A THREE-DIMENSIONAL SINGLE ROUGHNESS ELEMENT IN A TURBULENT BOUNDARY LAYER

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SUMMARY

An investigation of the influence of a single roughness element (sphere) in a turbulent boundary layer of a smooth flat plate is reported. The pressure distribution around the surface of the sphere was measured. Integration of the pressure distribution was used to compute the drag and lift forces on the element. Measurements of the mean and turbulent velocity distributions in the boundary-layer behind the sphere were made.

INTRODUCTION

The flow around three-dimensional objects in a surface boundary layer is of basic interest, both in view of local effects, and secondly, from a standpoint of the gross effects of roughness. The need to be able to predict the flow distribution around buildings is important both in the construction of buildings and in the operation of equipment near buildings. Secondly, viewing the earth's surface on a large scale each object represents a roughness element on the surface. These roughness elements greatly affect the turbulence and velocity distribution in the lower layer of the atmosphere. Thus, prediction of the roughness effects on diffusion in the atmosphere is of great value.

Experimental studies of single roughness elements have been made in connection with many specific flows. The major effort appears to have been associated with producing turbulence in laminar shear flows. A study reported by Chao and Sandborn, ref. 1, demonstrated that large variations in static pressure are found depending on where in the roughness the pressure was measured. Thus, a need for more information of the effect of single roughness elements was needed to adequately predict the rough boundary effects. Klebanoff and Diehl have studied the flow in the region downstream from two-dimensional roughness elements. Their work indicated that the effects of the element were evident at large distances from the disturbance.

The present study was designed to evaluate the effect of a simple three-dimensional roughness element on the boundary layer downstream. Also, the element, a sphere, was identical to that employed by Chao and Sandborn, so a comparison between the pressure distribution on a single element could be made with the distribution in a group of spheres.

TEST SETUP AND PROCEDURE

A smooth flat plate 7 feet long and 4 feet wide, supported by four 30-inch legs, was used for the present experiments. This plate was placed in the free stream of the large wind tunnel. Static-pressure taps are located along the center line of the plate at four -inch intervals. The plate was made of 3/4-inch plywood with a smooth fiberglas finish and a sharp leading edge.

The static-pressure distribution along the flat plate has a positive gradient for the first 2 feet from the leading edge, Figure 1. From the 2 foot station the pressure is seen to be relatively uniform. The variations in static pressure are due to the slight waviness of the surface of the plate. From the 5 foot station to the trailing edge of the plate a negative-pressure gradient exists.

The roughness element was a 3/16-inch diameter sphere with static-pressure taps on its surface at $\alpha = 0^0$, 30^0, 45^0, 90^0, 120^0 and 150^0 from the vertical axis, Figure 2. These pressure taps are connected to small metal tubing with an outside diameter smaller than the inside diameter of the pressure taps in the flat plate. Thus, the spheres can be placed directly over the plate static taps. The pressure distribution around the sphere was determined by rotating the sphere. At each point of rotation and for each different static tap location the average pressure was measured with a capacitance type pressure transducer. The output of the pressure transducer was recorded on a Y-t plotter, ref. 1. The time average pressure was obtained by graphic integration of the pressure trace

$$p = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} p(t)\,dt \qquad (1)$$

The time period used for the measurements was 200 seconds.

The longitudinal turbulent velocities were measured with a transistorized, constant-temperature anemometer, ref. 3. The hot-wire sensing element was a 0.0002 inch diameter tungsten-platinum plated wire.

RESULTS AND DISCUSSION

Vertical-velocity profiles were taken along the center line of the plate at a free-stream speed of 30 feet per second. The maximum boundary-layer thickness at the trailing edge of the plate was 1-1/2 inches. The velocity measurements were made with a 3/16-inch diameter pitot-static tube. Mean and turbulent velocity profiles were taken at 32, 48 and 64 inches from the leading edge. These profiles are shown in Figures 3a, b, and c. In Figure 4 the mean velocity profiles are plotted non-dimensional and compared with boundary measurements reported by Klebanoff and Diehl, ref. 2. In order to avoid arbitrariness of the boundary-layer thickness δ, the distance from the plate is non-dimensionalized by the boundary layer momentum thickness. From the figures it can be seen that the profiles are similar and are comparable with the results of Klebanoff and Diehl, ref. 2.

The turbulent intensities at x = 44.5, 45, 45.5, 46 and 47 inches with a sphere at x = 44 inches are plotted on Figure 5. No appreciable difference in turbulence intensities was observed when the sphere was present. In Figure 6 the mean-velocity profiles at 3, 2, 1-1/2 and 1 inches downstream from a sphere at x = 44 inches are compared with the undisturbed velocity profile at x = 48 inches. The effect of the sphere is limited to a height of the same dimension as the sphere. The defect due to the sphere vanishes very quickly in the downstream direction.

Figure 5 is the turbulent intensity distribution observed directly downstream of the sphere at the 44 inch location. The variation in intensity of turbulence due to the sphere was of the same order as the accuracy of the measurements, so no definite conclusions on the variation of turbulence can be drawn.

Figure 7 indicates the static-pressure distributions around the surface of the sphere at different angular locations (see Fig. 2 for angle definition). The free stream velocity was 30 feet per second and the sphere was at a station 36 inches from the leading edge of the plate. The sphere is roughly 1/6 the height of the boudary layer. By using spherical coordinates, as shown in Figure 1, the drag and lifting force on the sphere can be calculated as follows:

$$(\text{force in x-direction}) = \int_0^{\pi/2} \int_0^{2\pi} (p \sin\alpha \cos\beta)\, R^2 \sin\alpha \, d\beta \, d\alpha$$

and

$$(\text{force in vertical direction}) = \int_0^{\pi/2} \int_0^{2\pi} (p \cos\alpha)\, R^2 \sin\alpha \, d\beta \, d\alpha$$

where R is the radius of the sphere and angles α and β are defined in Figure 2.

The x-force and vertical force on the sphere were found to be x-force = 4.07×10^{-5} lbs and vertical force = 0.86×10^{-5} lbs respectively. The "static" pressure was defined in ref. 1 as $\frac{\text{vertical force}}{\pi R^2} = 3.12 \times 10^{-4}$ psi.

Figure 8 a through c compares the present measurements on the single sphere with measurements made in the group of spheres by Chao and Sandborn, ref. 4. The pressure on the rear portion of the sphere of ref. 4 is a great deal less negative than the present observations. The separation of flow denoted by the sharp change in pressure for the present data can not be identified in the data of ref. 4. As might have been expected, it will be extremely difficult to predict the pressure around the sphere when other roughness elements are also present.

CONCLUDING REMARKS

The present study demonstrates that the effect of a single sphere on the velocity and turbulent distribution in a turbulent boundary layer is small. It has become obvious that a roughness element which has a large effect is desired in future studies. One of the main objectives of the present experiments was to compare the pressure distribution on a single sphere with that measured on a sphere in a group of spheres. For the single sphere the "average pressure" is defined by a line on the forward face of the sphere. The average pressure on the sphere which is surrounded by a group of other equal sized spheres was found to be defined by a small area on the rear face. There is a wide variation in how the surrounding roughness elements affect the flow over a single element. Thus, there is little hope of defining "static" pressure distribution within a rough boundary from information on a single roughness element.

