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SOME REMARKS ON THREE-DIMENSIONAL WAKES AND JETS

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Nicholas Trentacoste and Pasquale M. Sforza

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POLYTECHNIC INSTITUTE OF BROOKLYN

DEPARTMENT
of
AEROSPACE ENGINEERING
and
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LIST OF SYMBOLS

Symbol	
X	Axial Coordinate
Y	Cross-Plane Coordinate Aligned with Major Axis of Wake Model or Jet Orifice
Z	Cross-Plane Coordinate Aligned with Minor Axis of Wake Model or Jet Orifice
d	Width of Minor Axis of Wake Model or Jet Orifice
ℓ	Length of Major Axis of Wake Model or Jet Orifice
$e=d/\ell$	Eccentricity of Wake Model or Jet Orifice
U	Velocity in Direction of X-Axis
U_e	Velocity of External Stream of Wake
U_{oc}	Velocity at Exit of Jet Orifice
U_o	Velocity on the X-Axis
$\overline{U}_o=U_e-U_o$	Velocity Difference
$\overline{U}=U_e-U$	Velocity Difference
$Y_{\frac{1}{2}}$	Half-Width Boundary Distance Measured from X-Axis to Point in Y Direction at which $\overline{U}/\overline{U}_o=\frac{1}{2}$ for the Wake and $U/U_o=\frac{1}{2}$ for the Jet
$Z_{\frac{1}{2}}$	Half-Width Boundary Distance Measured from X-Axis to Point in Z Direction at which $\overline{U}/\overline{U}_o=\frac{1}{2}$ for the Wake and $U/U_o=\frac{1}{2}$ for the Jet
Barred Quantities	Quantities Made Dimensionless with Respect to d, e.g., $\overline{X}=X/d$, etc.

SOME REMARKS ON THREE-DIMENSIONAL WAKES AND JETS †

by

Nicholas Trentacoste* and Pasquale M. Sforza**

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ABSTRACT

A succinct account of the similarities between three-dimensional wake and jet flow fields is presented. Discussion is confined to the behavior of the centerline velocity, the half-width growth, and the appearance of velocity irregularities. In addition, the most recent experimental data from the Polytechnic Institute of Brooklyn Aerospace Laboratory (PIBAL), concerning three-dimensional wakes and jets, is included.

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I. INTRODUCTION

Recently, substantial interest has been generated in the area of three-dimensional, turbulent, incompressible wakes (Cooper and Lutzky (1955), Kuo and Baldwin (1964), Kuo (1965), Kuo and Baldwin (1966), Verna (1966), and Kuo and Baldwin (1967)), and jets (Sforza, Steiger and Trentacoste (1966), Trentacoste and Sforza (1966), and Trentacoste and Sforza (1967). The present authors feel that there are some striking similarities between the mean properties of these two flow fields that have not yet been elaborated upon.

The purpose of this note is to present a succinct description of these similarities. Herein discussion will be confined to comparisons of (1) the behavior of the centerline velocity, (2) the half-width growth, and (3) the appearance of velocity irregularities in three-dimensional wakes and jets. The cited references contain complete descriptions of the flow fields under discussion.

Careful study of the published results of Cooper and Lutzky (1955), Verna (1966), and Kuo and Baldwin (1967), concerning three-dimensional wakes, reveals that there is a lack of quantitative data for the near field, i.e., the region between the obstacle and stations 15 to 20 characteristic body diameters downstream of the obstacle. The present authors, in their published work concerning three-dimensional jets, have shown that the near field of the jet is of fundamental importance in its description. Thus, the absence of corresponding information on the near field of the three-dimensional wake detracts from a more complete undertanding of the phenomena occuring there. In this context, the authors consider the available experimental results for three-dimensional wakes as preliminary in nature. Therefore, our comparisons between the near field results for three-dimensional jets and those for three-dimensional wakes should be considered qualitatively for the present time. The present paper hopefully will serve to point out areas of investigation which may aid to an improved understanding of the three-dimensional wake.

Fig. 1 contains schematic representations of the three-dimensional wake and jet flow fields with definitions of the various terms used throughout this paper.

II. CENTERLINE VELOCITY BEHAVIOR

The rate of decay of the axial velocity defect, $(U_e-U_o)/U_e$, for three-dimensional wakes becomes equivalent in the far field to that for axisymmetric wakes. This feature has been observed experimentally in wakes behind elliptic discs (Kuo and Baldwin, 1966) and in wakes behind rectangular plates (Cooper and Lutzky, 1955); typical results are presented in Fig. 2. Similarly, in three-dimensional jets (Sforza, Steiger, and Trentacoste 1966), from rectangular and elliptical orifices the axial velocity U_o/U_{oc}, decays at the same rate as that of a circular jet far downstream of the orifice, as depicted in Fig. 3. The similarity between these two flow fields appears in that:

(a) The flow fields of both the three-dimensional wake and jet suffer a "loss of memory" of their initial conditions far downstream of the initial station.

(b) The wake axial velocity defect, $(U_e-U_o)/U_e$, and the jet axial velocity, U_o/U_{oc}, decay at the same rate as circular wakes and jets, respectively, far downstream of the initial station. The surrounding flow at these axial stations, however, is not truly axisymmetric in nature. The entire flow field becomes fully axisymmetric at stations much further downstream than the point at which the centerline velocity defect or axial velocity decay rate take on their respective axisymmetric values.

