T H E   U N I V E R S I T Y   O F   M I C H I G A N

COLLEGE OF ENGINEERING
Department of Engineering Mechanics

TESTS ON MODELS OF NUCLEAR REACTOR ELEMENTS

IV. Model Study of Fuel Element Supports

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ABSTRACT

Head losses have been determined for flow through a bundle of fuel element rods supported by four different forms of supports at variable spacings. The drag coefficient for each type of support has been computed from the measurements of the pressure drop, and the influence of the boundary proximity has been determined.

A. INTRODUCTION

The experimental study of the fuel element supports was undertaken as an effort to determine the influence of the form and spacing of the supports on the head losses for flow through a bundle of rods. Experimental tests[1] have indicated that a large percentage of the head losses are caused by the presence of the supports necessary to maintain the desired spacing between rods. In fact, the head loss for flow through a rod bundle maintained at the desired spacing by means other than supports was found to be very close to that through a smooth pipe of an equivalent diameter which was computed on the basis of the hydraulic radius.

The laboratory tests were conducted using a Plexiglas model of a blanket subassembly furnished by APDA and used in previous experimental investigations. The large size of the rods, and of the spacing between them, facilitated the fabrication of the different forms of supports. The ratio, however, of the rod diameter to the support thickness was the same as that of the core section of the APDA models; thus geometrical similarity was maintained.

The four different forms of supports used were (a) cylindrical with its axis at 90° with the flow, (b) cylindrical with its axis at 45° with the flow, (c) streamlined strut, and (d) lenticular strut. Three different spacings, in the direction of the flow, were used for each form of support. The rod bundle Reynolds number, computed on the basis of the open area and equivalent diameter of the flow area, was varied from about 1,000 to 20,000, and the fluid was water.

The experimental results are presented in two ways. In the first, the head loss divided by the discharge squared is plotted against the rod bundle Reynolds number for different spacings and forms of supports used in the tests. In the second, the coefficient of drag of each form of support was computed from the pressure drop measurements and is plotted against the Reynolds number based on the thickness of the support and the mean velocity. Tests with only the supports in the container, that is, without fuel element rods, provided data for the determination of the effect of the boundary proximity on the value of the drag coefficient.

B. DESCRIPTION OF EXPERIMENTAL TESTS

A Plexiglas model of a blanket subassembly, furnished by APDA for previous tests, was used for the model study of the fuel element supports. The circulating water system of the laboratory was utilized as a source of supply. The general arrangement of the apparatus is shown in Fig. 1; the throttling valve, shown in this figure, allowed for control of discharge over a wide range.

The container of the rod bundle consisted of a square section Plexiglas case. The inside dimensions of the case were 2.469 by 2.469 in. The rod bundle consisted of 25 Plexiglas rods, of 0.385-in. diameter, arranged in a square array of five by five and spaced 0.095 in. apart. The calculation of the open area, and that of the equivalent diameter, in the rod section is given in the Appendix.

The head loss, over a length of approximately 38 in., was measured with an air-water manometer connected to two piezometer openings. The piezometers were located at the upper side of the container and at approximately equal distances from the ends of the rods. The average velocity of flow through the rod bundle was determined from discharge measurements, made with the use of a weighing tank, and the computed open area.

The profiles of the four different forms of supports are shown in Fig. 2. These profiles are sections through each support in a direction parallel to the flow direction; the thickness of the support was 0.095 in. and it was the same for all support forms; the length of the cylindrical supports at 45° was 3.3 in. and that of all other forms, approximately 2.33 in. Plates I and II are photographs of the arrangement of the supports, with the rods partly withdrawn. Two rows of rods were supported at each section where supports were located. Horizontal and vertical supports, alternately arranged, maintained the even spacing between rods and prevented their contact. Four support sections, each supporting two rows, constituted a complete cycle which was repeated throughout the length of the rods. For example, if the spacing between two support sections was 4.8 in., each rod was supported at intervals of 19.2 in. in the horizontal direction and the same distance in the vertical direction.

Geometrical similarity between the Plexiglas model and the core section of the APDA reactor element models was maintained by having the same ratio of rod diameter to support thickness; in the case of the Plexiglas model, this ratio was 4.05, and in the case of the core section, 3.93.

Each form of supports was tested for head losses at three different spacings of the support sections; this spacing refers to the distance between consecutive supports regardless of their orientation, horizontal or vertical. The first spacing, 4.8 in., divided by the thickness of the support, 0.095 in. gave the same ratio, 50, as the corresponding ratio for the core section. The other two spacings, 7.2 in., and 9.6 in., were selected as 50% and 100% increases of the original spacing, respectively.

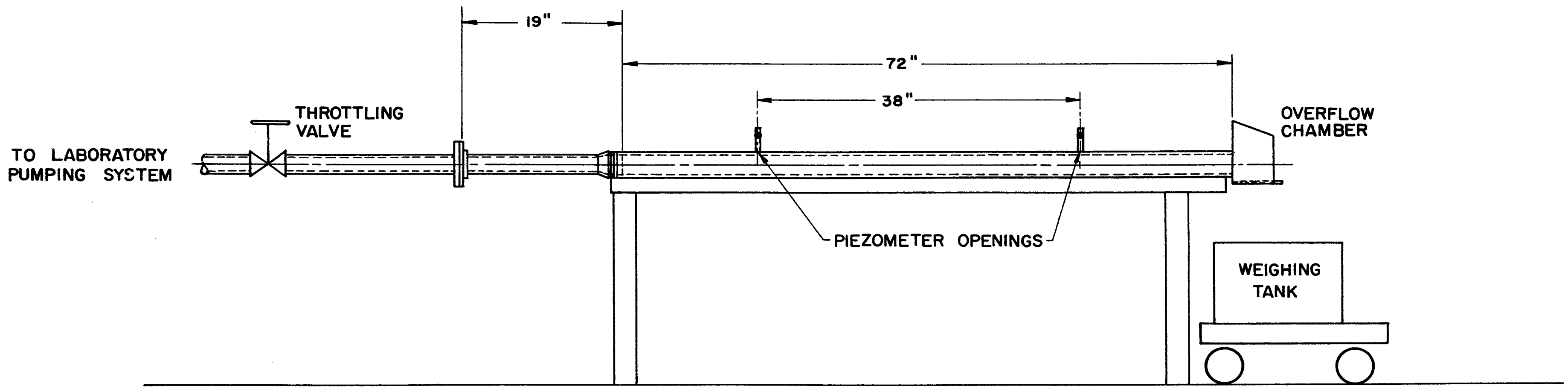


Fig. 1. General arrangement of apparatus.

