INVESTIGATIONS TO DEVELOP WIND TUNNEL TECHNIQUES TO MEASURE ATMOSPHERIC GASEOUS DIFFUSION IN MODEL VEGETATIVE SURFACES

Colorado State University
Fluid Dynamics and Diffusion Laboratory
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Second Annual Report

by

E. J. Plate

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I. Introduction

In the original contract with the Agricultural Research Service, the research program for the study of modelling parameters of diffusion in vegetative surfaces was sketched only in the broadest sense. It remained to be explored, along which lines an experimental program leading to the objectives of the contract could most fruitfully be developed. In the course of study, it became apparent that not less than four different fundamental questions needed to be answered before any modelling parameters could be defined.

The first problem which required solution was the establishment of diffusion characteristics for a standard or reference turbulent flow. It appeared advisable to express the diffusion characteristics of gas plumes in vegetated regions in terms of deviations from a standard reference case. In boundary layer studies, turbulent flow over a smooth boundary is most generally used as the reference for describing wall effects; therefore, the turbulent boundary layer along a smooth flat plate was chosen as the reference flow. For a diffusion source, a line source located at the floor was considered most fundamental, partly because it offers certain experimental and theoretical advantages, and partly because many diffusion phenomena in agriculture such as evaporation from area sources and dispersion of insecticides from aircraft are related to the line-source problem.

The results of this initial study have been reported in the first and second semi-annual reports. In the meantime, a paper was prepared on this subject by M. Poreh and J. E. Cermak and submitted for publication. The paper draft is appended as Appendix I. In it, the problem of diffusion from a line source into a turbulent boundary layer over a flat plane boundary has been discussed by using the concepts and tools commonly associated with the theory of boundary layer development. While these concepts are quite adequate to describe gaseous diffusion in a phenomenological sense, they do not explicitly yield modelling parameters for practical field applications.

For practical modelling parameters, quantities are needed which can be measured or defined in the atmosphere as well as in the laboratory. This need constitutes the second problem. Recently this problem has yielded to analysis through the concept of "Lagrangian Similarity." J. E. Cermak used this concept and applied it to, among other sets of data, the data for the study mentioned above. His paper, which in a sense summarized the experimental efforts on diffusion studies in the Fluid Dynamics and Diffusion Laboratory of Colorado State University, has been accepted by the Journal of Fluid Mechanics for publicaion in an early issue. A draft copy is attached to this report as Appendix II.

Successful as the modelling laws based on the hypothesis of Lagrangian Similarity appear, they are nonetheless not easy to apply since they depend on some quantities which are well defined, but very difficult to measure in the atmospheric boundary layer. The most important of these parameters are the roughness height z_o and the friction velocity u_* . Both are parameters which also determine the mean-velocity profile, and are usually derived from it by assuming a given shape of the mean velocity distribution. It is well established that for both wind tunnel and field measurements the velocity distribution for neutral stability can be expressed, with a fair degree of approximation, by a logarithmic velocity-distribution law. This has been verified for smooth boundaries and also for rough boundaries where the roughness element height is small compared with the boundary layer, and comparable to the thickness of the viscous sublayer.

If, however, the roughness elements penetrate substantially into the boundary layer -- like crops appear to do -- the validity of a logarithmic velocity-distribution law cannot be taken for granted, and a thorough examination of the velocity distribution within and above the elements has to be performed before any conclusions can be drawn on the quantities z_0 and u_*. Furthermore, the significance of the ground level shear becomes questionable, and the shear representative for the flow above the roughness level may be unrelated to the ground shear in a complex manner. Furthermore, the effective roughness height z_0, which for a rigid and dense assembly of roughness elements appears to depend on the roughness geometry only, will for flexible elements, like plants, become a function of velocity also and cannot be assumed a constant. This increases the difficulty of its definition.

In view of the above features which are pertinent to large and flexible crops, a third problem was investigated, namely the determination of the velocity profile above and within a roughness consisting of large flexible elements. Some initial results of this investigation will be reported on in section 2. They will be extended in the near future to cover some cases of diffusion into this type of boundary.

The fourth problem concerns the effect of the extent of the roughness. As fields of crops do not always extend far enough to permit establishment of fully developed turbulence conditions, and because single rows-shelter belt type obstructions - may have profound effects on the diffusion processes on their lee side, a study was initiated on the diffusion into a boundary layer which is obstructed by a flat plate placed on the wall perpendicular to the flow direction. This program, outlined in the Third-Semi-Annual Report has essentially been concluded. It is reported in section 3.

II. Velocity distribution in and above flexible boundaries

A first step in deciding on the types of flexible boundaries to be used, consisted in studying the literature on field data in order to obtain some information on the properties which such a roughness should have. However, the references are very scarce indeed. The only data found was taken during the 1930's and reported on by Paeschke (as reported by Geiger reference 1) on wind profiles over different crops, some data on wind profiles in tree stands (Geiger, Ref. 1), data reported by Lemon (2) and data taken by Lemon as reported by Tan (3). All these data were presented in raw form. Only the last of the quoted references

(3) contains an attempt at an analytical description. This approach, however, merely resulted in a number of different empirical coefficients which appeared to be valid only for the particular crop (corn or wheat) and velocity of air considered. Considerable efforts were made to reduce these data into a meaningful dimensionless form, but no satisfactory results have been forthcoming.