SYMBOLS

x = distance along surface from leading edge of flat plate

y = distance normal to surface, measured from surface of plate

U = mean velocity in boundary layer

U_1 = mean velocity in free stream

ν = kinetic viscosity of air

p = static pressure

δ = boundary-layer thickness

δ^* = boundary-layer displacement thickness

$$\int_0^\infty \left(1 - \frac{u}{u_1}\right) dy$$

θ = boundary-layer momentum thickness

$$\int_0^\infty \frac{u}{u_1} \left(1 - \frac{u}{u_1}\right) dy$$

$\mathbb{R}_\theta$ = Reynolds number based on boundary-layer momentum thickness

$$\left(\frac{u_1 \theta}{\nu}\right)$$

R = radius of sphere

α = spherical angle coordinate (Figure 1)

β = spherical angle coordinate (Figure 2)

REFERENCES

1. Chao, J. L. and Sandborn, V. A.; "Evaluation of Static Pressure Along a Rough Boundary;" Colorado State University, Report CER64VAS-JLC10.

2. Klebanoff, P. S. and Diehl, Z. W.; Some features of artificially thickened fully developed turbulent boundary layers with zero pressure gradient. NACA TN 2475, 1951.

3. Kovasynay, L. S. G., Miller, L. T., and Vasudeva, B. R.; A simple hot-wire anemometer. Project Squid Technical Report JHU-22-P (Johns Hopkins University), 1963.