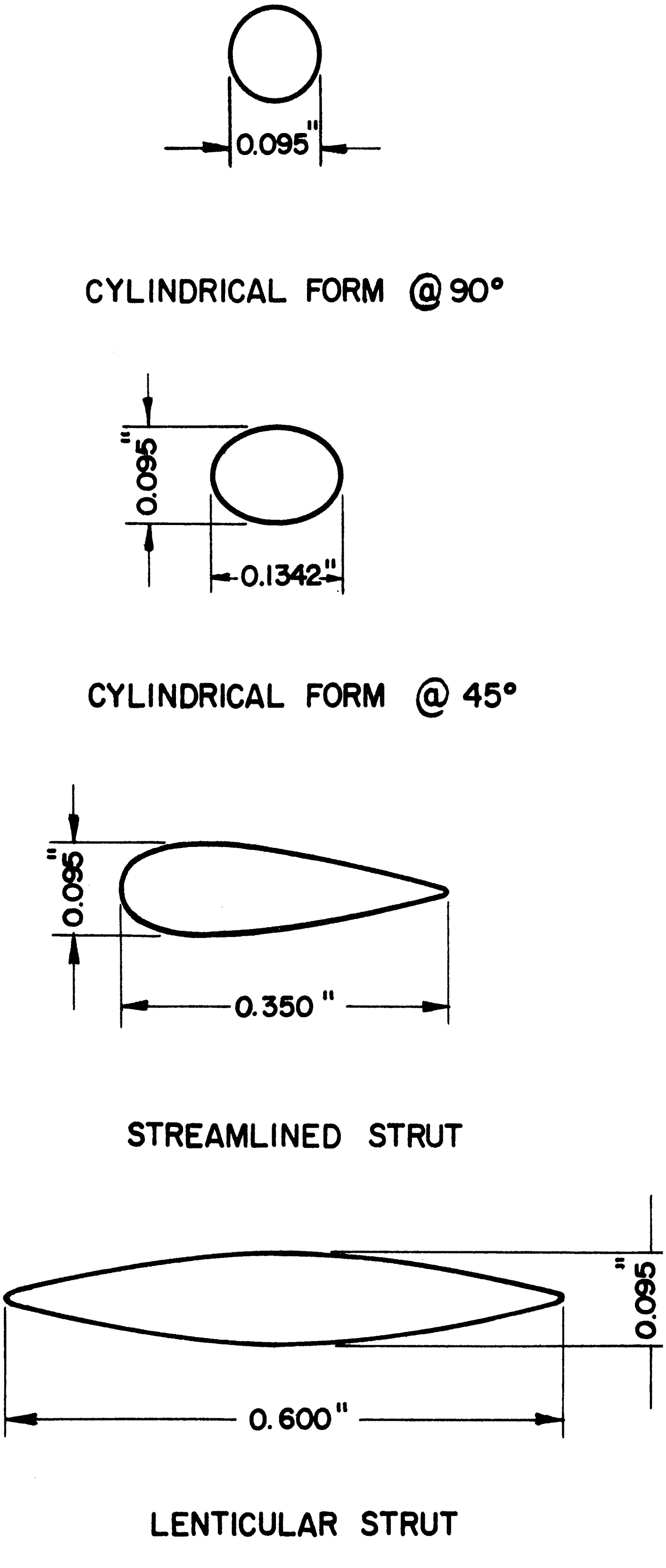
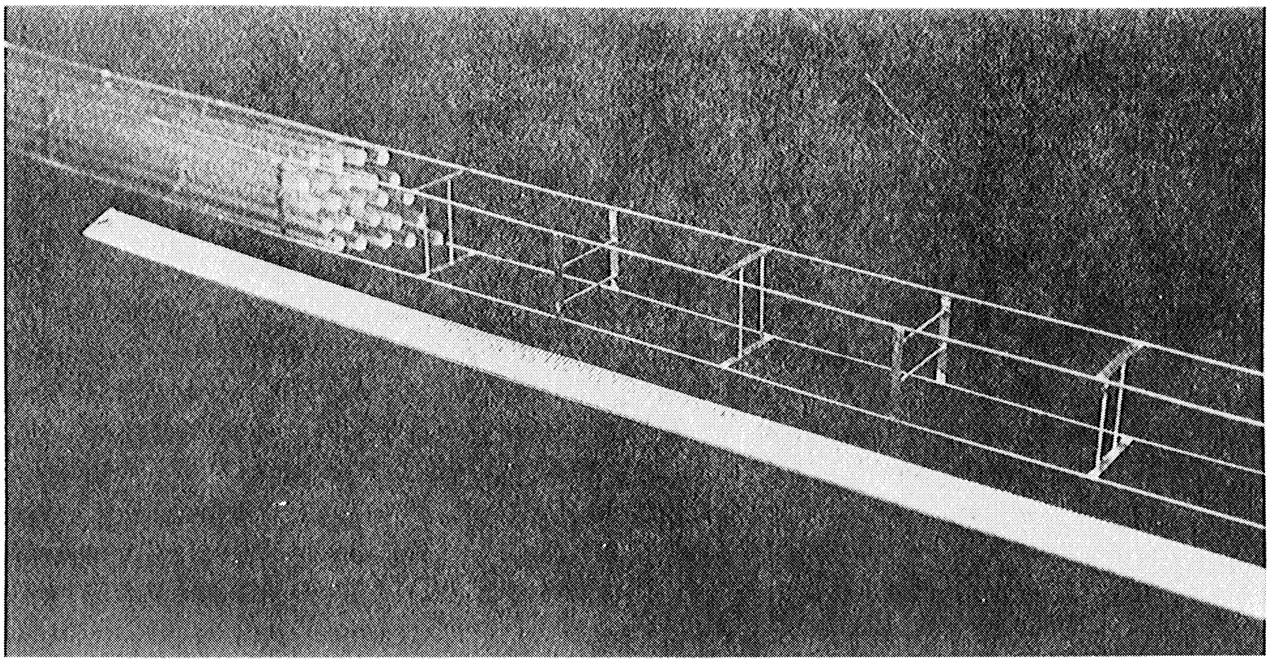
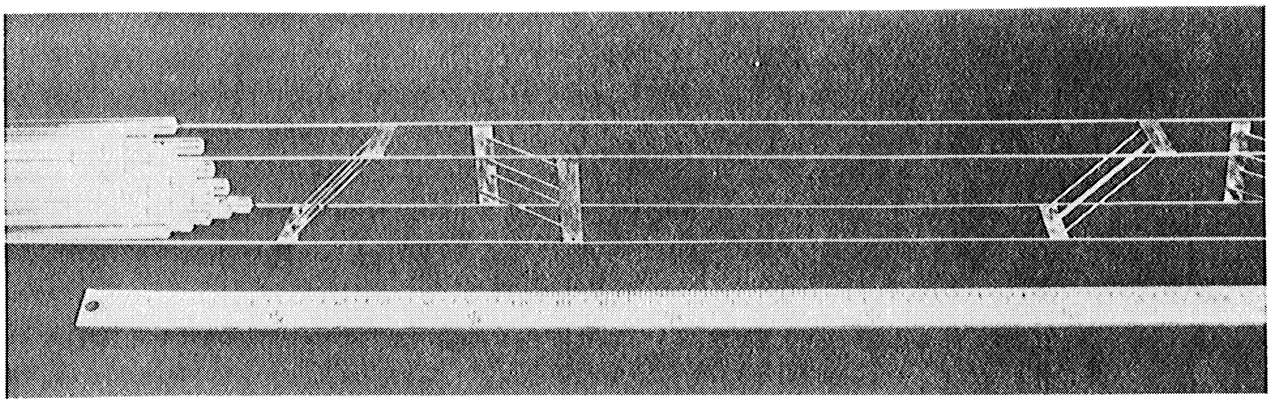


Fig. 2. Profiles of supports parallel to the direction of flow.



(a)

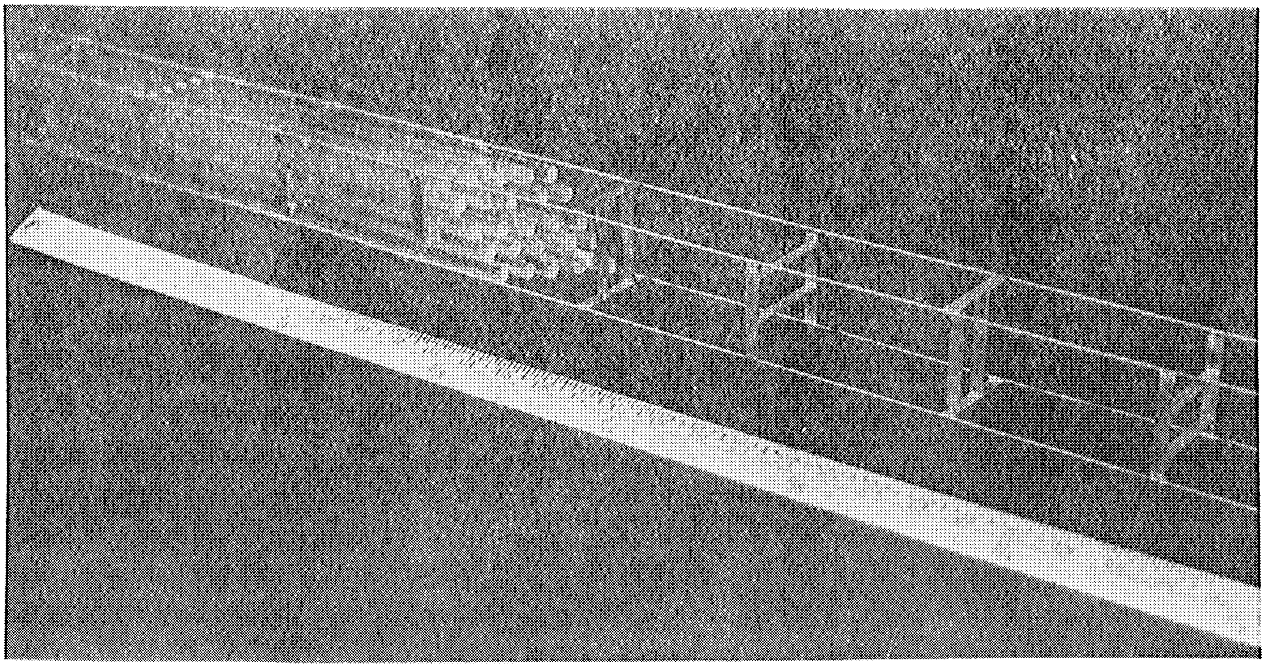
Cylindrical supports at 90°, 4.8-in. spacing.



(b)

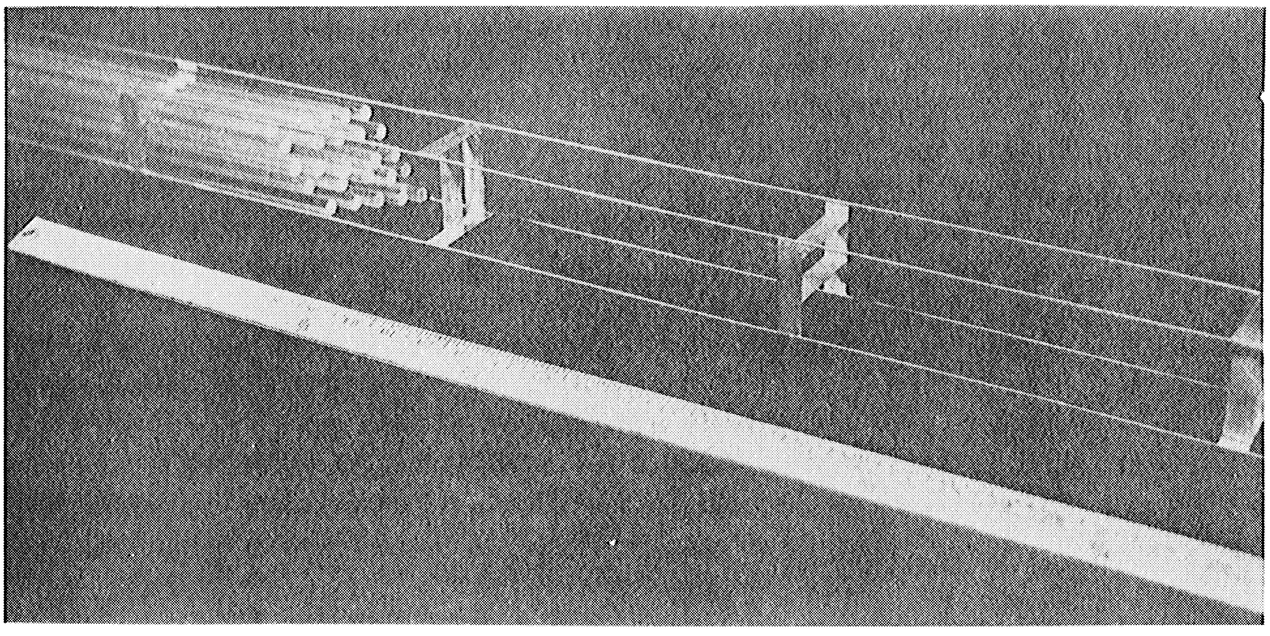
Cylindrical supports at 45°, 4.8-in. spacing, adjacent supports moved together.

Plate I



(a)

Streamlined strut supports, 4.8-in. spacing.



(b)

Lenticular strut supports, 9.6-in. spacing.