Convenience was the determining factor for choosing roughness elements. They consist of strips of plastic, flexible material fastened to lumber strips as shown in Fig. 1. The spacing between rows of strips can be varied to permit investigation of variations of geometry, and two different sizes of plastic strips were used. The first data were obtained with plastic strips 0.25" wide, 0.01" thick, and 4" high. They were arranged to face the direction of the wind with their broad side, with a transverse spacing of one element per linear inch, and a spacing in the direction of flow of one row every 2 inches. The results obtained with these elements revealed some interesting features.

The experimental set up is shown in Fig. 2. No velocity measurements were taken in front of the roughness elements. However, it is unlikely that a boundary layer had been developed, at any wind speed, which was thicker than the height of the roughness elements. So any effects of the test-section floor in front of the roughness elements should only be noticeable in the canopy, i.e. within the roughness cover where they quickly would be obliterated by the high shear created by the roughness elements.

An initial experiment was performed in order to determine the geometry of the roughness elements under the action of wind. At no wind speeds, the elements were of curved shape, all elements being deformed approximately by equal amounts, but deflected randomly either to the upwind or the downwind direction. With gradual increase of the wind velocity, the former of the elements would first be straightened somewhat and then deflected downwind, so that at a wind speed of approximately 20 fps almost all elements lean somewhat in the downstream direction. For higher speeds the deflection of the elements by wind becomes more noticeable, the elements become bent down and the height of the roughness cover decreases. This is shown in Fig. 3.

Measurements of velocity profiles were taken at the three stations indicated in Fig. 2. The profiles were repeatable, i.e., for the same ambient wind speed, the same velocity profile could be obtained. This was by no means obvious, since a possibility existed that the roughness elements might fatique with time, under their own weight or under the wind drag. Fortunately, nothing of this nature happened. The velocity profiles are compiled in Fig. 4.to Fig. 6.

Considerable effort was made to correlate, in an empirical manner, the velocity profiles within and above the roughness cover. Within the roughness cover, no systematic profiles could be obtained. The profile is strongly dependent on where the profile was taken between the elements. Furthermore, because of the limited length of the roughened surface, fully established velocity profiles were not obtained. In the near future, it is planned to survey the flow within the cover more extensively and to lengthen the rough surface so that a representative average profile might be obtained.

The velocity distributions above the roughness elements are presented in Fig. 7 in non-dimensional form by plotting the ratio of the local velocity u to the ambient air velocity u_m against the ratio of an adjusted height $z - h$ (where h is the roughness height which is determined from Fig. 3) to the adjusted boundary-layer thickness $\delta - h$. The boundary-layer thickness had to be determined from the velocity profiles, by inspection, since the more accurately defined momentum or displacement boundary-layer thickness could not be determined. This is due to the fact that essentially two different flow regimes exist, the flow within, and the flow outside of the cover, which are nevertheless closely interrelated. Geometrically, these regions can be separated by using the roughness height as limit between the two regimes; dynamically, however, the separation is less easily accomplished, and the adjustment of displacement or momentum thickness for the outer flow is not clear. The results of Fig. 7 are surprising in some respects. The most striking feature is the fact that over the greater part of the boundary layer above the roughness the velocity distribution is almost linear. The second feature of considerable interest is the fact that any type of similarity existed at all, since the complex interaction between the two flow regions made it appear doubtful that the ambient velocity alone would suffice to describe the flow above flexible roughness. No theoretical explanations for these results are offered at this time. It is first required that the experiments be extended, and turbulence measurements be included before an attempt of theoretically interpreting the test results can be made.

The test data do not show much similarity with the available field data. Perhaps this can be attributed to the fact that the velocity distribution is not fully developed over the experimental roughness, and that the experimental roughness does not modify an existing boundary layer, but a uniform flow field. These two possibilities make it advisable to extend the length of the roughened area considerably, and to place the origin of the roughened area in a part of the flow field where the thickness of the undisturbed boundary layer exceeds the height of the roughness elements. This will be accomplished by placing the roughness in the large wind tunnel and pursuing the investigation of the velocity distributions by including turbulence measurements. The costs for this part of the study will be shared by the U. S. Army, through a grant to Colorado State University on the investigation of the nature of aerodynamic roughness. Only after these measurements are made, will a line source of ammonia be introduced. The diffusion study within and above the flexible roughness and their interpretation and comparison with field data will conclude the work under the present contract. The results of this phase will be presented in a Ph.D. Dissertation.