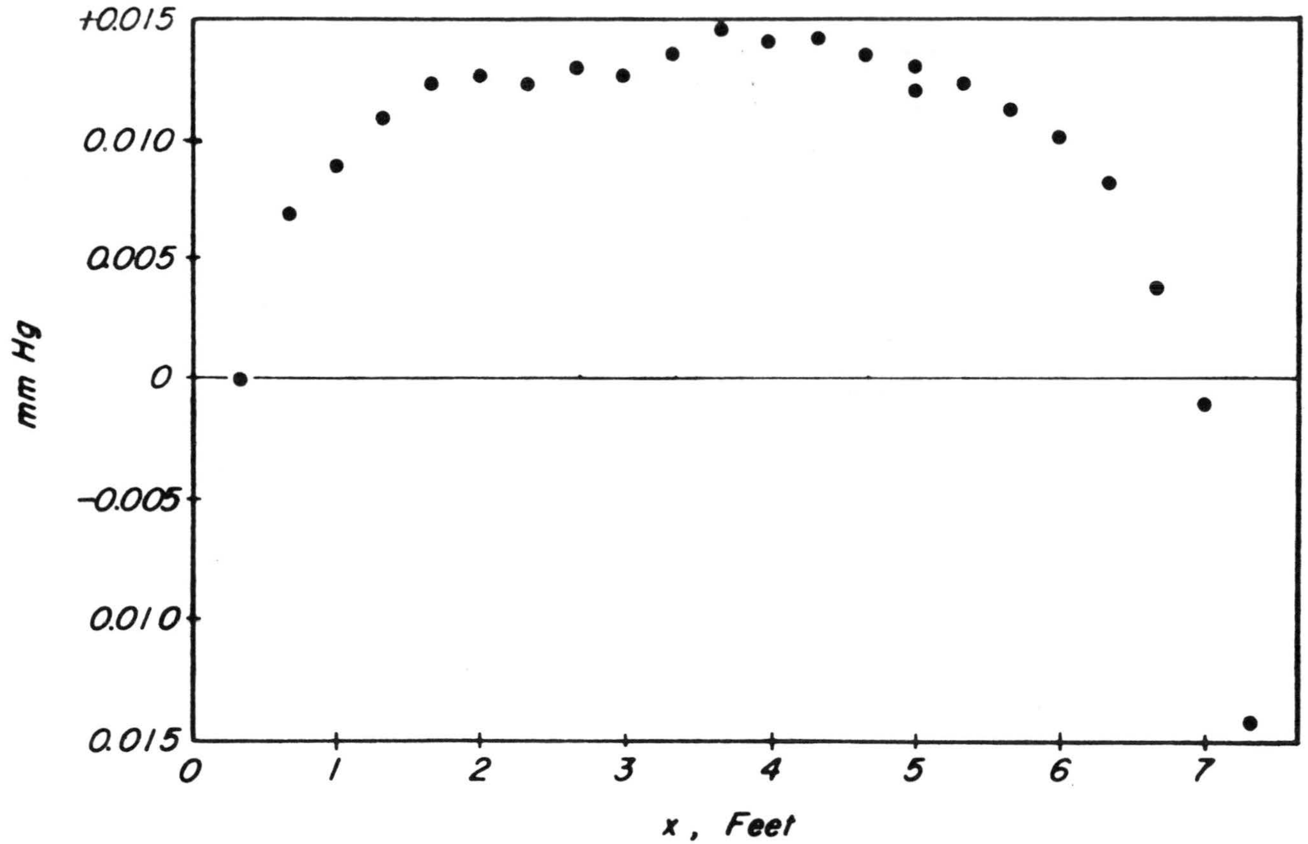

FIGURE 1 PRESSURE DISTRIBUTION ALONG FLAT PLATE

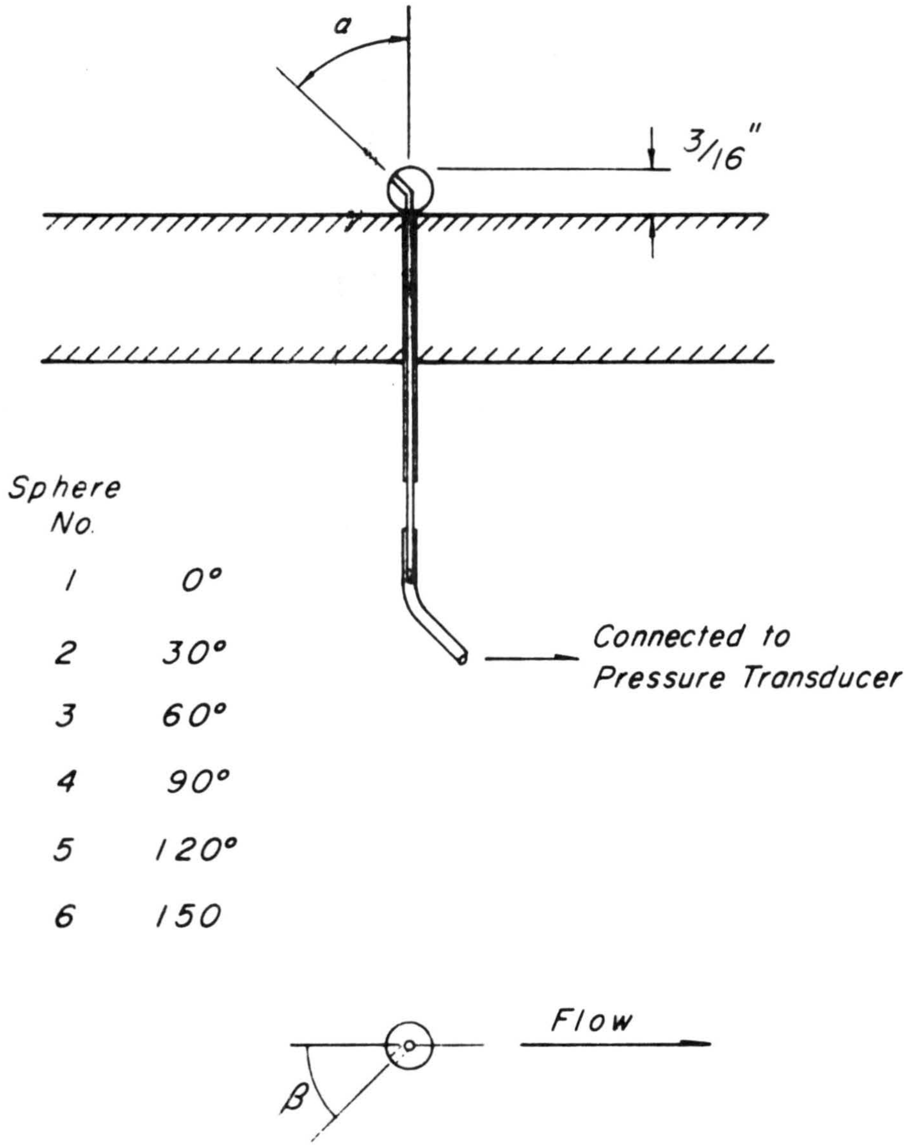

FIGURE 2 DETAILS OF SPHERES AS USED IN EXPERIMENT

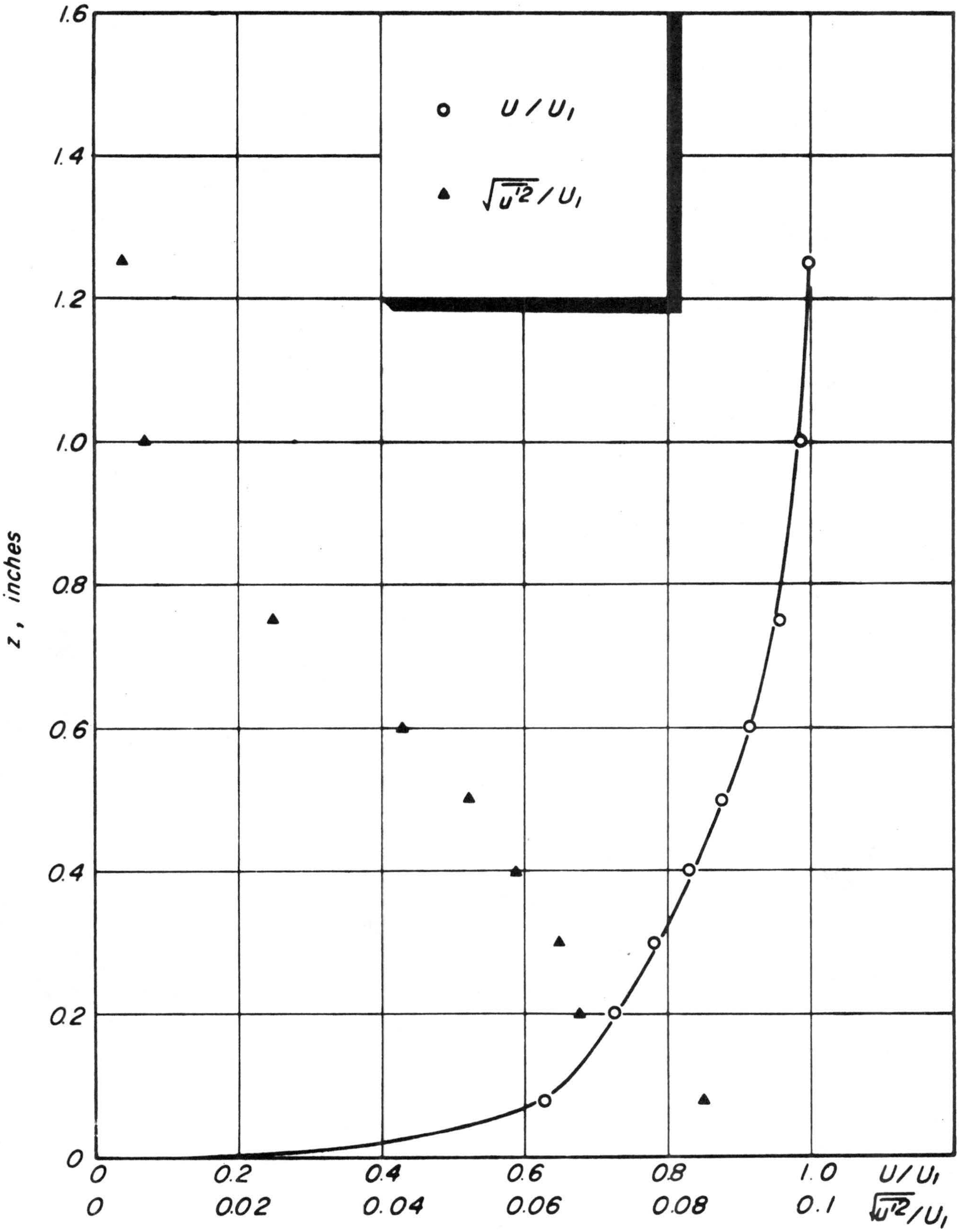