The axial velocity decay in the near field of the three-dimensional jet has been found to depend only on the eccentricity, e, of the orifice, (this part of the flow has been termed the Characteristic Decay Region:, Sforza, Steiger, and Trentacoste 1966). It is felt that similar effects would be manifested by the decay of the axial velocity defect in three-dimensional wakes. Unfortunately, however, the available data bearing on this point is insufficient to permit a more positive statement at this time. Recent preliminary experimental results obtained at the Polytechnic Institute of Brooklyn Aerospace Laboratories (PIBAL) for the wake behind a body of e = .157 have shown that there exist various decay rates of axial velocity defect in the three-dimensional wake (Fig. 2). It can be seen in Fig. 2 that beyond a certain axial station (in this case $x/d \simeq 20$) the axial velocity defect decays at the same rate as that of an axisymmetric wake, and coincides with the results of Cooper and

Lutzky (1955) and Kuo and Baldwin (1967). The displacement of the PIBAL results from those of Kuo and Baldwin and Cooper and Lutzky is believed to be due to the difference in the drag coefficients of the respective bodies.

III. HALF-WIDTH BOUNDARIES

The half-width boundaries for three-dimensional wakes are defined as those distances in the cross plane directions Y and Z where $\overline{U}/\overline{U}_o=\frac{1}{2}$, for the three-dimensional jet, they are defined as the distances where $U/U_o=\frac{1}{2}$, see Fig. 1. It should be noted that all distances are measured from the centerline, or X axis.

In the case of three-dimensional slender jets, i.e., ($e \leq 0.90$), the major axis half-width ($Y_{\frac{1}{2}}/d$) is found to decrease initially while the minor axis half-width ($Z_{\frac{1}{2}}/d$) grows; at some intermediate station they crossover, grow similarly, but at different rates, and finally tend to approach each other far downstream where the jet tends to axisymmetry, as shown in Fig. 4. It is interesting to note, on comparison of Figs. 3 and 4 that the crossover point corresponds to the point at which the axis velocity decay rate takes on the axisymmetric value.

This crossover phenomenon has not been stated in the work on three-dimensionsional wakes of Cooper and Lutzky (1955) and Kuo and Baldwin (1967), and is not obvious since their data for the growth of the wake in the Y and Z directions is plotted on a logarithmic graph. In addition, the lack of data in the near field of the wake obscures this observation. One may, however, take the half-widths, $Y_{\frac{1}{2}}/d$ and $Z_{\frac{1}{2}}/d$ directly from the velocity profile data of Kuo and Baldwin (1967), and display them on a linear graph as is shown in Fig. 5. It is evident that the wake grows qualitatively in the same fashion as the jet (Fig. 4) with a crossover point lying in the region where the axial velocity defect decay rate takes on its axisymmetric value. This latter observation can be seen from a comparison of Figs. 2 and 5. The half-width data reported by Verna (1966) for the wake behind a rectangular body of e =.50 is shown in Fig. 6a, and also depicts the crossover. In Fig. 6b the PIBAL results for the half-width growth in the wake of a slender three-dimensional body of e = .157 is presented, and clearly shows the crossover phenomenon. Upon comparison of the streamwise location of the half-width crossover point in the latter case, with the corresponding axial velocity defect decay (Fig. 2), one clearly sees that this point lies in the region where the axial velocity defect begins to decay at the same rate as the axisymmetric wake.

IV. VELOCITY IRREGULARITIES

A characteristic feature of slender three-dimensional jets is the appearance of off-center peaks in the velocity profiles (U/U_o) in the Y direction in the near field of the jet, that is, at streamwise stations before the axial velocity decay becomes axisymmetric. The appearance of these off-center peaks in axisymmetric jets and jets issuing from square orifices has not been detected to date. The cause of such phenomena is believed to be the rolling up of vortex sheets shed from the three-dimensional orifices. These irregularities appear at about 10 characteristic orifice diameters from the jet outlet and subsequently disappear near the point where the axial velocity decay rate becomes axisymmetric in character. Their subsequent decay is due to the action of viscosity and turbulent diffusion processes. This facet of three-dimensional jet flow fields has been described by Trentacoste and Sforza (1967).

It is also to be noted that a similar phenomenon occurs in the three-dimensional wake for discs with e = .20 and .60 but not for discs of e = 1.0 (Kuo and Baldwin 1967). Analogous phenomena occur in the work of Cooper and Lutzky for the wakes behind rectangular plates of eccentricity of .333, .20, and .10, but not for the square plate. The PIBAL results also show the existence of velocity irregularities in the wake of a body of eccentricity e = .157. These irregularities subsequently die out further downstream in the region where the decay rate of the axial velocity defect in the wake is axisymmetric. These irregularities appear to persist for larger streamwise distances than in the jet, possibly due to the fact that the shearing stresses that diffuse the vorticity generated by the obstacle are smaller than those existing in the jet. A characteristic feature of the irregularity phenomena is that they appear in the planes parallel to the direction of the largest half-width of the flow field. Representative data concerning these irregularities is presented in Fig. 7 (a) for the wake and in Fig. 7 (b) for the jet.