III. Diffusion in a boundary layer disturbed by a flat plate.

The diffusion study on the effect of a plate located perpendicular to the flow on the smooth wind-tunnel floor has been reported on to some extent in Semi Annual Report No. 3. Since then, more data have been taken to determine the effect of distance between plate and source on the diffusion at a large distance from the plate. The data showed considerable scatter, and no conclusions could be drawn on this question; however, it appears that the scatter is random so that the distance between source and plate does not enter as a parameter determining the diffusion process.

A great majority of all velocity profiles were taken. However, calculations based on the mean velocity profiles were not always satisfactory, and as soon as the large wind tunnel is ready to operate some of the tests shall be repeated. Future experiments on the velocity profiles shall include measurements of turbulent intensities and their spectra.

A theoretical analysis of the concentration field is extremely difficult, if not impossible, and the only way to producing meaningful conclusions lies in developing an empirical approach based on inspection of the experimental data. The most fruitful approach seemed to assume that similarity exists between concentration profiles; that is, that all profiles could be expressed in the form:

$$C = Af(\xi) \tag{1}$$

where C is a dimensionless concentration,

A is a prarmeter which may depend on the flow field but is independent of height and concentration,

ξ is the dimensionless height, and

$f(\xi)$ is a universal function of dimensionless height only.

As was shown in Progress Report No. 3, at a distance far downstream from the plate equation 1 is approximately true, and that report presented definitions of the similarity parameters and the profile shape $f(\xi)$. The similarity parameter for the concentration profile was chosen to be the maximum concentration C_{max} and the similarity parameter for the height was assumed to be that height at which the concentration had dropped to one half the maximum value. A plot of these parameters as functions of the variables of the flow field versus the distance from the source had been presented in Progress Report No. 3, and well defined trends were established.

As a next step in the analysis, the profile shape was investigated. Based on previous analysis (See Appendix I), a profile function of the following form was assumed:

$$f(\xi) = e^{-\xi^{\alpha}} \tag{2}$$

where the exponent α would have to be determined experimentally. Two ways are open for this determination. The first would be to plot the concentration versus the logarithm of the dimensionless height on log-log paper, and visually fit in a best fitting straight line whose slope would yield the exponent α. The second one would be to do the curve fitting analytically by using a digital computer. The latter way was chosen, and the equation

$$\frac{C}{C_{max}} = e^{-B \ln 2 \left(\frac{y}{\lambda} \right)^{\alpha}} \tag{3}$$

was used for regression analysis in which B and α are the constants which have to be determined from a best fitted line, and the coefficient $\ln 2$ has been introduced to satisfy the condition that at $y = \lambda$ the concentration $C = \frac{1}{2} C_{max}$. In order to make a linear regression analysis possible, the method of least squares was applied to a linear form of equation 3 which is obtained by twice taking the logarithm of both sides:

$$\ln \left[\frac{\ln \frac{C_{max}}{C}}{\ln 2} \right] = \ln B + \alpha \ln \frac{y}{\lambda} \tag{4}$$

Essentially, the factor B can be incorporated into λ to yield a better estimate of λ than the one originally used. The slope was found to be extremely sensitive to small changes in concentration values; or the other way around, the value of α can vary considerably without materially affecting the shape of the curve. No systematic trend could be detected in the scatter of the α - values, and consequently this type of regression analysis was not very informative.

In order to improve the analysis it was assumed that the effect of the plate would be to shift the peak concentration upward by a value h_o which would be a function of plate height, station, and flow variables and which had to be determined experimentally. Since for a simple regression analysis only two constants are disposable, the equation of the profile with inclusion of the zero shift

$$\ln \left[\frac{\ln \frac{C_{max}}{C}}{\ln 2} \right] = \ln B + \alpha \ln \frac{y - h_o}{\lambda - h_o} \qquad (5)$$

had to be approached in a slightly different manner. Starting from the case of equation (4) ($h_o = 0$) h_o was varied in small increments until the mean-square deviation from the curve reached a minimum value. The corresponding h_o was to be further analyzed. However, the uniqueness of the minimum value of the mean-aquare deviation was questionable, and the trend indicated by the machine calculations resulted in considerably larger scatter of the slopes α than the previous program had shown. Therefore, in a final attempt, the slope α was arbitrarily held fixed at the value 1.8 found by previous investigations of concentrations in the boundary layer (see for example Appendix I.) and the fitting was repeated with only B as disposable constant. The evaluation of this analysis is still in progress.

Future work on this program shall consist of velocity and turbulence measurements, and of repeating some of the experiments on concentrations. Also, a run with higher velocity than the previous runs will be made. The results of this study shall be used for a Ph.D. Dissertation.

IV. References

1. Geiger, R. "The climate near the ground", Harvard University Press, Cambridge, Mass. 1957.

2. Lemon, E. R. "Photosynthesis under field conditions II: An aerodynamic method for determining the turbulent carbon dioxide exchange between the atmosphere and a corn field." Agronomy Journal, Vol. 52, p. 697-703, 1960.