FIGURE 3 MEAN AND TURBULENT VELOCITY DISTRIBUTION ON THE PLATE
a) x = 32 inches

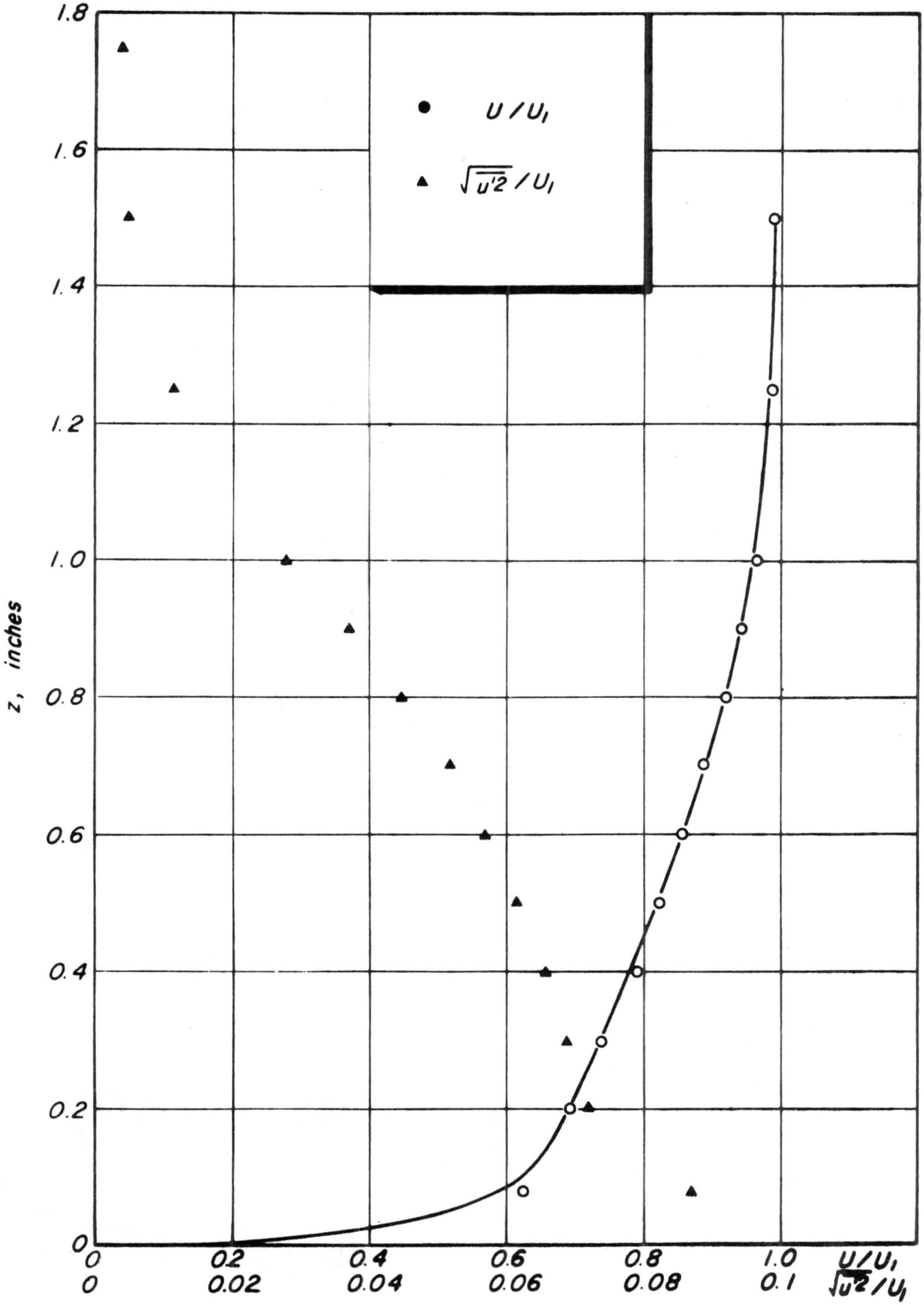

FIGURE 3 (CONTINUED) b) x = 48 inches

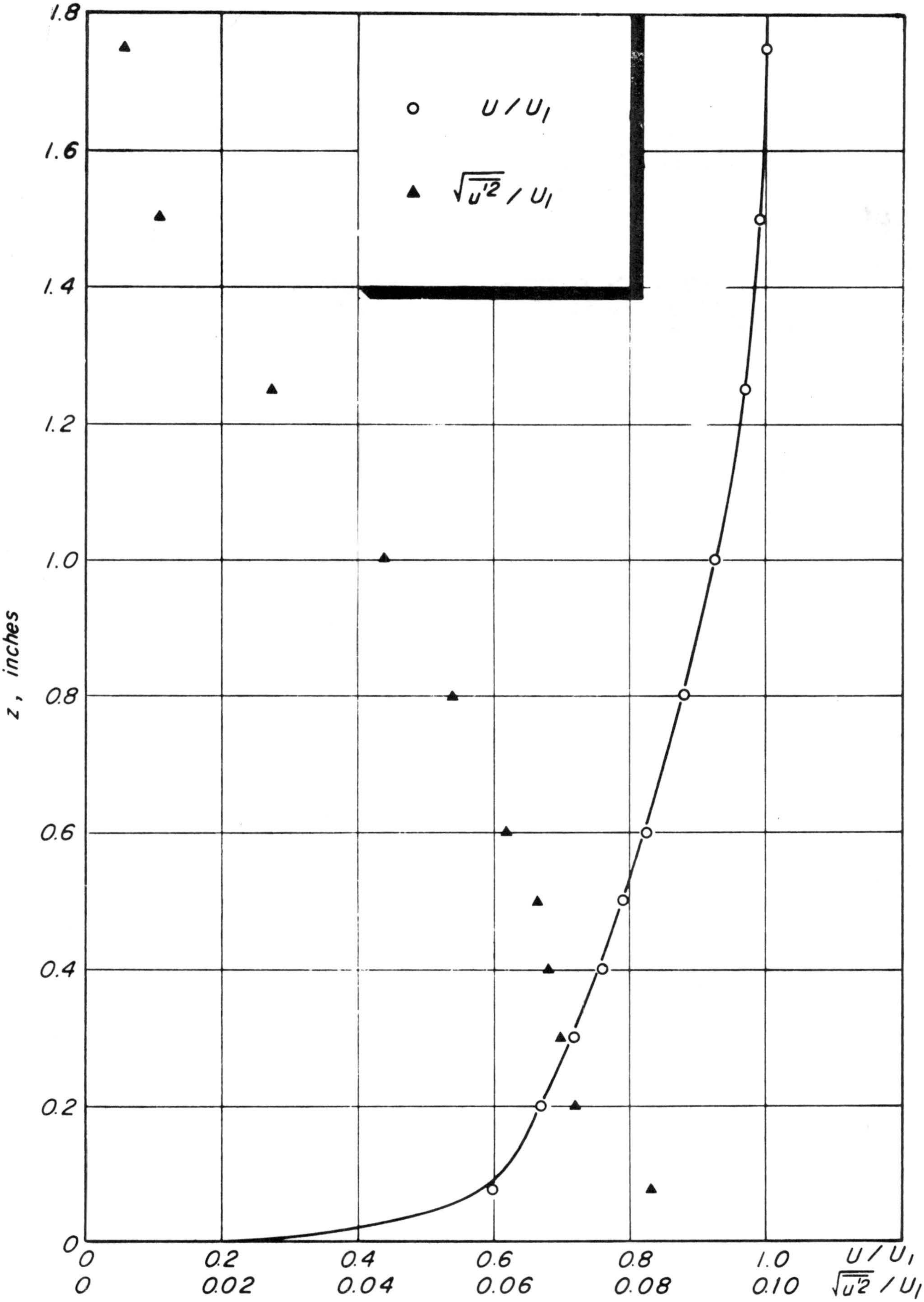