Plate II

C. ANALYSIS OF EXPERIMENTAL RESULTS

The head loss for flow through a bundle of rods, with or without supports, is presented in the form of $\Delta h/Q^2$, in which Δh is the drop in piezometric head and Q the discharge. This ratio is used in place of the usual friction factor f because all geometric quantities such as length and equivalent diameter and spacing of the rods are constant throughout a given test. The Darcy-Weisbach equation can be rearranged to yield

$$\frac{\Delta h}{Q^2} = f\left(\frac{L}{2gA^2d_e}\right) = f\left(\frac{8L}{g\pi^2 d_e^5}\right) ,$$

in which the terms within the parentheses are constant with A denoting the open area and d_e the equivalent diameter. Δh, however, includes the local losses due to the presence of supports so that the conventional meaning of f would be altered in this instance. The length L, the distance between the two piezometer openings, was approximate multiples of the spacing of consecutive support sections. Therefore, division of $\Delta h/Q^2$ by L represents the head loss for a representative foot of length of a supported rod bundle, and it is this quantity that was used in the subsequent plots.

The rod bundle Reynolds number (see Appendix) is based on the mean velocity of flow and the equivalent diameter of the flow area (not including the supports). The range of this number is approximately from 1,000 to 20,000.

In Figs. 3-6, the experimental results are presented using the above described two parameters. As it was expected, the head loss per foot of length was found to be less as the spacing of the support sections was increased. The head loss for flow in a rod bundle without supports (the supports located between the two piezometer openings were removed) but with the same square array was found to be very near that for a smooth pipe of a diameter equal to the equivalent diameter of the rod bundle; the loss in the former case was approximately 7% higher. It is obvious, then, that the additional head loss in a rod bundle is due to the presence of the supports.

In Fig. 7 the results of a series of tests with cylindrical supports at 45°, in which adjacent supports (i.e., two consecutive horizontal, or vertical, support sections) were spaced progressively closer together, are presented. In these tests the number of support sections per foot of length was kept the same as in the case of the 4.8-in. spacing. The relatively small variation of the data, within the experimental error, indicates that, for cylindrical supports at 45°, all four rows of rods can be supported in the same support section without appreciable increase in the head loss. Plate I shows the adjacent supports 0.25 in. apart.

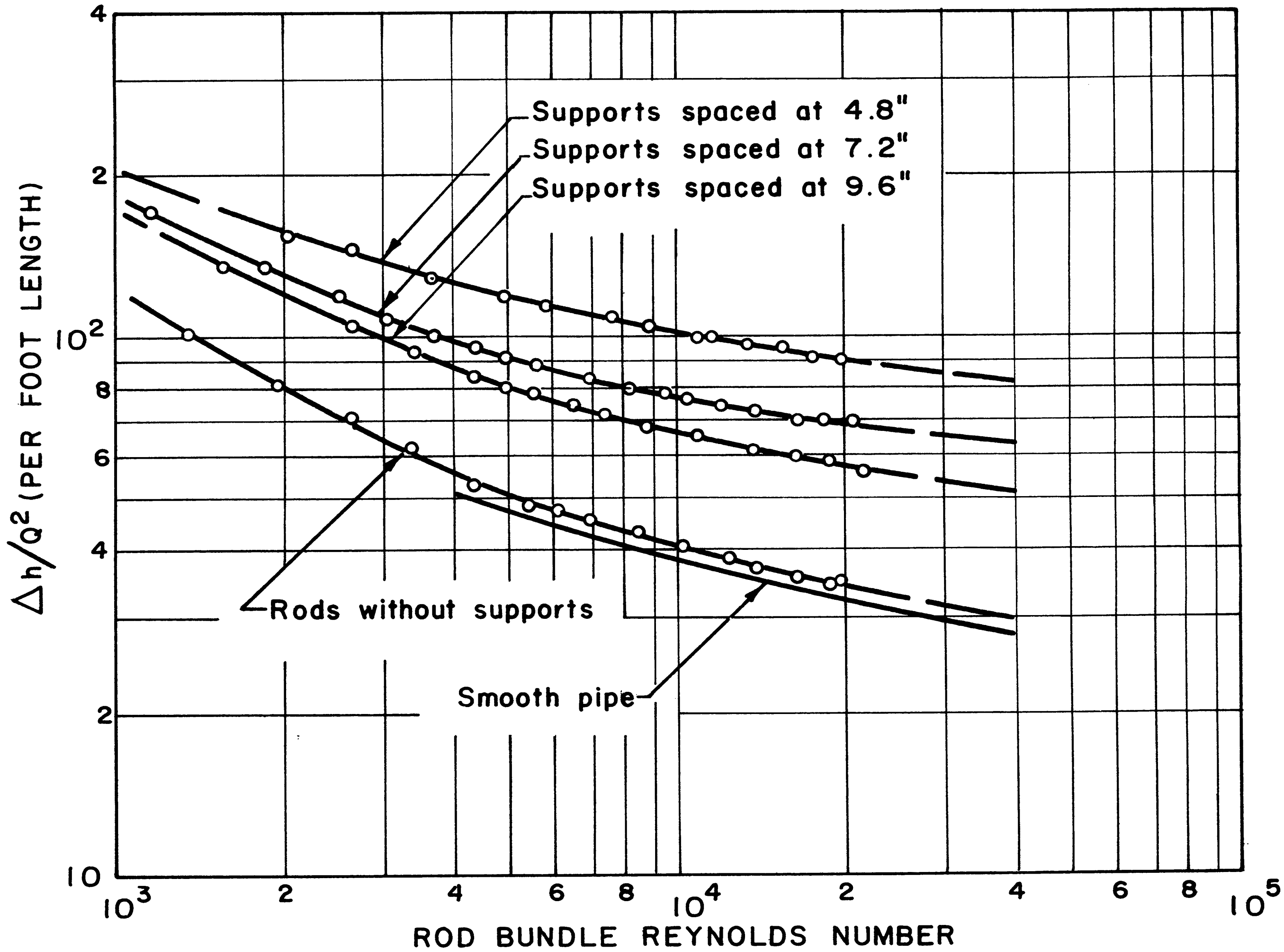


Fig. 3. Head loss in rod bundle with cylindrical supports at 90°.

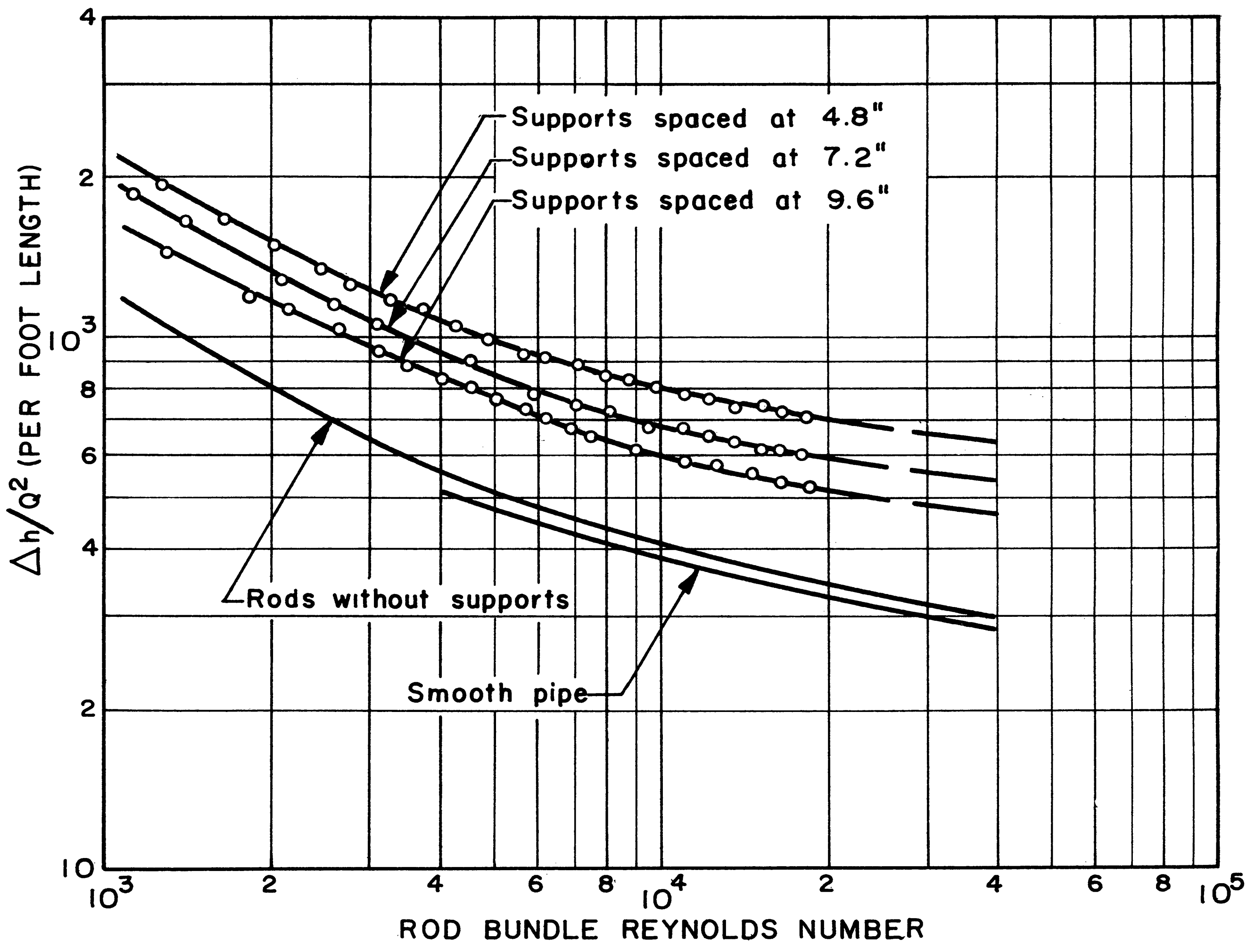


Fig. 4. Head loss in rod bundle with cylindrical supports at 45°.