3. Tan, H. S. and Ling, S. C. "A Study of atmospheric turbulence and canopy flow" Therm Advanced kResearch Report 611, February, 1961, Ithaca, New York

FIGURES

Figures

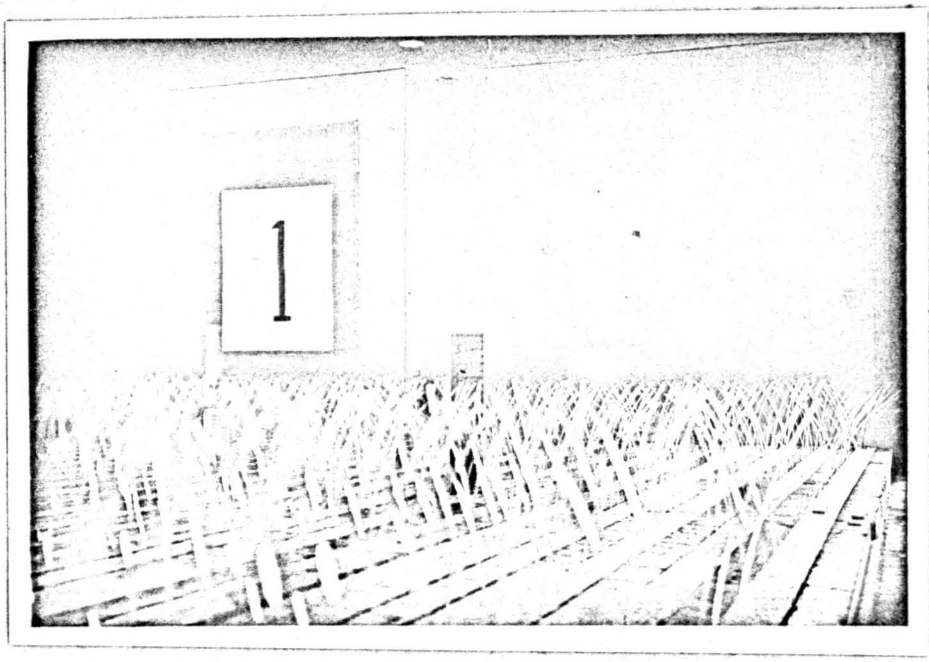

FIG. 1 FLEXIBLE ROUGHNESS ELEMENTS

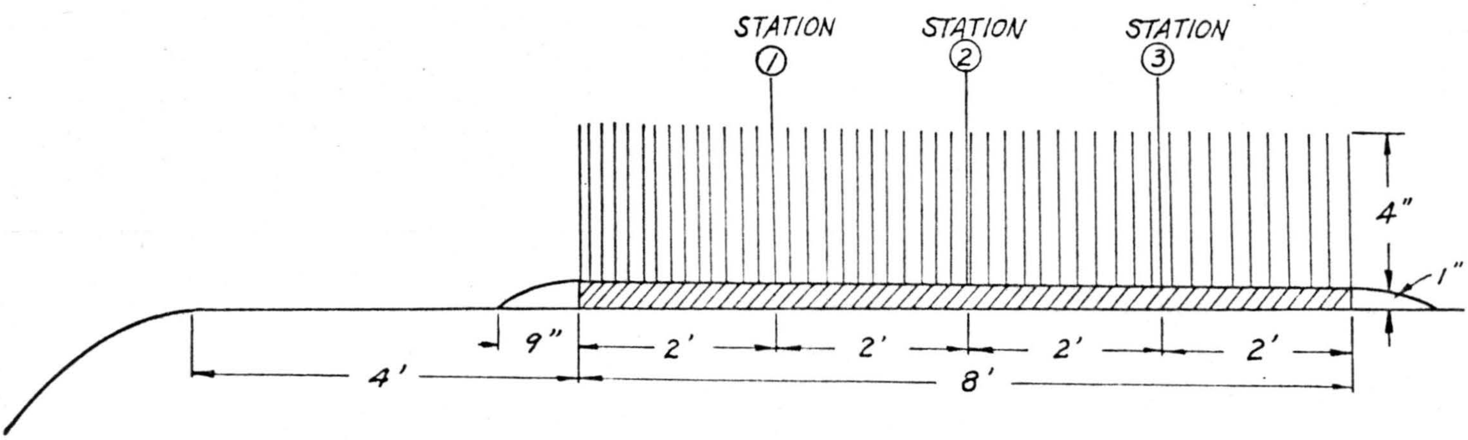

FIG. 2 EXPERIMENTAL ARRANGEMENT SHOWING ROUGHNESS AND STATIONS WHERE VELOCITY MEASUREMENTS WERE TAKEN