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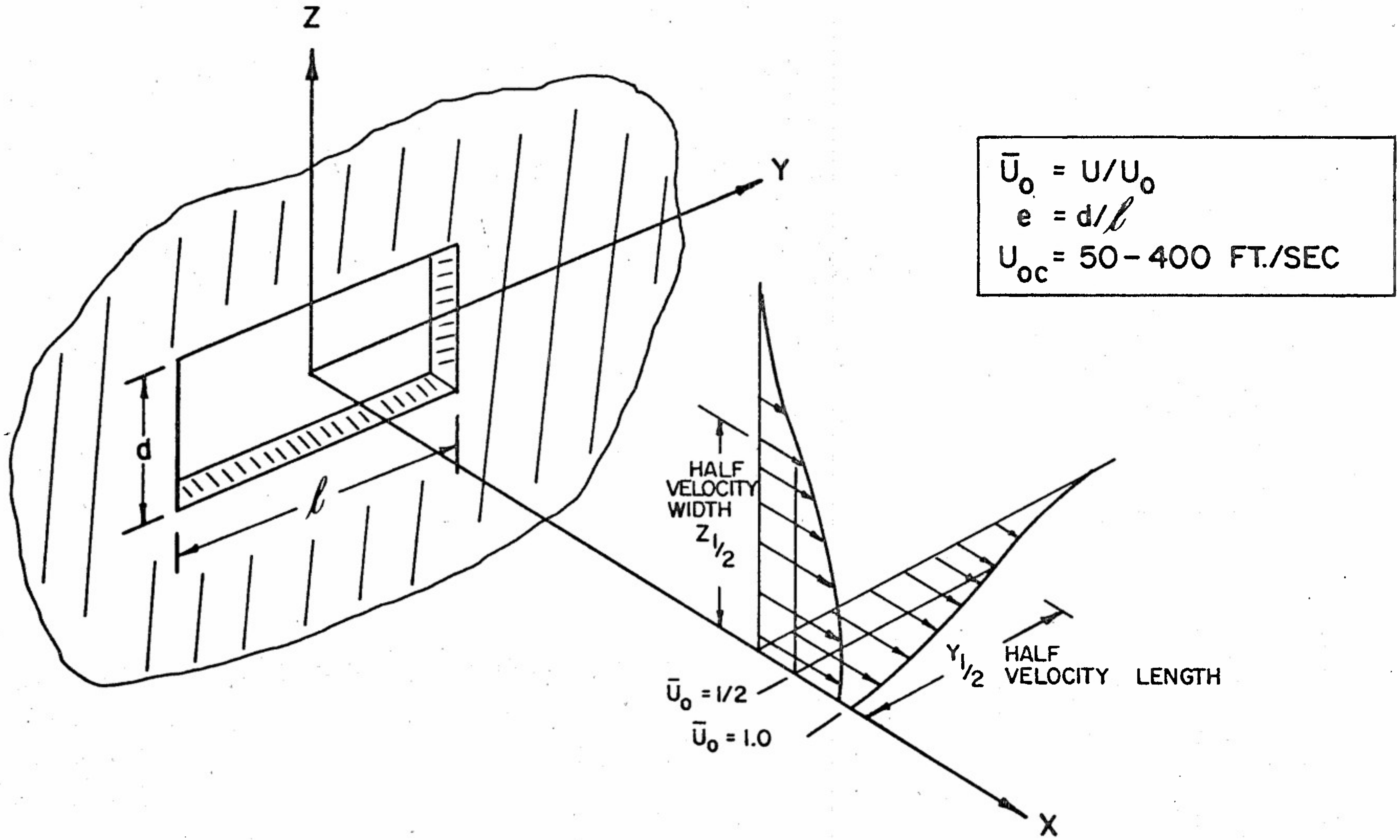


Fig. No. 1a SCHEMATIC REPRESENTATION OF THREE-DIMENSIONAL JET FLOW FIELD. RECTANGULAR SLOTS IN A THIN PLATE. SFORZA, STEIGER, and TRENTACOSTE (1966).