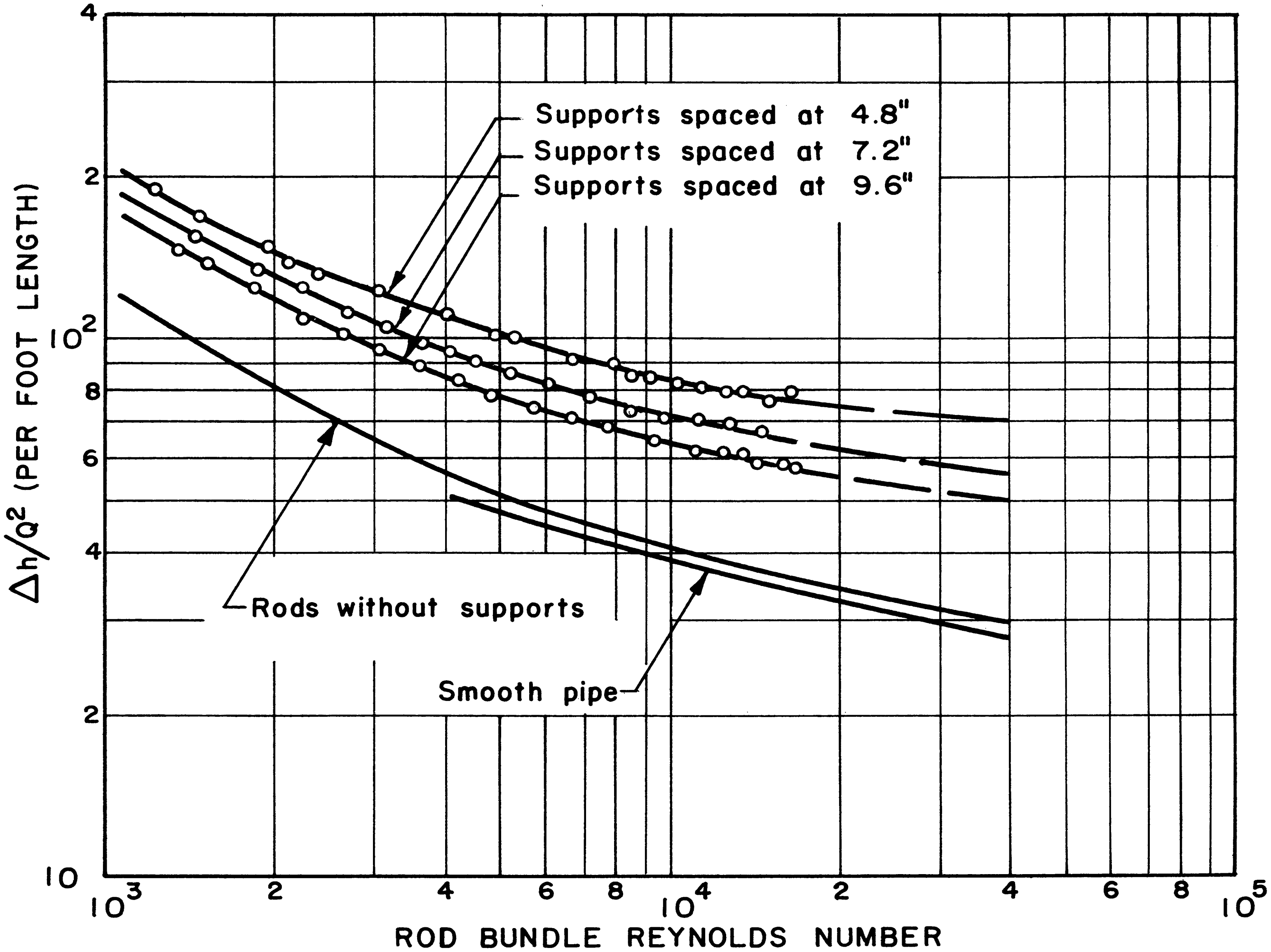


Fig. 5. Head loss in rod bundle with streamlined strut supports.

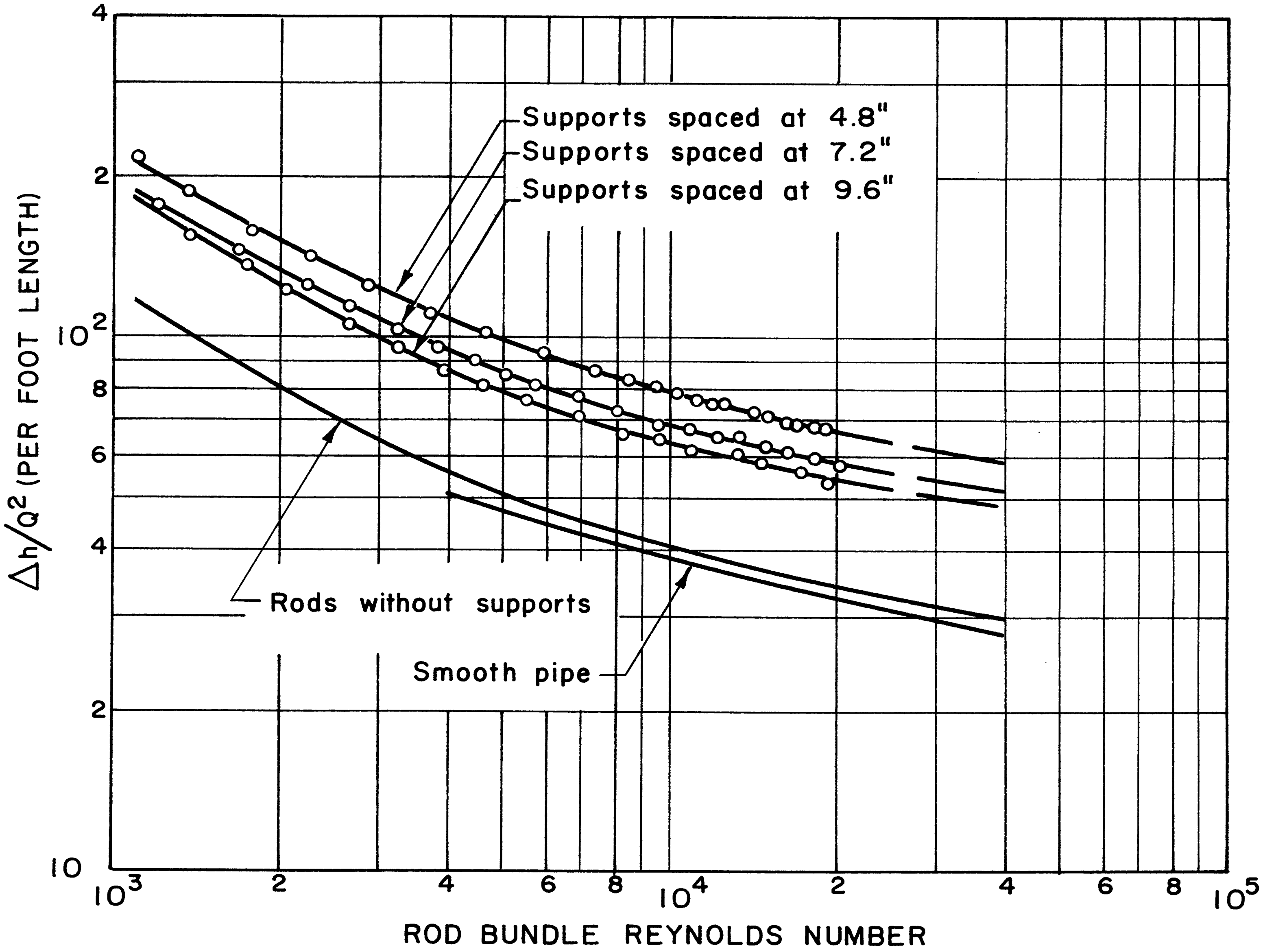


Fig. 6. Head loss in rod bundle with lenticular strut supports.

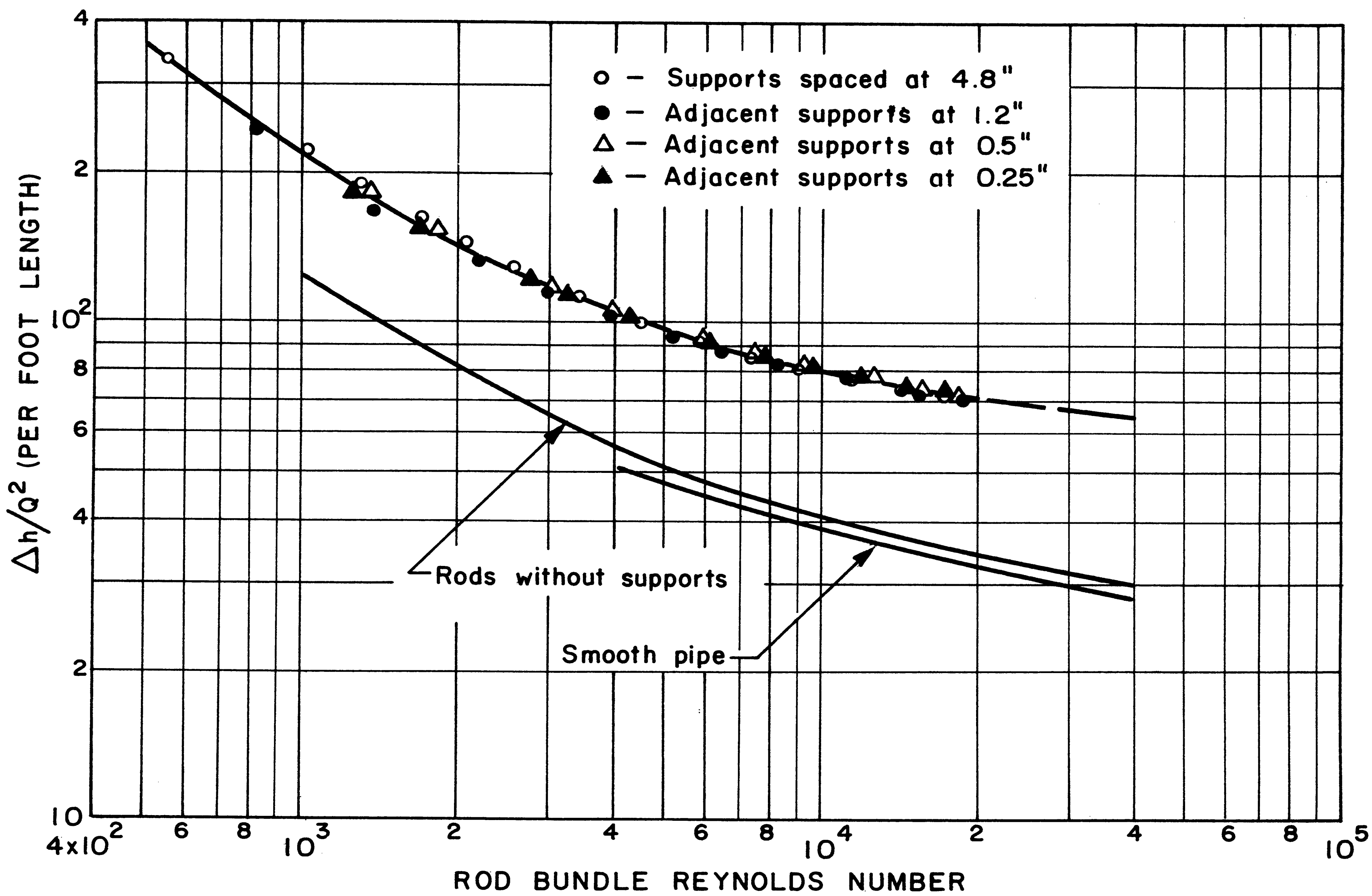


Fig. 7. Head loss in rod bundle with cylindrical supports at 45°, adjacent supports moved together.