FIGURE 3 (CONCLUDED) c) x = 64 inches

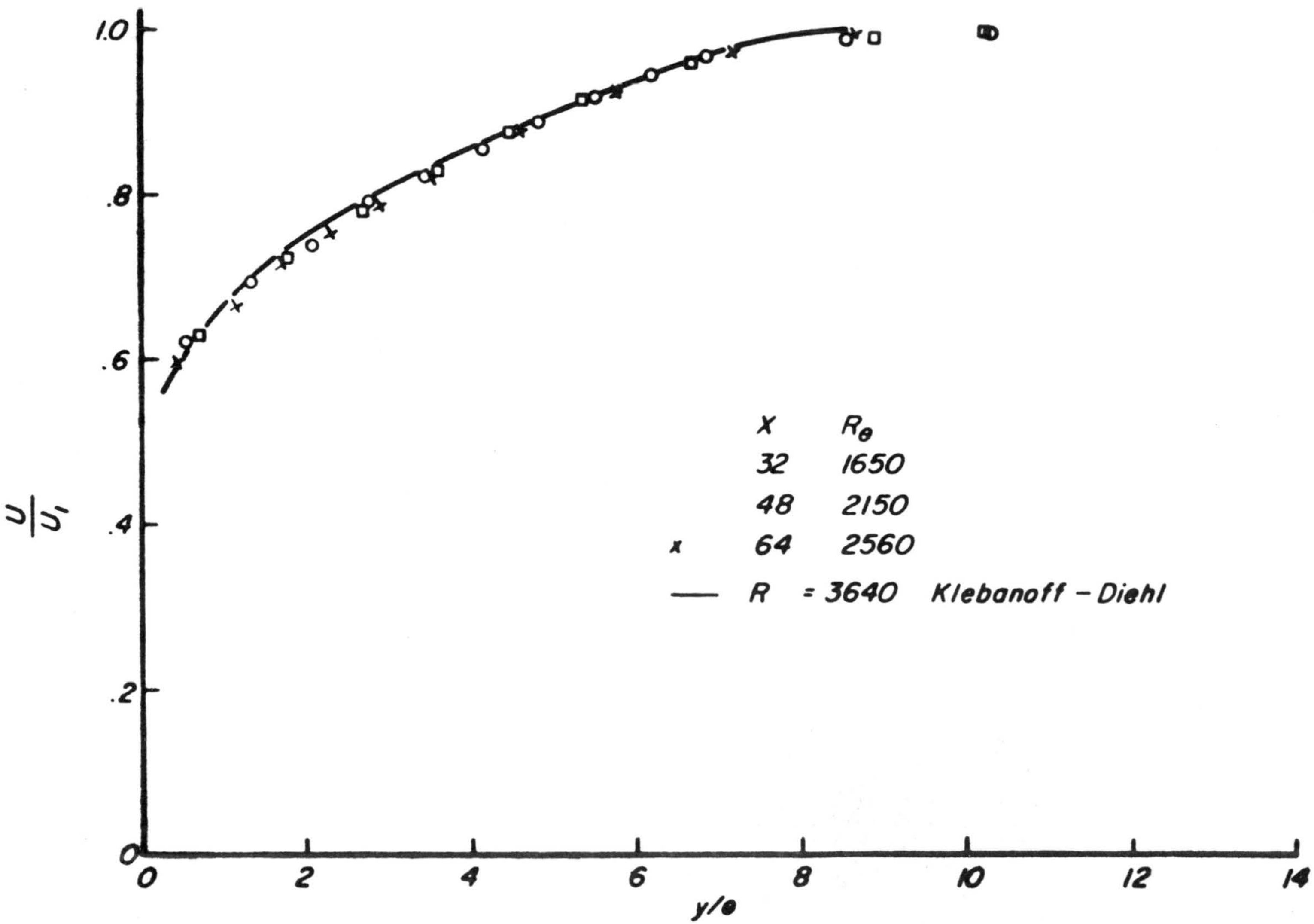

FIGURE 4 COMPARISON OF NONDIMENSIONAL MEAN VELOCITY DISTRIBUTION

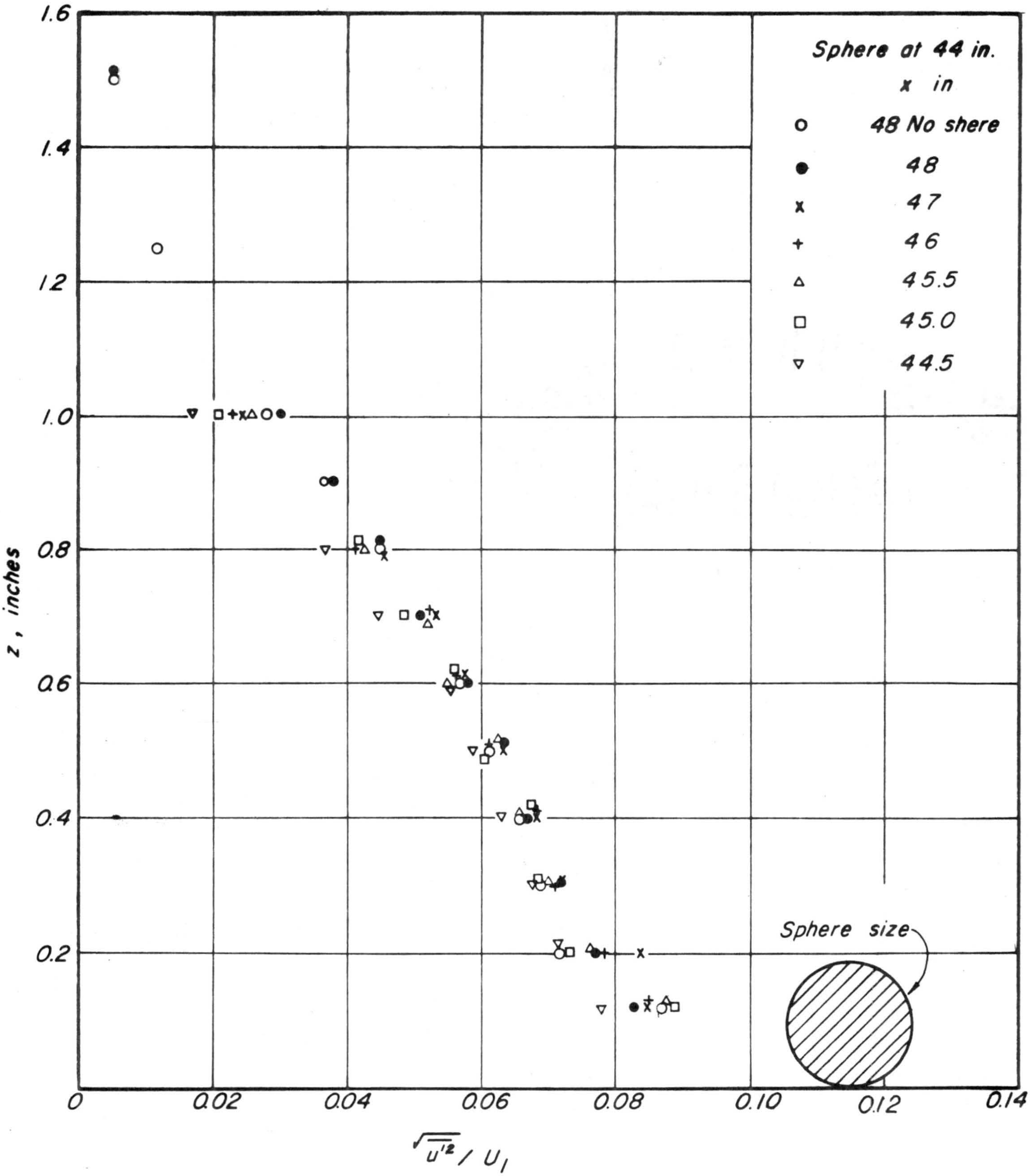