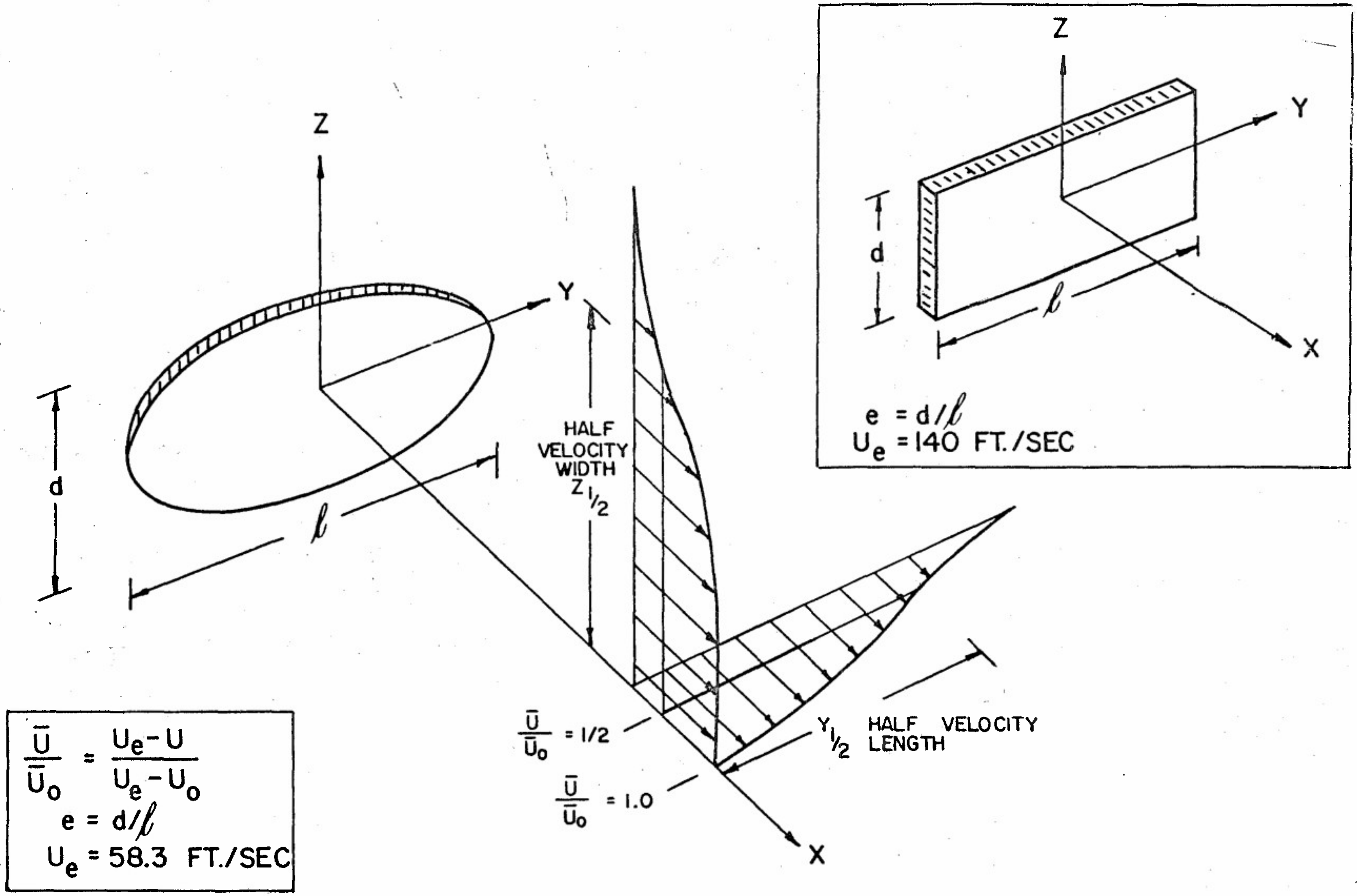


Fig. No. 1b SCHEMATIC REPRESENTATION OF THREE-DIMENSIONAL WAKE FLOW FIELD. THIN ELLIPTICAL PLATES SUPPORTED BY WIRES, KUO and BALDWIN (1966).

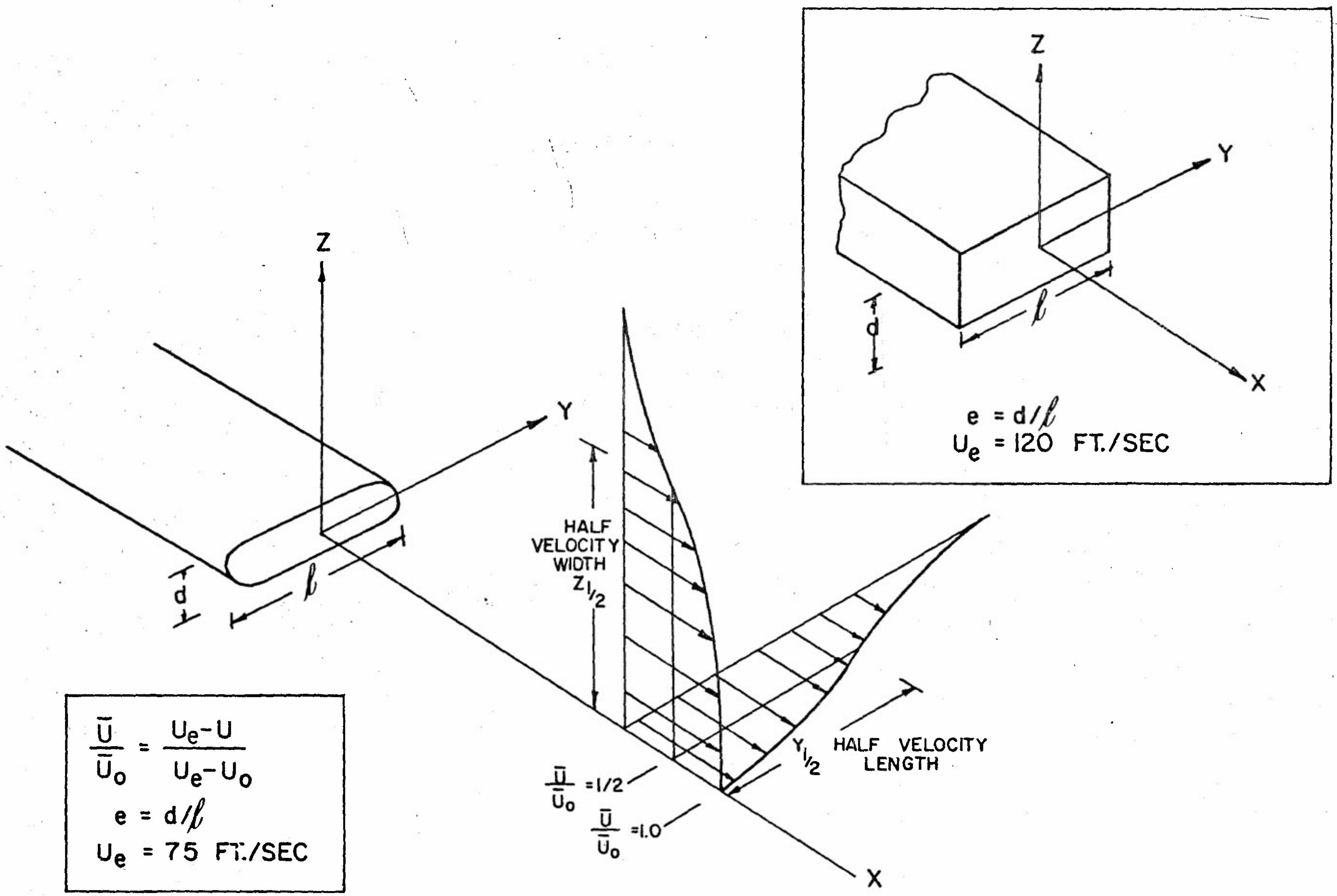


Fig. No. 1c SCHEMATIC REPRESENTATION OF THREE-DIMENSIONAL WAKE FLOW FIELD. SOLID OVAL BODY SUPPORTED UPSTREAM, PIBAL DATA (1968). UPPER RIGHT HAND CORNER, SOLID RECTANGULAR BODY SUPPORTED UPSTREAM, VERNA(1966).