In Figs. 8-10, the mean curves plotted through the experimental points in the previous figures were plotted again to compare the head losses for different support forms at the same spacing. From this comparison it is clearly seen that, for Reynolds numbers above 3000, and support spacings of 4.8 and 7.2 in., the lenticular strut is the best as far as losses are concerned. Below this Reynolds number the large surface area of the lenticular strut causes a large portion of the head losses to result from skin friction and thus the losses for this form are larger than those for the other forms. At the spacing of 9.6 in. the difference in head losses between the four forms is smaller, with the skin friction playing an important roll in making the lenticular strut less efficient than the cylindrical at 45° for the whole range of Reynolds numbers.

From the standpoint of construction, the arrangement using cylindrical supports at 45° was the easiest to manufacture, when compared with the streamlined and lenticular struts; the head losses associated with cylindrical supports are also considerably less than those for the streamlined struts. Thus it appears that from practical considerations the arrangement using cylindrical supports at 45° is a better alternative to the cylindrical at 90°.

The relatively low head loss associated with the cylindrical supports at 45° can be attributed not only to the elliptical profile, in a section parallel to the flow direction, but also to the effect that an inclined support has on the flow as a whole; at any section perpendicular to the flow direction the constriction of the flow area due to the presence of the supports is considerably less than that for supports at 90° with the flow direction.

The head loss for flow through the rod bundle can also be presented as the sum of the head loss due to the rods only and that due to the presence of the supports. Such a division of the head loss makes possible the determination of a drag coefficient for each support form and the use of this coefficient to predict the pressure drop in a reactor element provided there exists geometrical similarity. This similarity is expressed as the ratio of the rod diameter to the support thickness and takes into consideration the effect of the boundary proximity on the drag coefficient.

Using the subscripts r and s to refer to the rod bundle and the supports, respectively, the total pressure drop in the rod bundle can be expressed as

$$\Delta p_t = \Delta p_r + \Delta p_s \quad , \tag{1}$$

or, the pressure drop due to the presence of the supports only, is

$$\Delta p_s = \Delta p_t - \Delta p_r \quad . \tag{2}$$

The drag force on the supports can be expressed[2] by

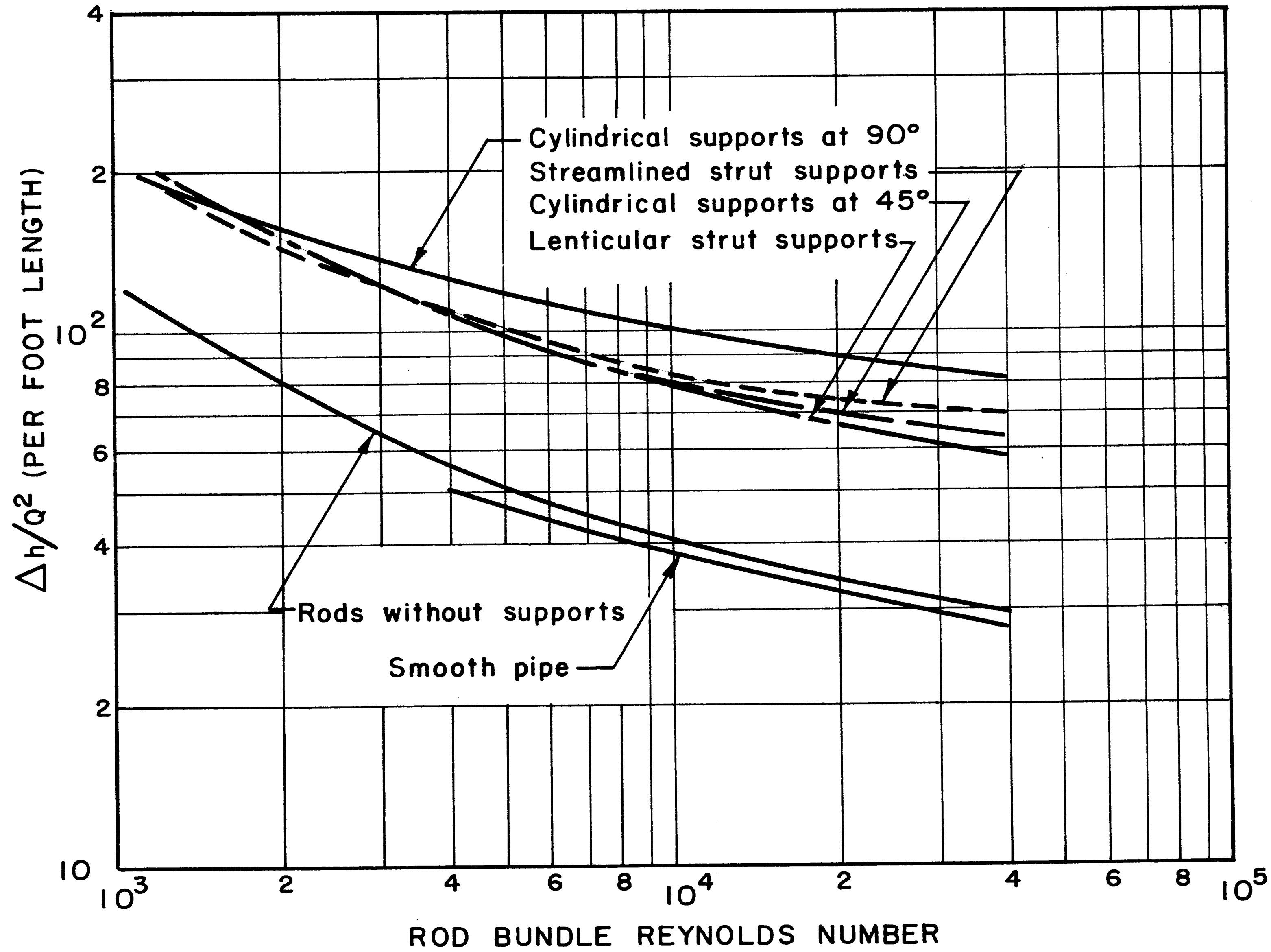


Fig. 8. Head loss in rod bundle with supports spaced at 4.8 in.

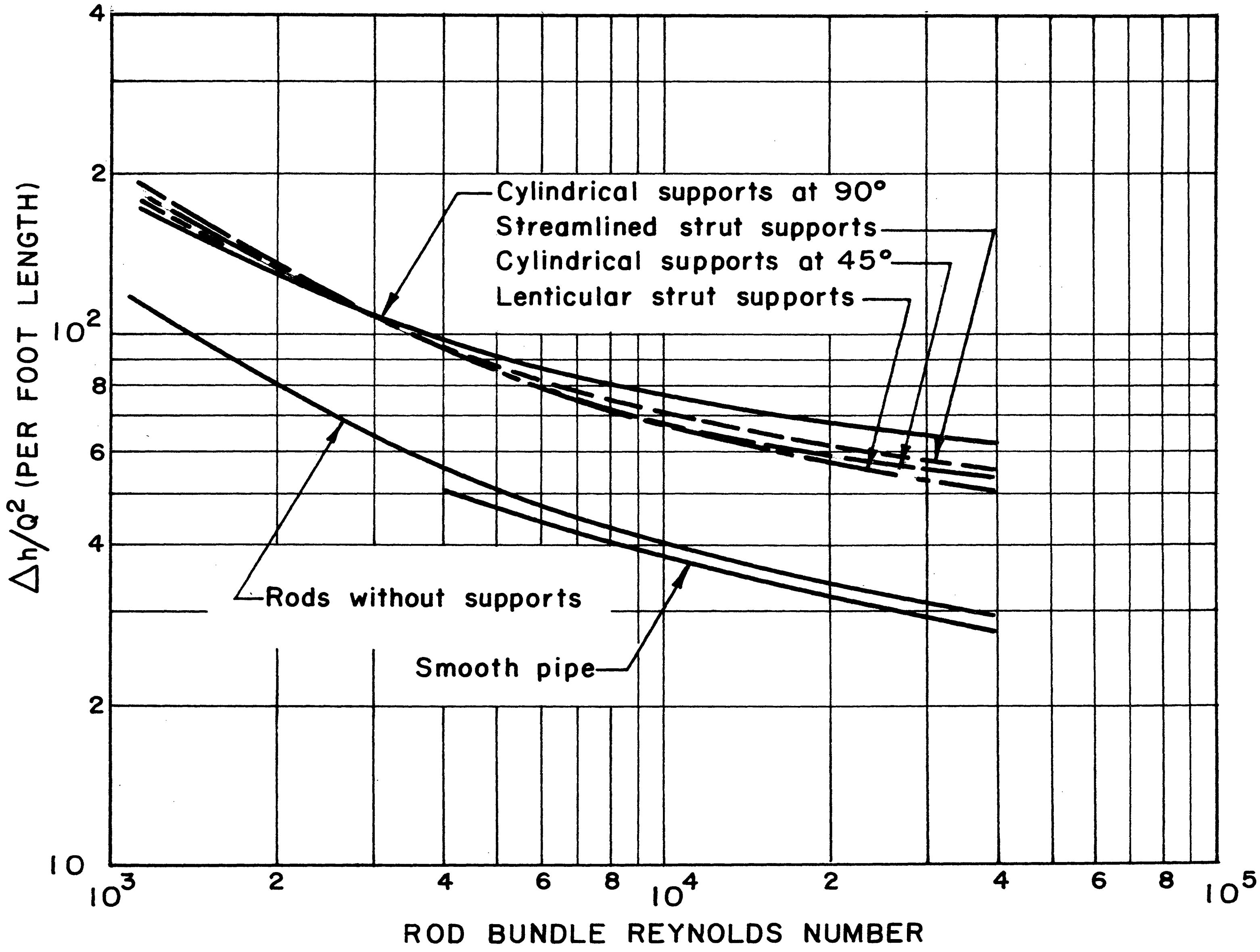


Fig. 9. Head loss in rod bundle with supports spaced at 7.2 in.