FIGURE 5 EFFECT OF A SINGLE ROUGHNESS ELEMENT ON THE TURBULENT VELOCITY DISTRIBUTION

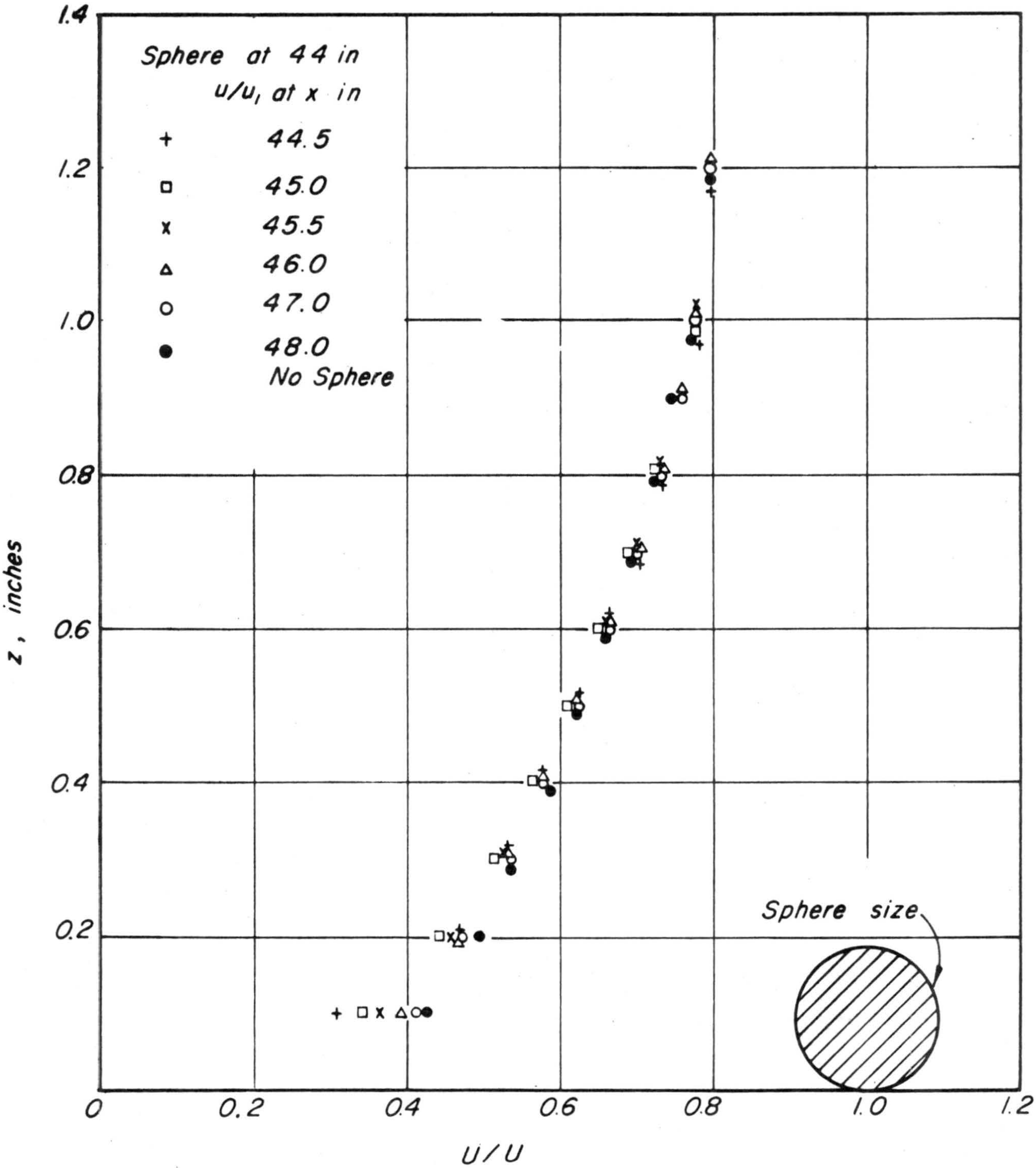

FIGURE 6 EFFECT OF A SINGLE ROUGHNESS ELEMENT ON THE VELOCIT DISTRIBUTION

