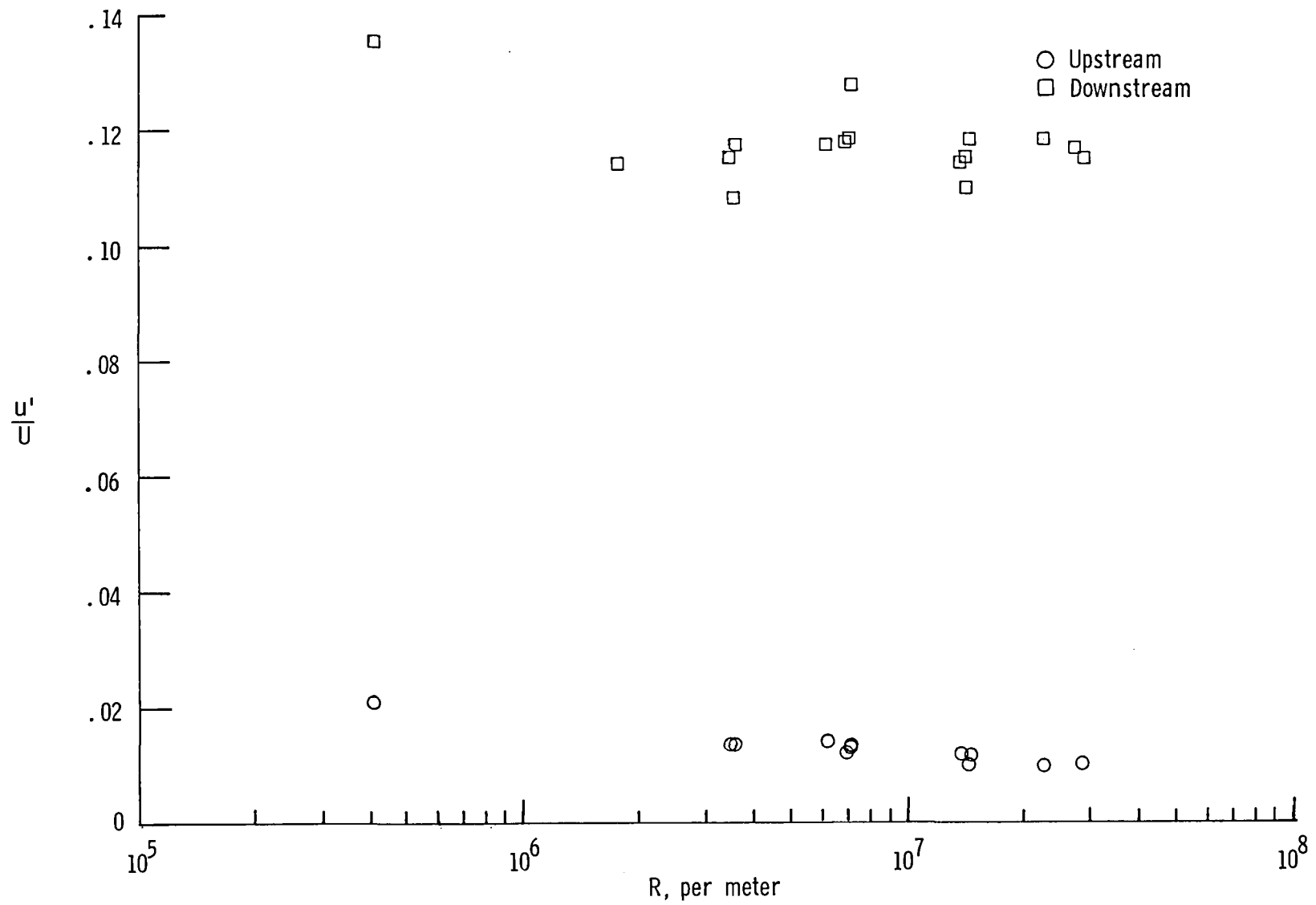
(b) Elliptical 2 configuration.

Figure 10.- Continued.

(c) Baseline configuration.

Figure 10.- Continued.

(d) Six-row configuration.

Figure 10.- Concluded.

1. Report No. NASA TM-85807	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle REYNOLDS NUMBER EFFECTS ON PRESSURE LOSS AND TURBULENCE CHARACTERISTICS OF FOUR TUBE-BUNDLE HEAT EXCHANGERS		5. Report Date June 1984
		6. Performing Organization Code 505-31-53-08
7. Author(s) William B. Igoe and Garl L. Gentry, Jr.		8. Performing Organization Report No. L-15721
		10. Work Unit No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The aerodynamic characteristics of pressure loss and turbulence on four tube-bundle configurations representing heat-exchanger geometries with nominally the same heat capacity were measured as a function of Reynolds numbers from about 4000 to 400 000 based on tube hydraulic diameter. Two configurations had elliptical tubes, the other two had round tubes, and all four had plate fins. The elliptical-tube configurations had lower pressure loss and turbulence characteristics than the round-tube configurations over the entire Reynolds number range.

17. Key Words (Suggested by Author(s)) Finned tubes Wind tunnel Heat exchangers Pressure loss Turbulence Reynolds number effects	18. Distribution Statement Unclassified – Unlimited Subject Category 02

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 26	22. Price A03

NASA-Langley, 198/