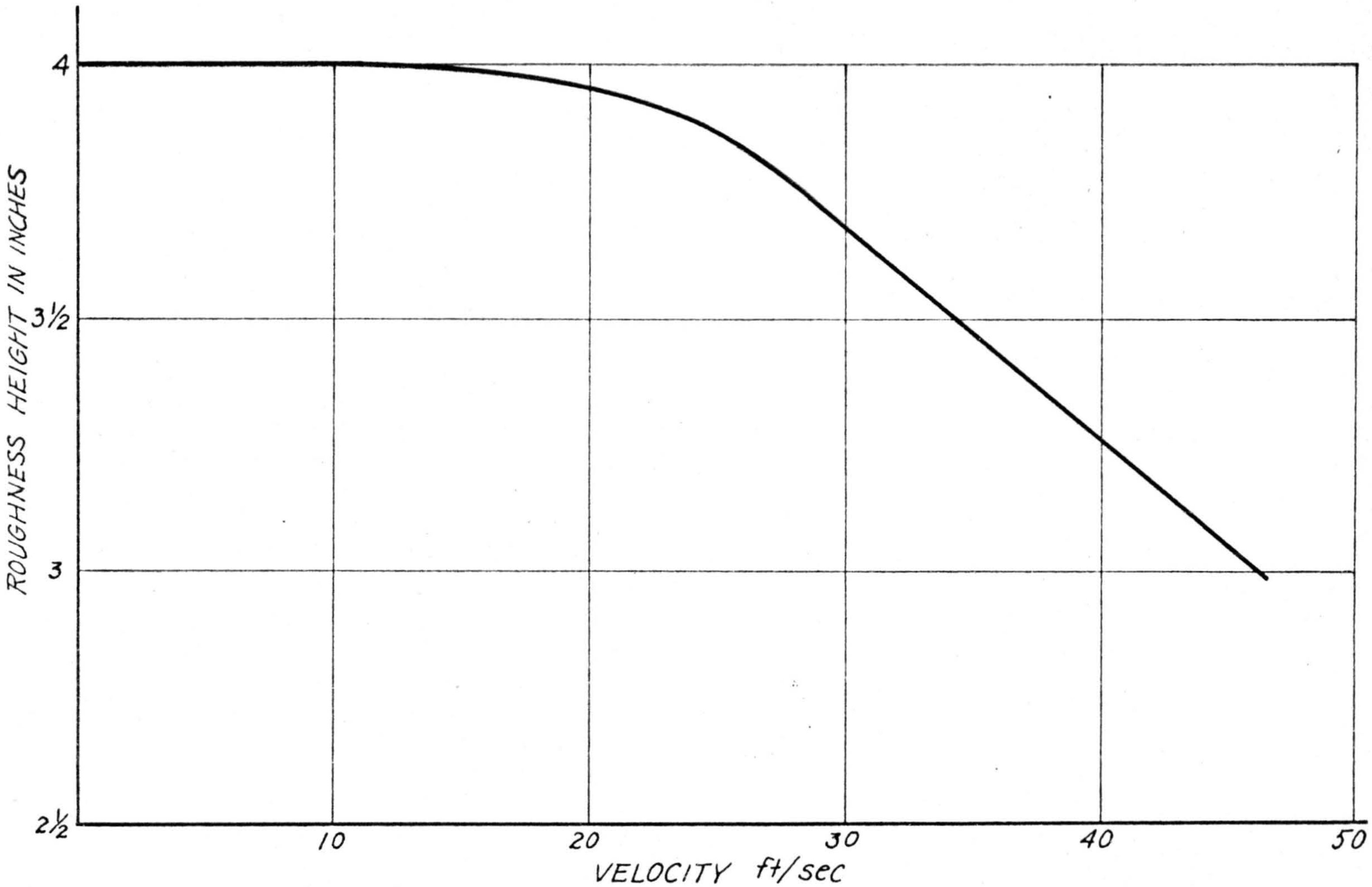

FIG. 3 CHANGE OF FLEXIBLE ROUGHNESS HEIGHT WITH WIND VELOCITY

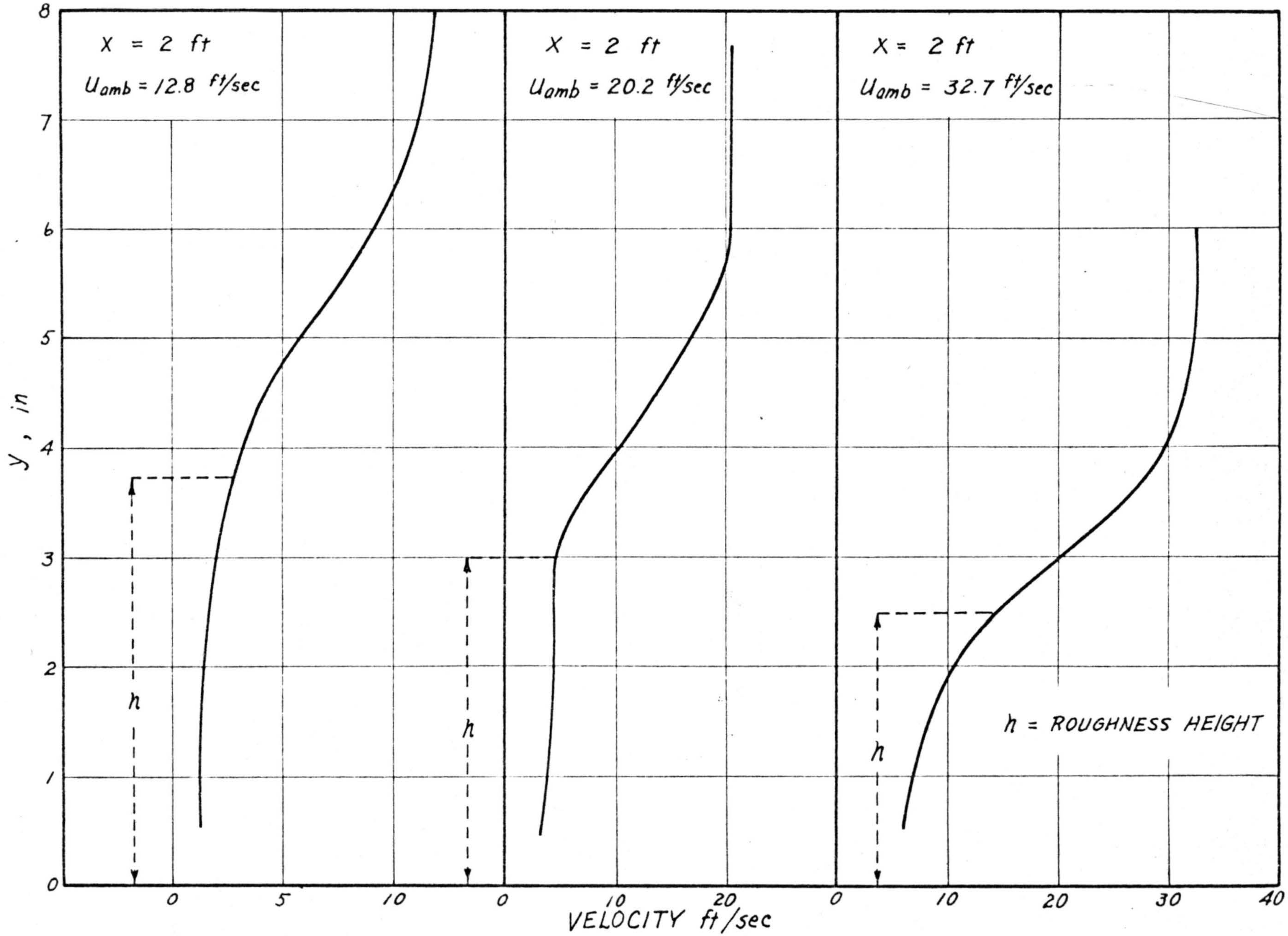