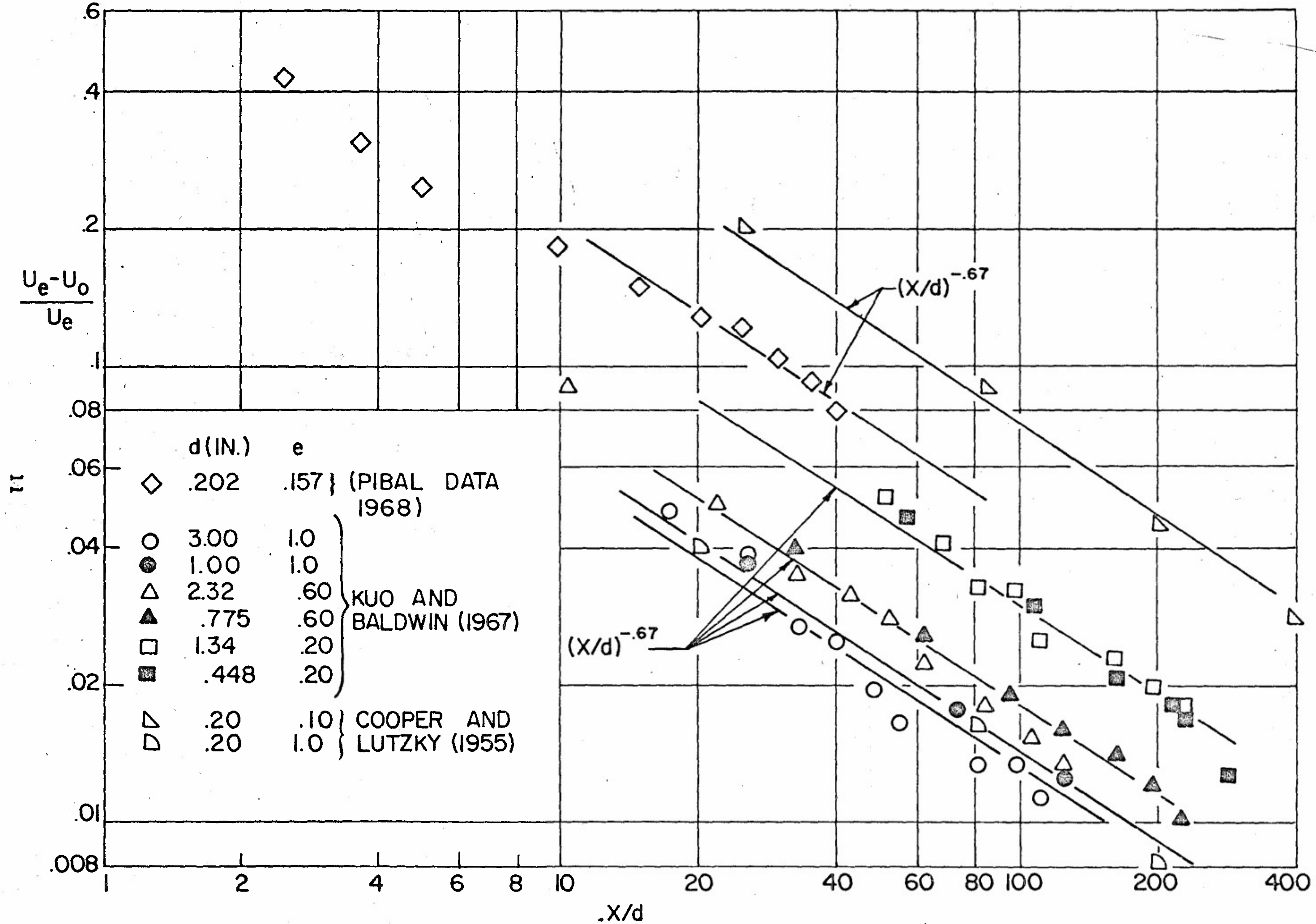


Fig. No. 2 AXIAL VELOCITY DEFECT DECAY OF THREE-DIMENSIONAL WAKE.