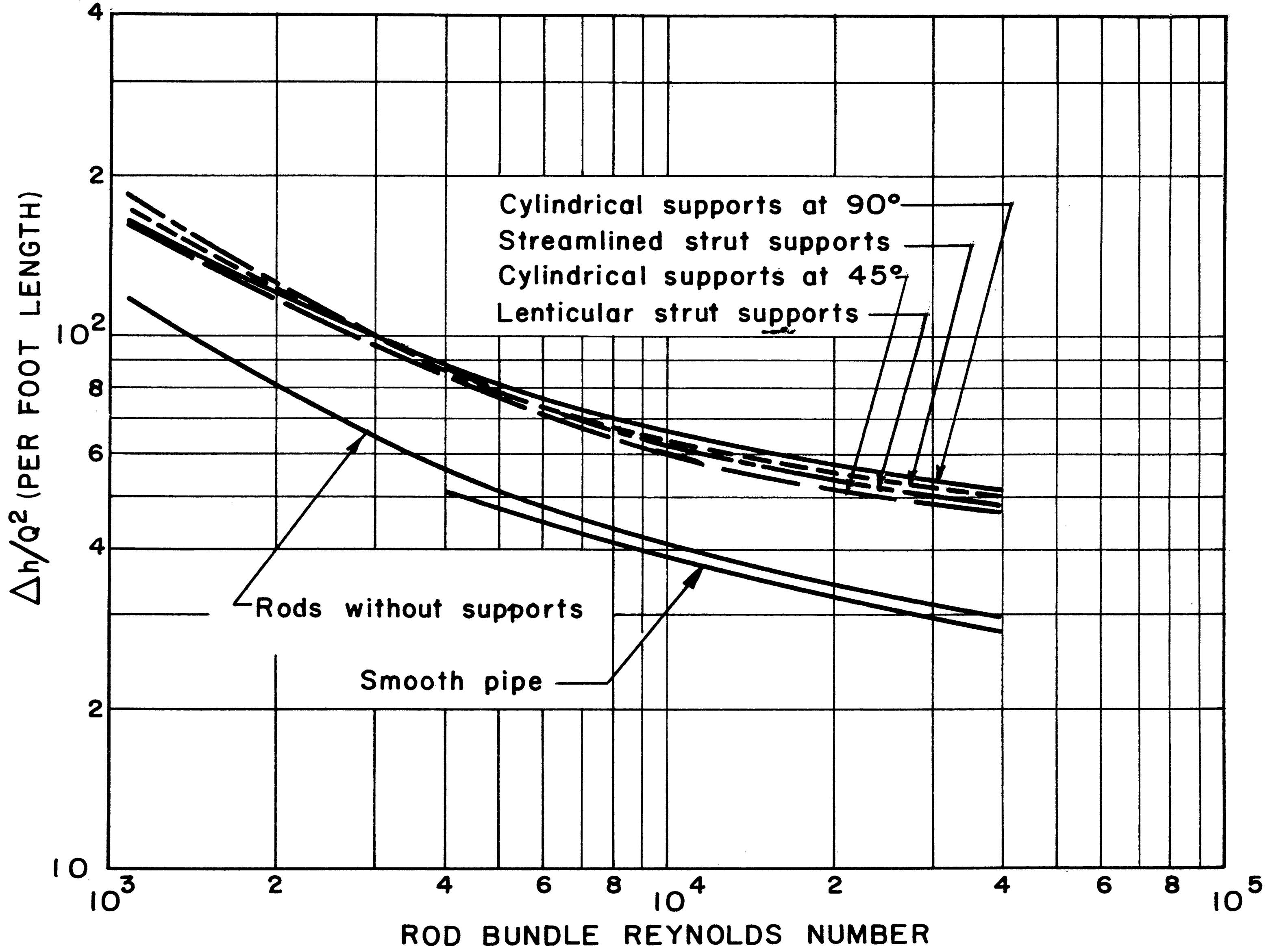


Fig. 10. Head loss in rod bundle with supports spaced at 9.6 in.

$$F_s = nC_s\gamma \frac{V^2}{2g} S \quad , \tag{3}$$

in which n is the number of individual supports per foot length, C_s the drag coefficient of the support, γ the specific weight of the fluid, V the mean velocity of the flow (Q/A, where A is the open area), g the gravitational acceleration, and S is the projected area of one support This force can also be expressed as

$$F_s = (\Delta p_s)A \quad , \tag{4}$$

where A again is the open area. Eliminating F_s between Eqs. (3) and (4) and solving for C_s, one obtains

$$C_s = \frac{2g(\Delta p_s)A}{n\gamma\ V^2 S} \quad . \tag{5}$$

From Eq. (2), and using $\Delta h/Q^2$ to express the head loss per foot length,

$$\Delta p_s = \gamma\ \Delta h_s = \gamma\left(\frac{\Delta h_t}{Q^2} - \frac{\Delta h_r}{Q^2}\right) Q^2 \quad . \tag{6}$$

Substitution of Eq. (6) in Eq. (5) yields

$$C_s = \frac{2g\ A}{nV^2 S}\left(\frac{\Delta h_t}{Q^2} - \frac{\Delta h_r}{Q^2}\right) Q^2 \quad , \tag{7}$$

or, if $Q = VA$ is substituted in Eq. (7),

$$C_s = \frac{2gA^3}{nS}\left(\frac{\Delta h_t}{Q^2} - \frac{\Delta h_r}{Q^2}\right) \quad , \tag{8}$$

in which $\Delta h_t/Q^2$ is the total head loss in the rod bundle, and $\Delta h_r/Q^2$ is the head loss without supports; both of these quantities can be obtained from Figs. 3-6 for a given Reynolds number and form of support. A sample computation for determining C_s is given in the Appendix.

It should be mentioned that the drag coefficient as defined by Eq. (8) includes the drag due to the two supporting plates that hold the supports at each section. These plates were 2.15 in. long and 0.040 in. thick; their width, in the direction of flow, varied from 0.25 to 0.60 in.

The drag coefficients for the four different support forms were computed using Eq. (8) and the results are shown in Figs. 11-14, in which C_s was plotted as a function of the support Reynolds number. This number was computed using

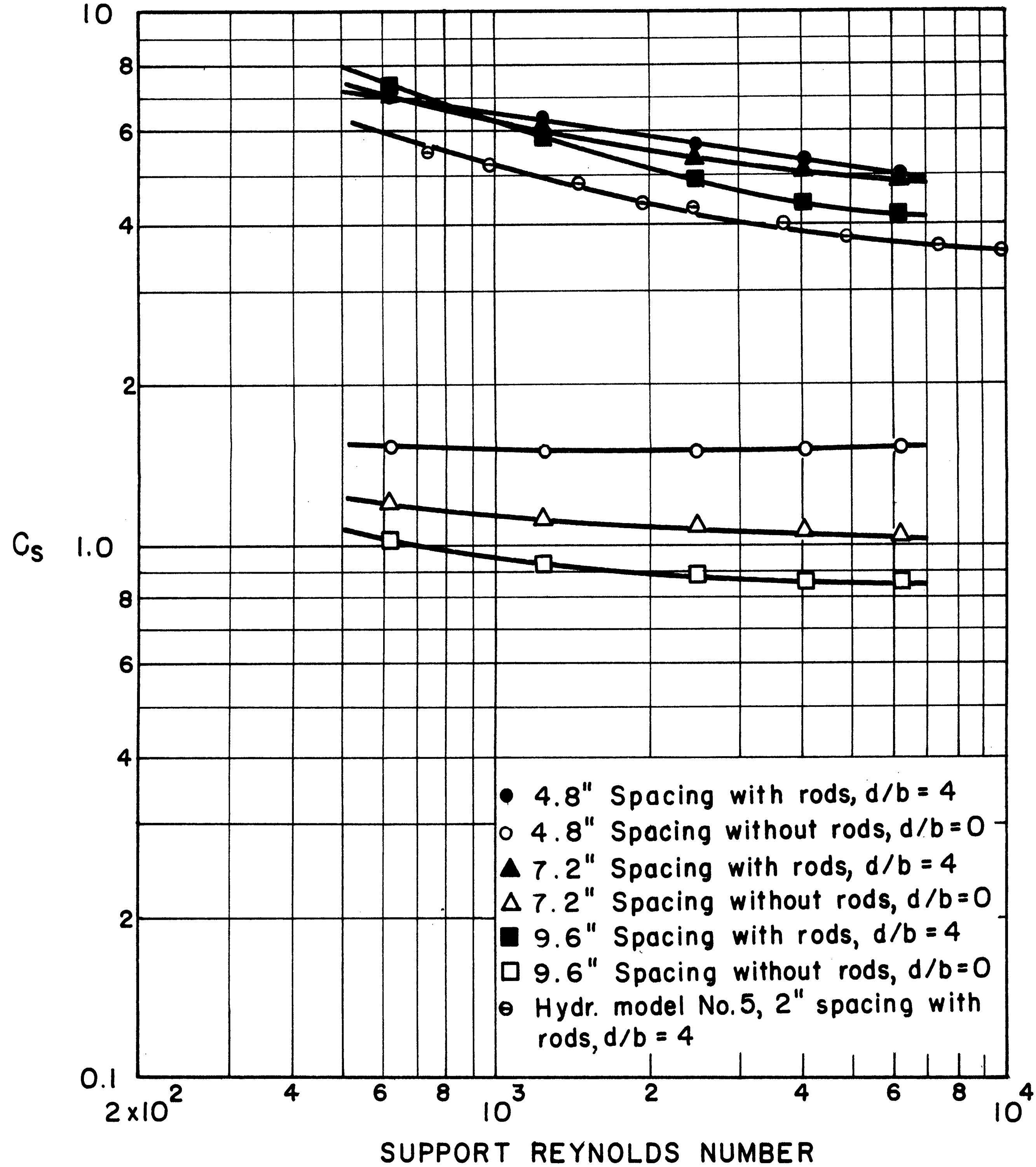


Fig. 11. Drag coefficient for cylindrical supports at 90°.