FIG. 4 VELOCITY PROFILES IN AND ABOVE FLEXIBLE ROUGHNESS: STATION I

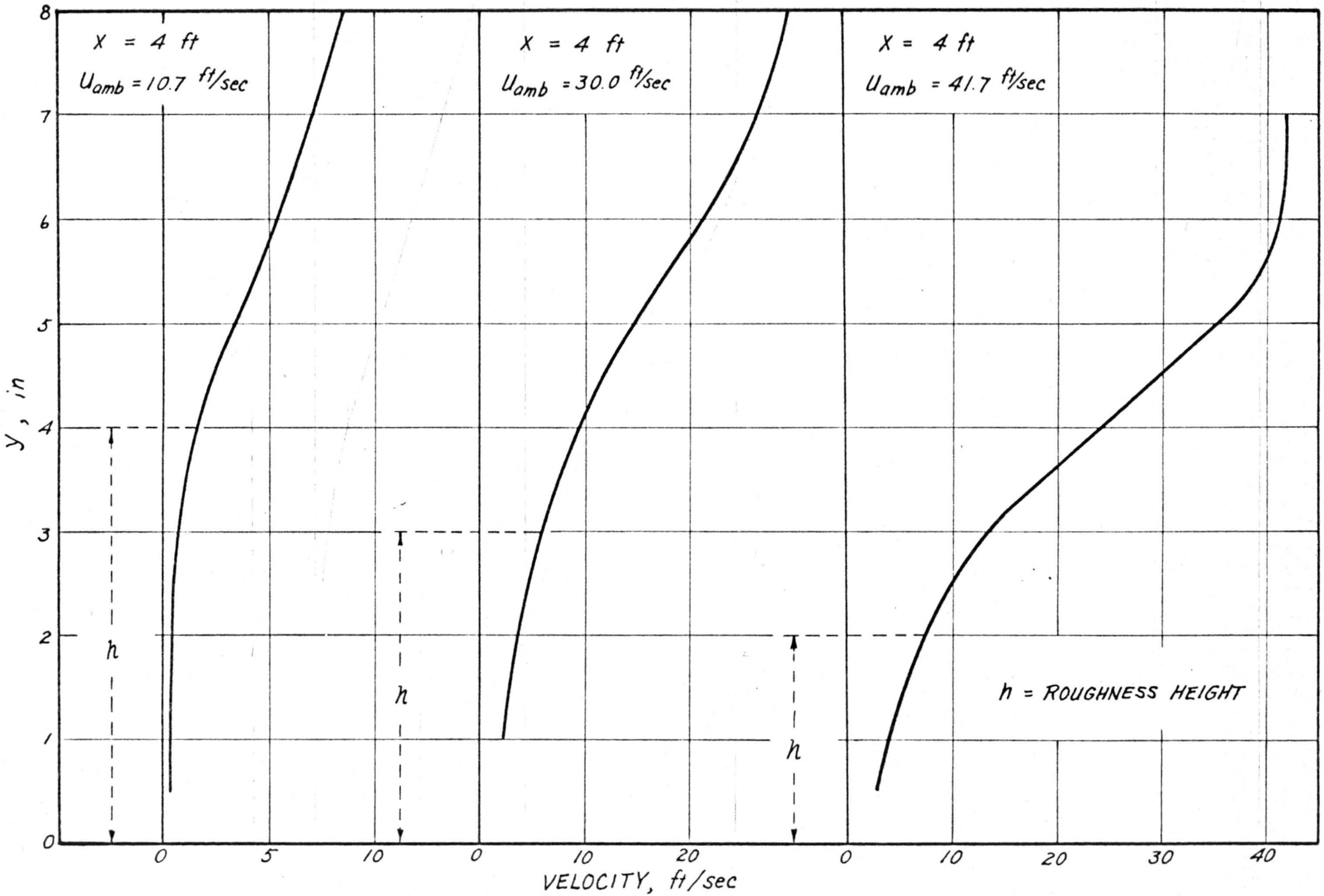

FIG. 5 VELOCITY PROFILES IN AND ABOVE FLEXIBLE ROUGHNESS: STATION 2

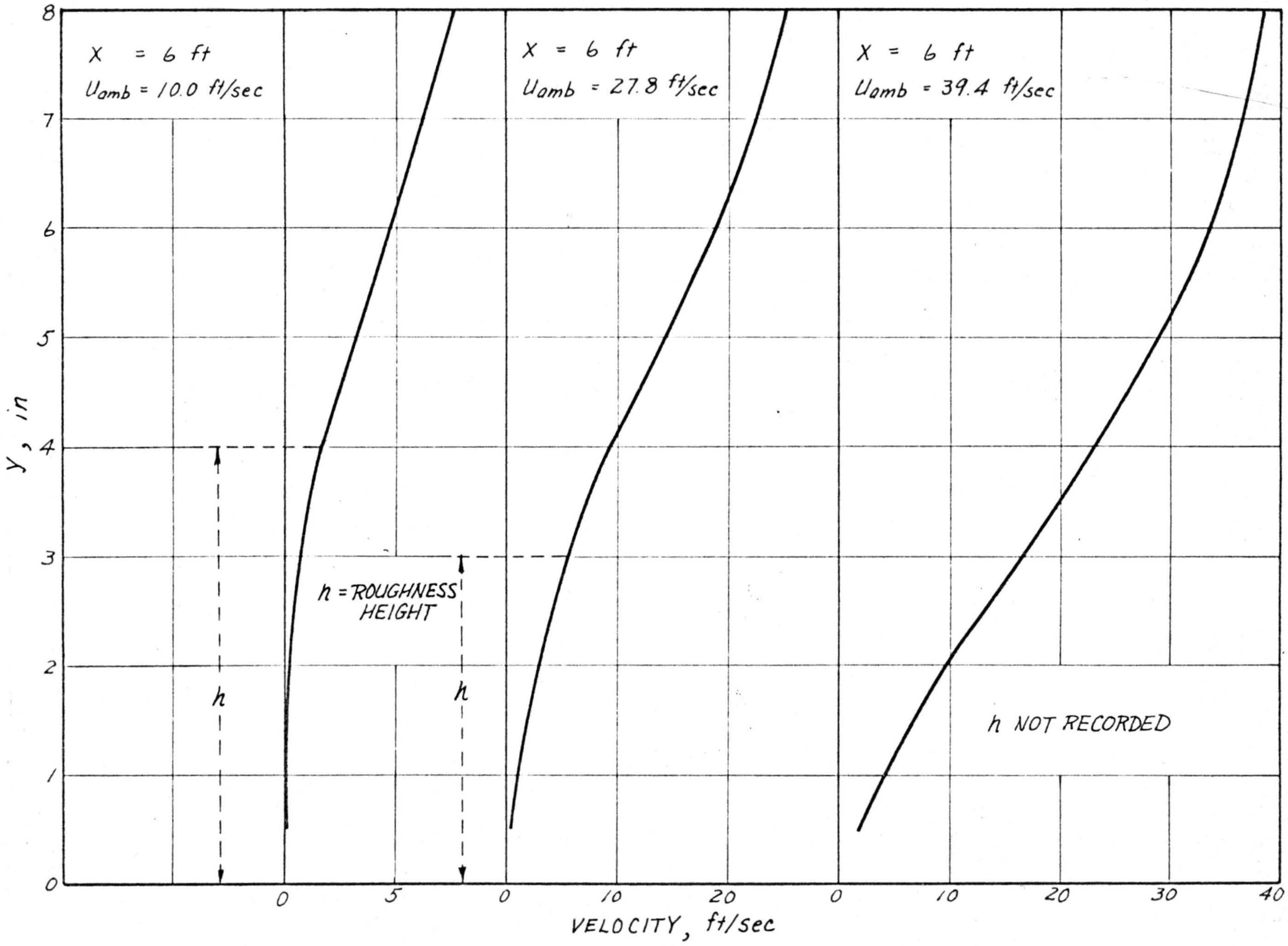