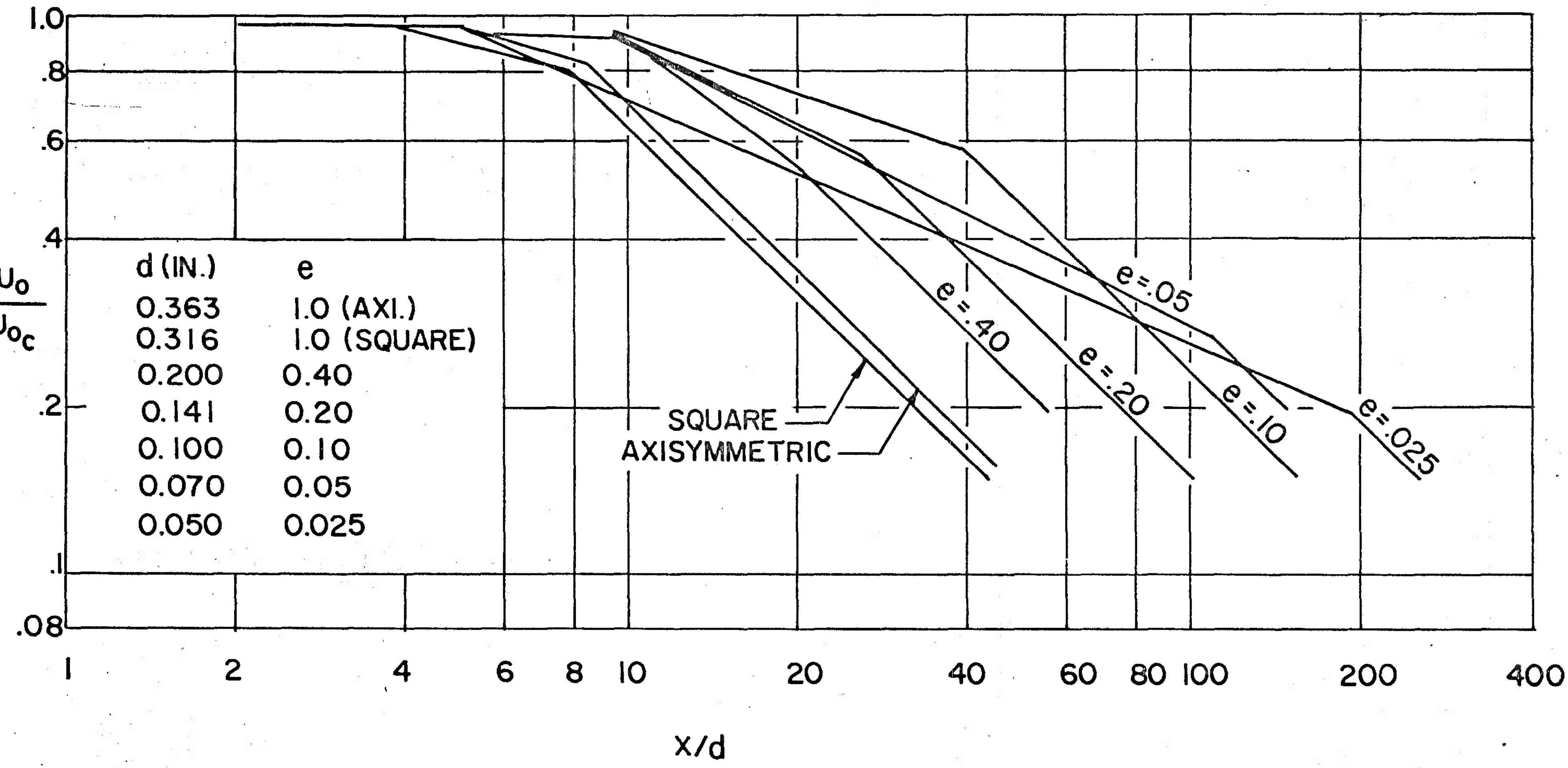


Fig. No. 3 AXIAL VELOCITY DECAY OF THREE-DIMENSIONAL JET (AVERAGE OF ALL VELOCITY DATA TAKEN TO DATE). TRENTACOSTE AND SFORZA (1967).

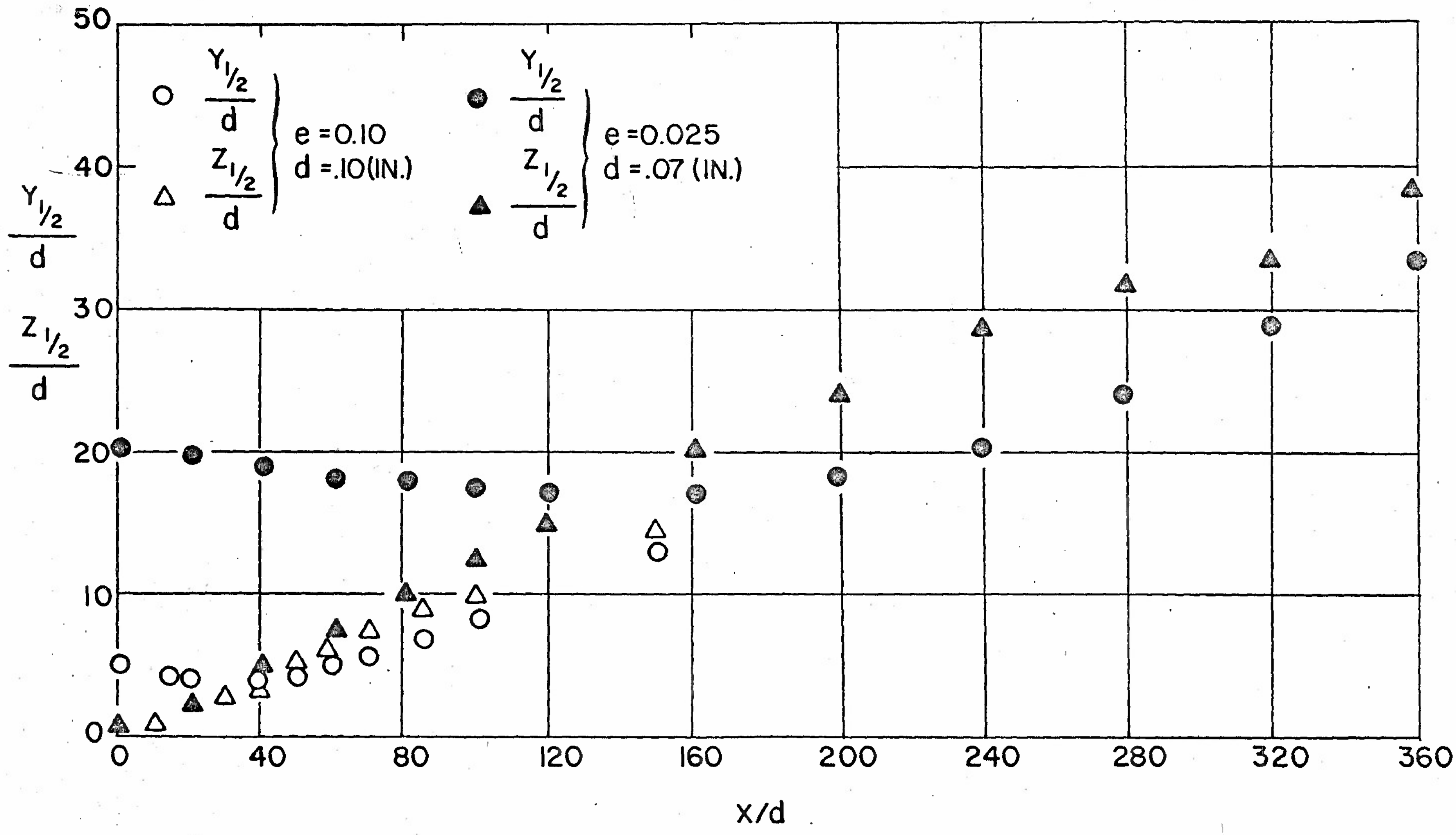


Fig. No. 4 HALF VELOCITY BOUNDARY GROWTH FOR SLENDER (e $\leq$.90) THREE-DIMENSIONAL JETS. TRENTACOSTE and SFORZA (1967).