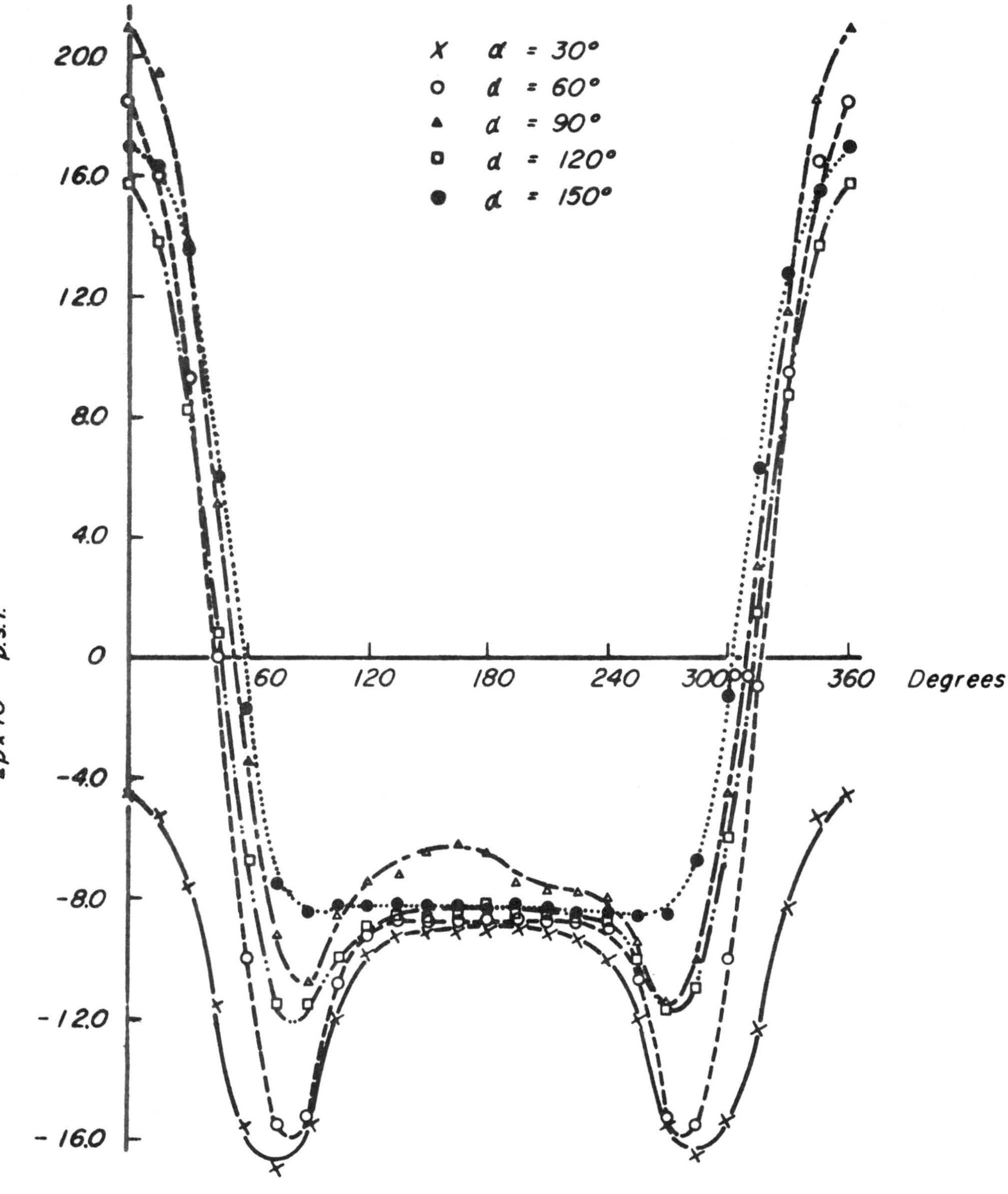

FIGURE 7 PRESSURE DISTRIBUTION AROUND THE SPHERE

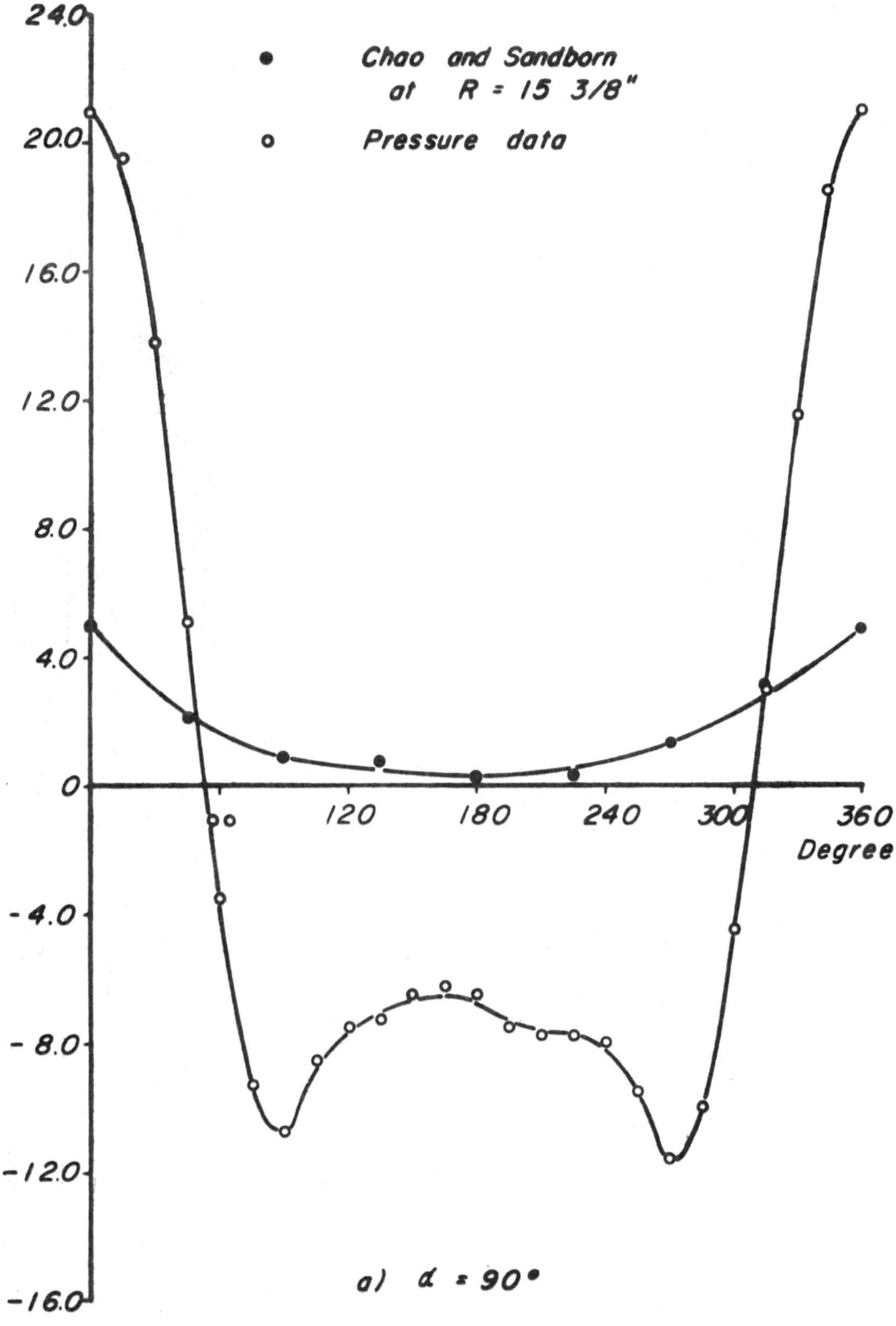

FIGURE 8 COMPARISON OF PRESSURE DISTRIBUTIONS AROUND SPHERE

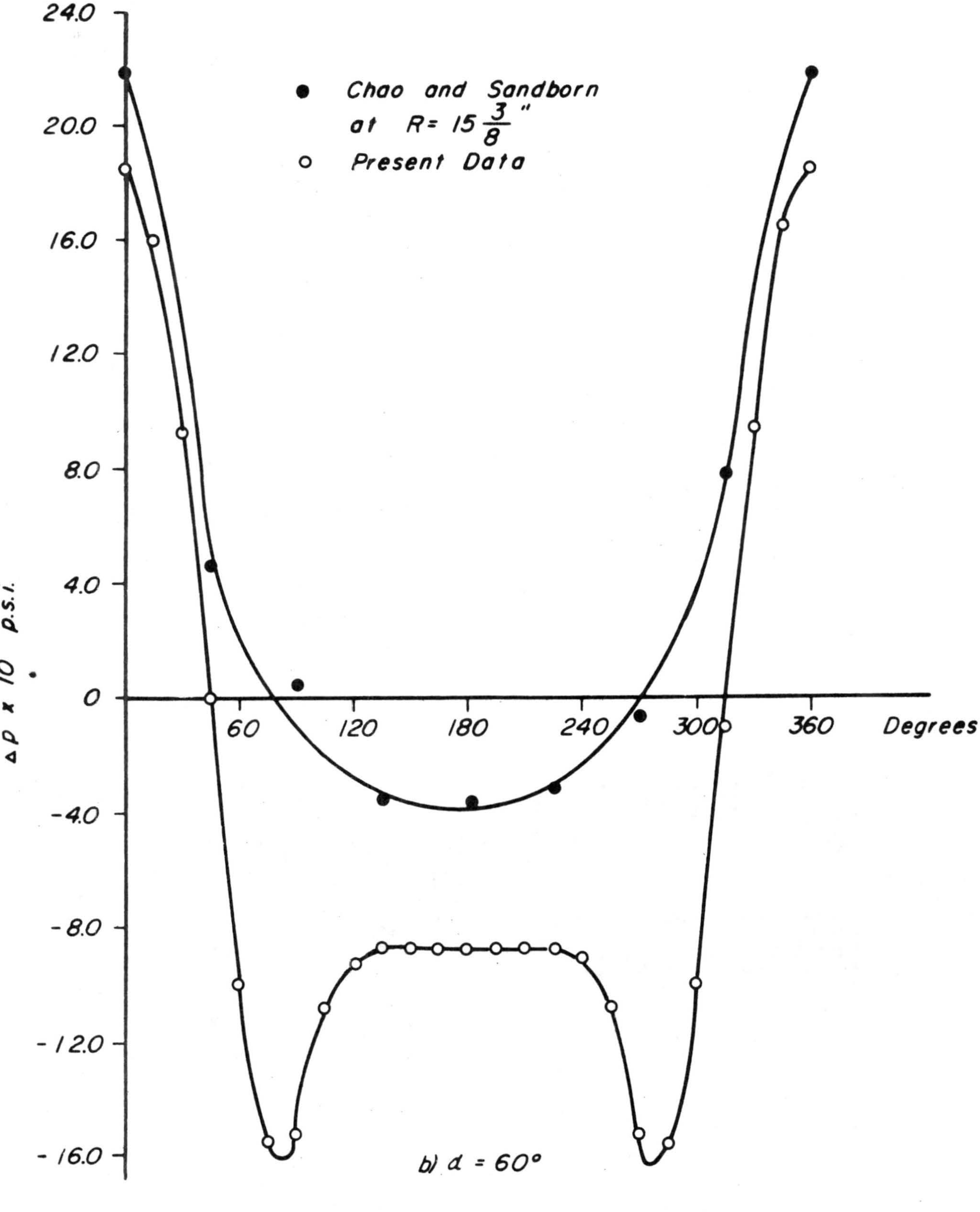