FIG. 6 VELOCITY PROFILES IN AND ABOVE FLEXIBLE ROUGHNESS : STATION 3

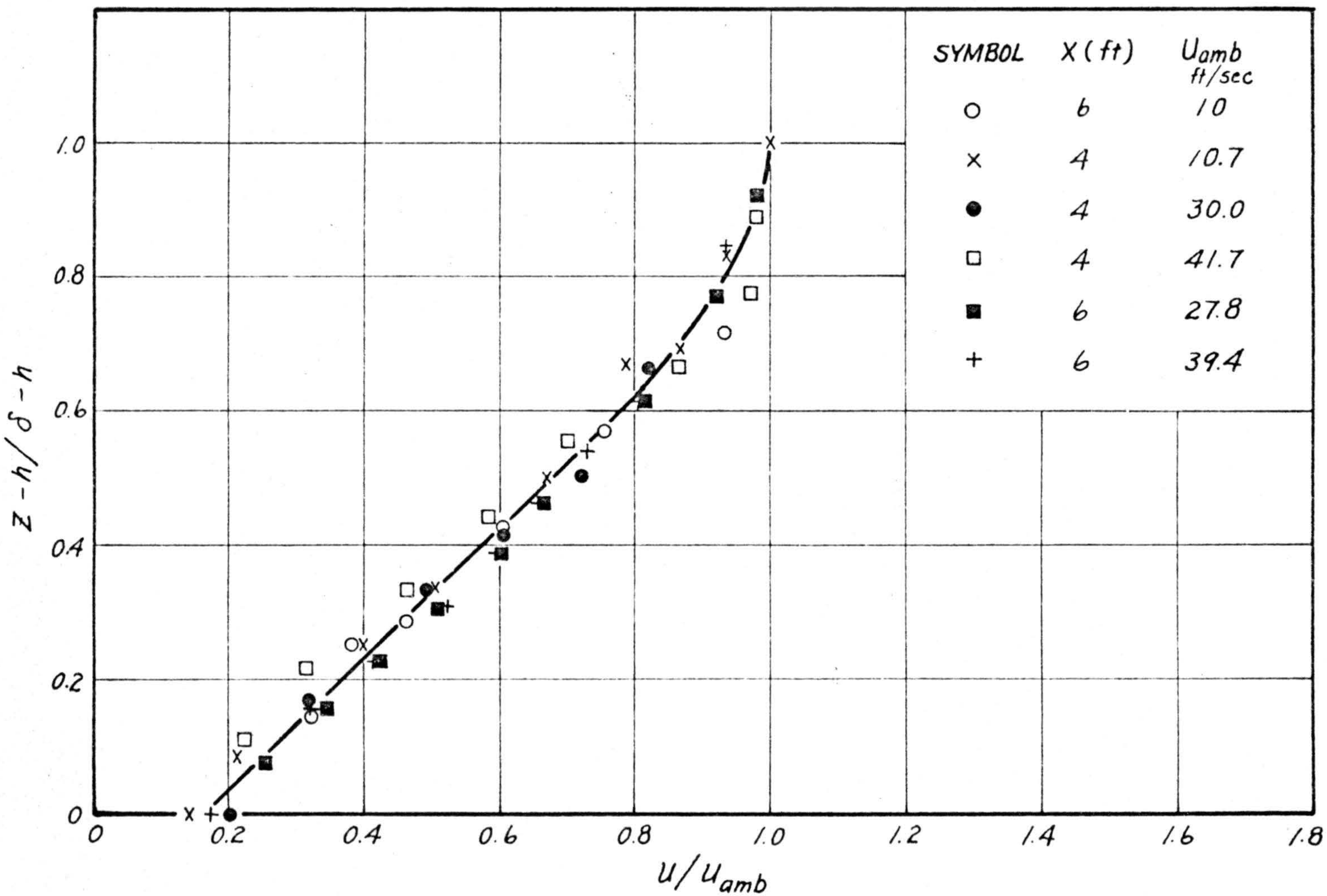

FIG. 7 DIMENSIONLESS PROFILES OF VELOCITIES ABOVE FLEXIBLE ROUGHNESS