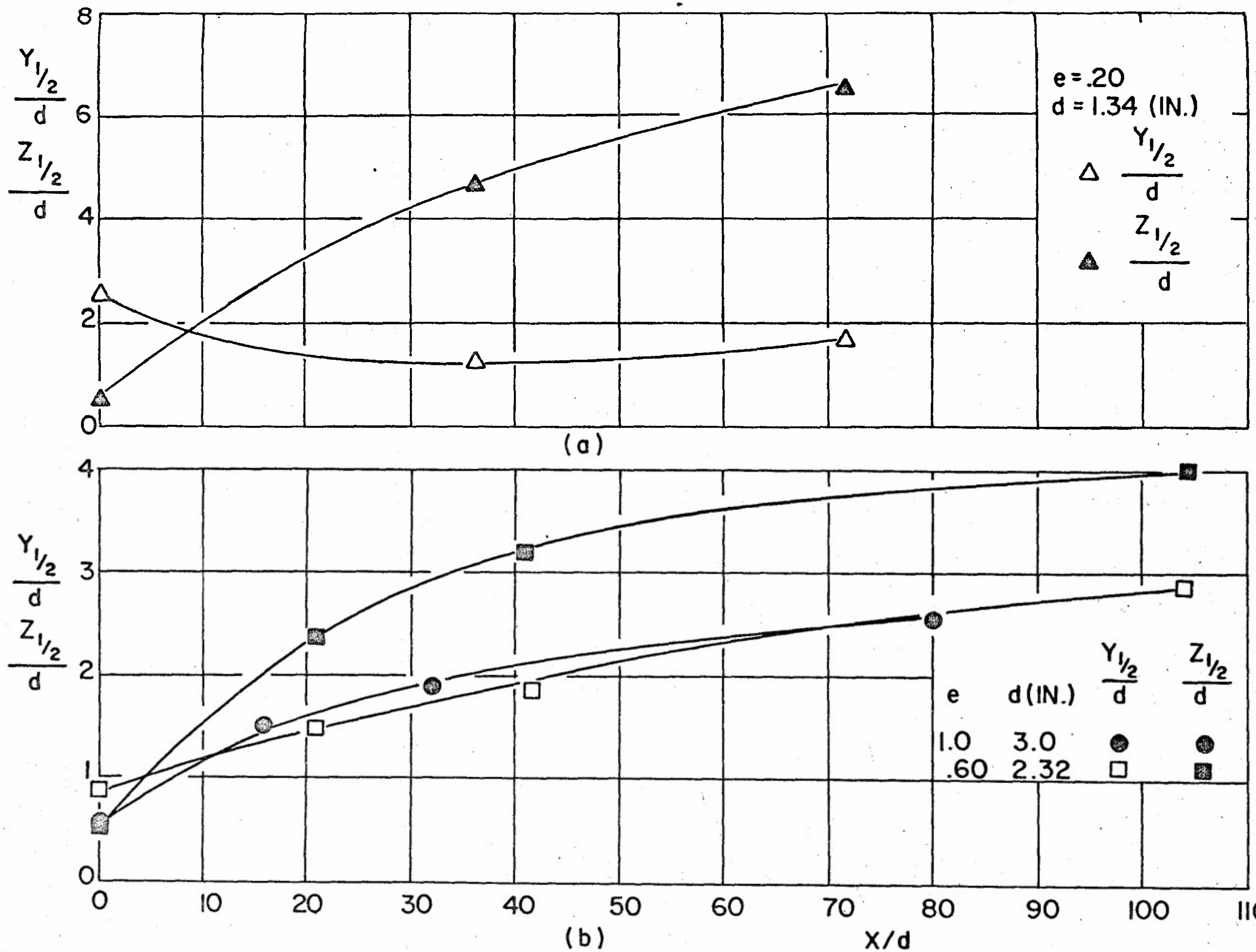
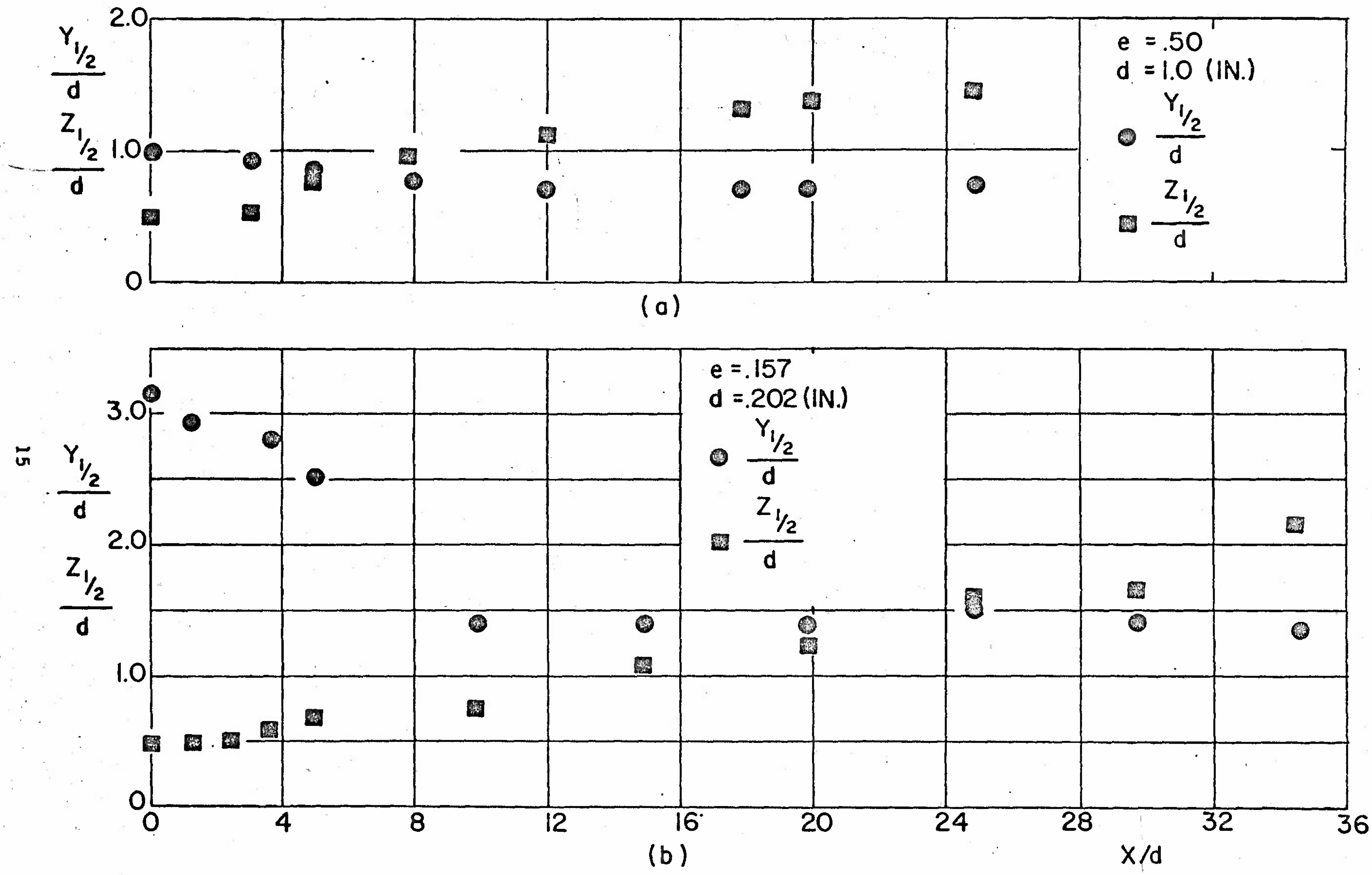