FIGURE 8 - (cont.) COMPARISON OF PRESSURE DISTRIBUTIONS AROUND THE SPHERE

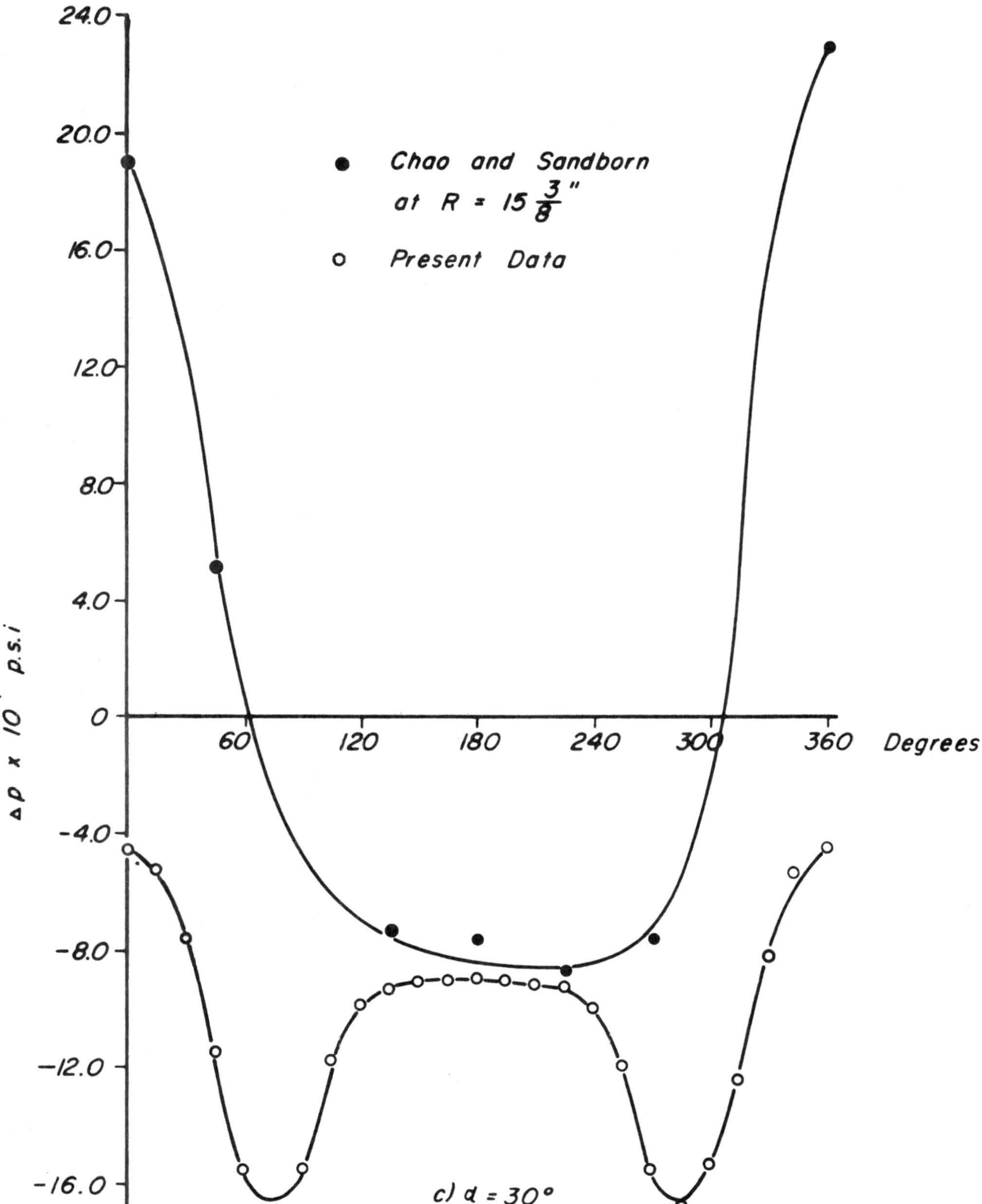

FIGURE 8 - (concluded) COMPARISON OF PRESSURE

DISTRIBUTIONS AROUND SPHERE