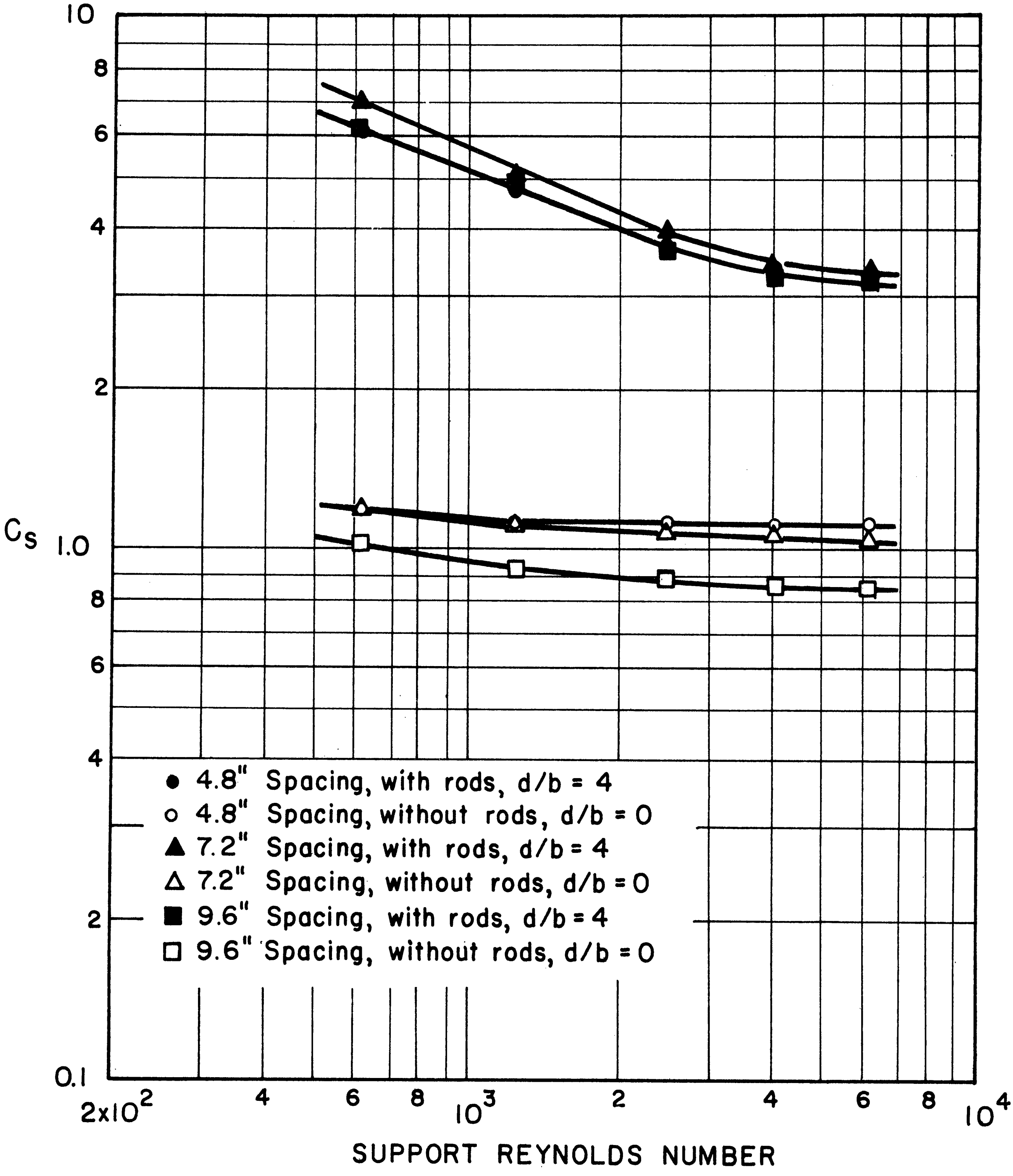


Fig. 12. Drag coefficient for cylindrical supports at 45°.

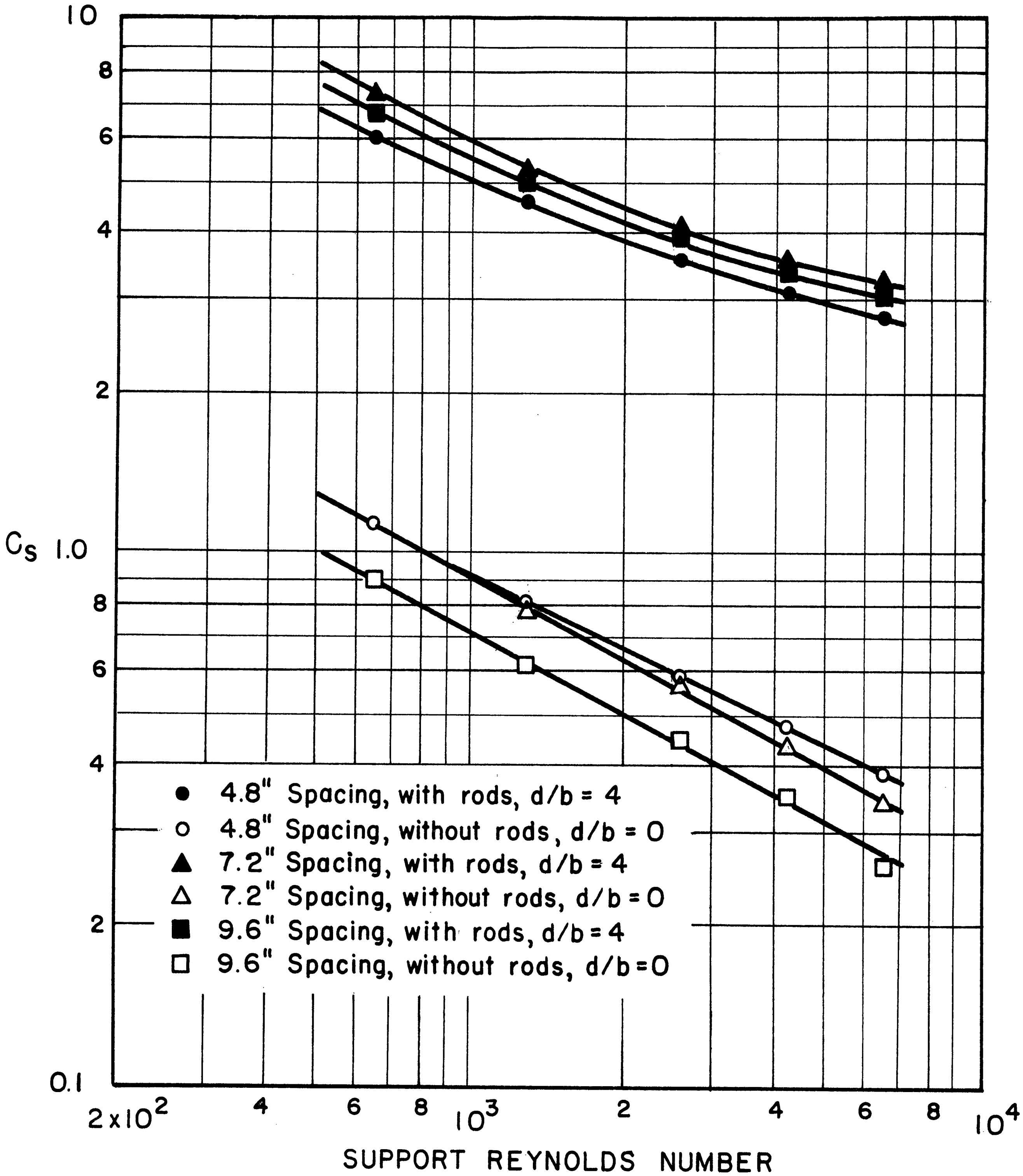


Fig. 13. Drag coefficient for streamlined strut supports.