Fig. No. 5 HALF VELOCITY BOUNDARY GROWTH FOR THREE-DIMENSIONAL WAKES. KUO and BALDWIN (1967).



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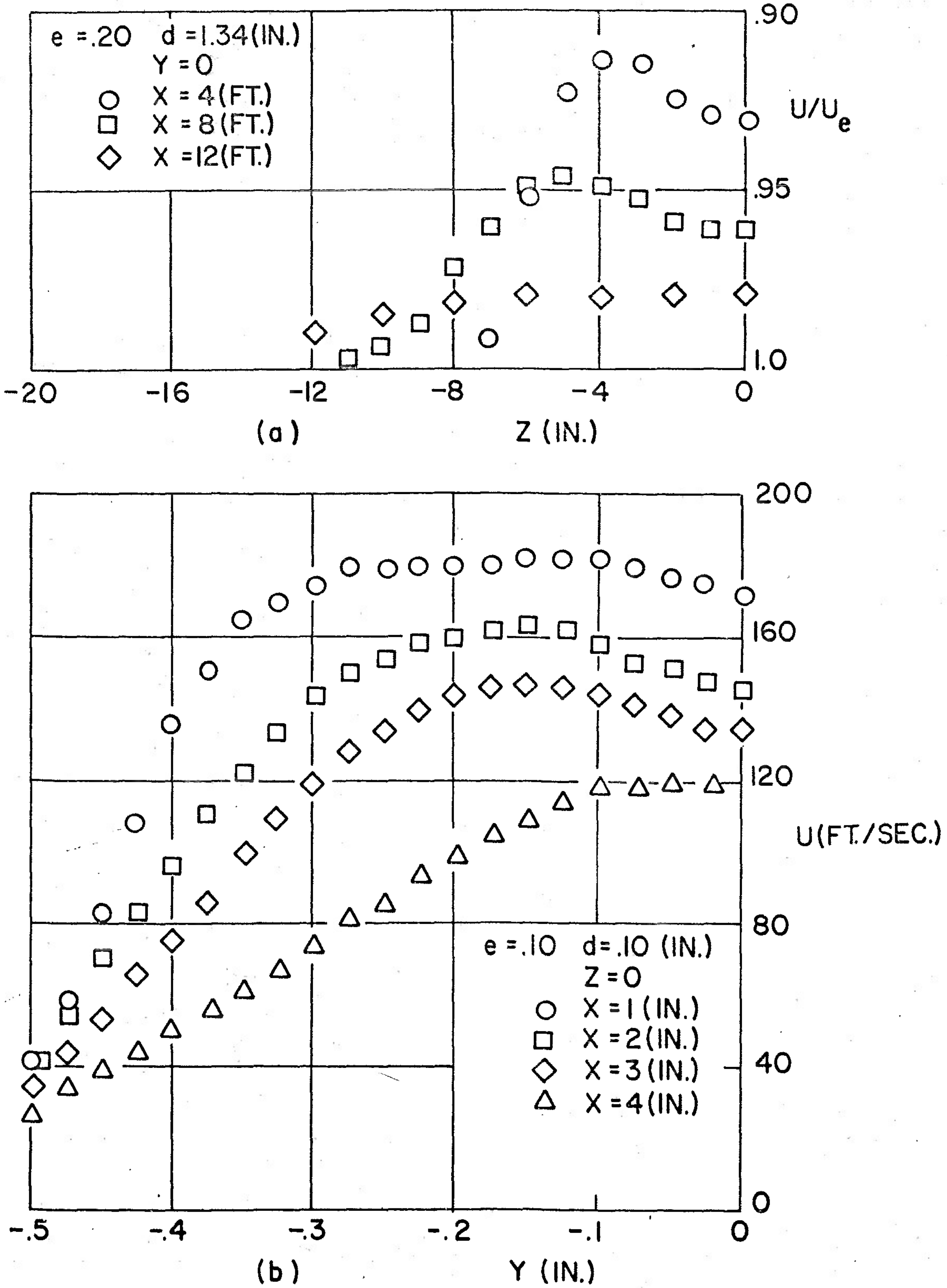

Fig. No. 7 (a) VELOCITY IRREGULARITIES FOR THREE-DIMENSIONAL WAKE. KUO and BALDWIN (1967).
(b) VELOCITY IRREGULARITIES FOR THREE-DIMENSIONAL JET, PIBAL DATA (1968).

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