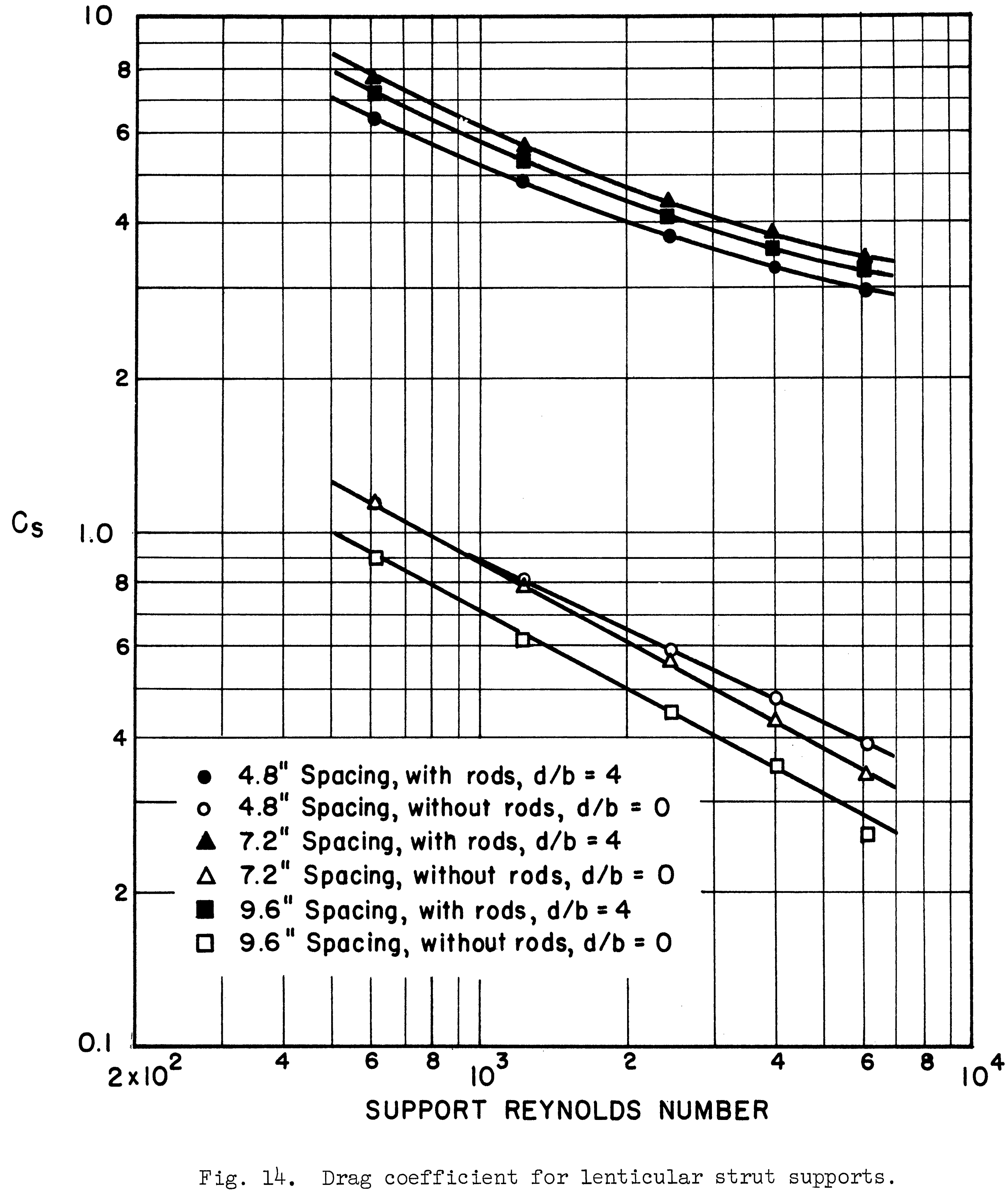


Fig. 14. Drag coefficient for lenticular strut supports.

the mean velocity V and the thickness of the support.

The drag coefficients for cylindrical supports at 90° with the direction of flow, and with rods, are shown in Fig. 11; the ratio of the rod diameter to the support thickness, d/b, for these data, as well as for that with rods in Figs. 12-14, was 4. The variation in the values of C_s for the three different spacings of the supports does not exhibit a consistent trend for the four different support forms, and it can be possibly attributed to the relative variation in the clearances between the rods and the supports. In the case of a tightly supported and spaced rod bundle, the head loss due to the presence of the supports would tend to be higher.

Data available from previous tests,[1] in which the APDA core section Hydraulic Model No. 5 was used, made it possible to compute the drag coefficient for similar supports, i.e., cylindrical in form and at 90° with the flow. For this model the d/b ratio was also approximately 4 (d = 0.157 in., b = 0.040 in.), the spacing of the support sections was 2 in., and there were alternately four or five supports at each section. The values of C_s are somewhat lower than those for the rod bundle, although geometrical similarity existed. The difference in this case too can be attributed to the variations in the clearances between the supports and the rods.

To determine the effect of the boundary proximity, additional tests were conducted with the rods removed from the Plexiglas model (d/b = 0); the head loss for the flow through the square case ($\Delta h_c/Q^2$) was assumed to be that of a smooth pipe of an equivalent diameter. The drag coefficient, under this condition, were found to be considerably less. In Fig. 11 the values of C_s, as expected, are close to those for cylinders in an infinite fluid.[2] The variation of C_s with spacing of the support sections for this form, as well as for the other forms in Figs. 12-14, indicates a definite trend; with larger spacings, the value of C_s decreases. This can be attributed to the effect that the supports have on the establishment of flow in the square case of the Plexiglas model. Tests with the square case only indicated that the length of the case is not sufficient for the full establishment of flow. When the supports are inside the case their presence augments the establishment of flow through the formation and shedding of additional eddies. Consequently, with larger number of supports flow conditions approach those of fully established flow, and the losses are higher and closer to those of a smooth pipe of an equivalent diameter.

It should be emphasized that the use of the drag coefficient concept in predicting the head losses in a reactor element is subject not only to the existence of dynamic similarity but geometrical similarity as well. Both of these conditions have to be satisfied in using the empirically determined drag coefficients for the different forms presented in this report.

ACKNOWLEDGMENTS

The experimental investigation presented in this report was carried out under the supervision of Professor Russel A. Dodge. Mr. Alvin J. Engerer, research assistant, helped with the collection of data, construction of the supports, and the computations in the analysis of the results. Mr. Milo Kaufman, technician, assisted in the construction of the supports and with many helpful suggestions in setting up the apparatus. The writer would like to thank these gentlemen for their help in carrying out this investigation.

APPENDIX

(1) Calculation of open area in rod section of the bundle:

Frontal area	2.469 in. square or 6.1 sq in.
Solid area	25 rods of 0.385-in. diameter or 2.92 sq in.
	4 longitudinal wires of 0.095-in. diameter (holding the supports together) or 0.028 sq in.
Open area	6.1 sq in. less 2.948 sq in. or 3.152 sq in., or 0.0219 sq ft

(2) Calculation of equivalent diameter of rod section of the bundle:

Cross-sectional area	3.152 sq in.
Wetted perimeter	4 sides of 2.469 or 9.89 in.
	25 rods of $\pi(0.385)$ in. circumference or 30.25 in.
	4 longitudinal wires of $\pi(0.095)$ in. circumference or 1.19 in.
Hydraulic radius	cross-sectional area of 3.152 sq in. divided by wetted perimeter of 41.33 in., or 0.0763 in.
Equivalent diameter	4 times the hydraulic radius or 0.305 in., or 0.0255 ft

(3) Calculation of rod bundle Reynolds number:

$$\text{Reynolds number} = \frac{Vd_e}{\nu} = \frac{Qd_e}{A\nu}$$

in which d_e is the equivalent diameter, Q the discharge, and A the open area.

(4) Calculation of typical point (C_s) of Fig. 11 with supports spaced at 4.8 in.:

(a) With Plexiglas rods:

n = number of supports per foot = $(12/4.8) \times 2 = 5$

S = projected area of one support

= (length of support) x (thickness of support)

$$= \frac{2.33 \times 0.095}{144} = 0.00154 \text{ sq ft}$$

Select rod bundle Reynolds number: 8000

$$8000 = \frac{Qd_e}{A\nu}\ ; \quad \text{or} \quad Q = \frac{8000\ A\nu}{d_e}$$

A = 0.0219 sq ft; d_e = 0.0255 ft; $\nu = 1.0 \times 10^{-5}$ sq ft per sec

Therefore

$$Q = \frac{8000 \times 0.0219 \times 1.0 \times 10^{-5}}{0.0255} = 0.0687 \text{ cu ft per sec}$$

Mean velocity:

$$V = \frac{Q}{A} = \frac{0.0687}{0.0219} = 3.14 \text{ ft per sec}$$

From Fig. 3:

$\frac{\Delta h_t}{Q^2} = 107$, and $\frac{\Delta h_r}{Q^2} = 43$ for rod bundle Reynolds number of 8000; therefore

$$\frac{\Delta h_t}{Q^2} - \frac{\Delta h_r}{Q^2} = 107 - 43 = 64$$

Using Eq. (8):

$$C_s = \frac{2gA^3}{nS}\left(\frac{\Delta h_t}{Q^2} - \frac{\Delta h_r}{Q^2}\right) = \frac{2 \times 32.2 \times (0.0219)^3}{5 \times 0.00154} \times 64 = 5.6$$

Support Reynolds number =

$$\frac{Qb}{A\nu} = \frac{0.0687 \times (0.095/12)}{0.0219 \times 1.0 \times 10^{-5}} = 2480$$

in which b is the support thickness.

(b) Without Plexiglas rods:

n = 5

S = 0.00154 sq ft

A' = open area = 0.0422 sq ft

d_e' = equivalent diameter = 0.183 ft

Support Reynolds number =

$$\frac{Qb}{A\nu} = \frac{Q(0.095/12)}{0.0422 \times 1.0 \times 10^{-5}} = 18{,}700\ Q$$

Select support Reynolds number: 2480; therefore

$$Q = \frac{2{,}480}{18{,}700} = 0.1328 \text{ cu ft per sec}$$

Reynolds number of flow =

$$\frac{Q\ d_e'}{A'\nu} = \frac{Q \times 0.183}{0.0422 \times 1.0 \times 10^{-5}} = 4.34 \times 10^5 \times Q$$

$$= 4.34 \times 10^5 \times 0.1328 = 57{,}600$$

For Reynolds number of 57,600, and for a smooth pipe of an equivalent diameter of 0.183 ft, $\Delta h_c/Q^2$ for the square case is 0.96; therefore

$$\frac{\Delta h_t}{Q^2} - \frac{\Delta h_c}{Q^2} = 3.33 - 0.96 = 2.37$$

Using Eq. (8):

$$C_s = \frac{2gA^3}{nS}\left(\frac{\Delta h_t}{Q^2} - \frac{\Delta h_c}{Q^2}\right) = \frac{2 \times 32.2\ (0.0422)^3}{5 \times 0.00154} \times 2.37 = 1.49$$

REFERENCES

1. McNown, J. S., Yagle, R. A., and Spengos, A., Tests on Models of Nuclear Reactor Elements. III. Head Losses in Core Sub-Assemblies, Univ. of Mich. Eng. Res. Inst. Report 2431-3-P, Ann Arbor, July, 1957.

2. Streeter, V. L., Fluid Mechanics, McGraw-Hill Book Co., New York, 1958.