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Study of Large-Scale Mixing in Developing Wakes Behind Streamlined Bodies

Final Technical Report
by
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ABSTRACT

Heat-tagging and conditional sampling techniques have been used to study the large-scale mixing process in the developing wake behind a streamlined body. The results have been used to understand the manner in which the large-eddy length scale evolves from a value appropriate to a boundary layer to that appropriate to the asymptotic far-wake.

*The NASA Technical Officer for this Grant is Dr. J.G. Marvin, of NASA Ames Research Center, Moffet Field, California.

N84-21517#

I. INTRODUCTION

This project was started in July 1981 as a continuation of an earlier research on two-dimensional wakes also carried out under NASA support (Grant NSG-2300). This earlier research [1] showed that the developing two-dimensional wake behind a streamlined body can be divided into three regimes, namely the 'near-wake' extending over a downstream distance x of approximately 25 momentum thicknesses (θ) from the trailing edge, the 'intermediate wake' extending over the region $25 \lesssim x/\theta \lesssim 350$ and the 'far-wake' extending beyond $x = 350\ \theta$. Detailed measurements showed that the turbulence structure of the flow is not in equilibrium in the region $x = 350\ \theta$ even though the mean velocity distributions appear to be nearly self-preserving. It is also well known that the existing turbulence models do not give good predictions of the asymptotic spread and decay rates of two-dimensional wakes. The predictions can be improved only if the nonequilibrium structure of turbulence can be adequately modelled.

The nonequilibrium of the turbulence structure is believed to be due to the slow development of the large eddy structure of the far-wake from that corresponding to the boundary layers on the two sides of the wake generator. In order to understand the evolution of the large scale structure it is necessary to study the process of mixing between the two boundary layers in the development region of the wake.

Andreapoulos and Bradshaw [2] studied the interaction of the boundary layers in the near-wake of a flat plate. They used the technique of 'heat-tagging' i.e., heating one of the boundary layers slightly with thin electrically heated wires embedded upstream in the boundary layer. Using temperature as the passive tracer, they studied the process of fine-grain mixing in the inner part of the near-wake, employing conditional sampling techniques. Their study included both symmetric and assymmetric wakes. In the latter case, assymmetry was produced by artificially roughening one side of the plate. Based on the study of the fine-grain mixing process, they were able to introduce additional physics into the modeling of the inner wake of the plate. Their experiments did not, however, cover the outer intermittent region of the wake nor did they extend beyond about 50 momentum thicknesses downstream. Hence, information on large-scale mixing and evolution of the large structure in the wake cannot be obtained from these experiments.

The main objective of the present study was to extend the heat-tagging technique to the outer part of the wake as well as the intermediate wake so that the 'large-scale' mixing process in this region can be investigated. While the general approach was similar to that of Andreapoulos and Bradshaw, significant differences exist between the two studies with regard to both the experimental technique and the analysis of the results.

The present experiments were conducted in the symmetric wake of a flat plate. The measurements extended upto about 260 momentum thicknesses downstream of the trailing edge. Unfortunately, it was not possible to complete the experiments on an asymmetric wake within the grant period. These experiments will, however, be completed in the next few months under internal support. The work done so far has resulted in an M.S. thesis and the continuing work forms a part of a Ph.D. thesis. The experiments completed during the grant period and the results obtained from them are described below. The work completed so far has generated enough interest that it is being pursued beyond the Grant period, under internal support. A more detailed documentation and analysis of the present experimental results will be presented in a forthcoming departmental report.

II. EXPERIMENTAL ARRANGEMENT

II.1. Apparatus and Model

The experiments were conducted in the closed circuit, open-jet, low speed wind tunnel of the Iowa Institute of Hydraulic Research. The test section has a 0.5 m regular octagonal cross-section formed by gradual transition from a 1.8-meter square approach section. The test section is 1 meter long. There is no measureable longitudinal pressure gradient in the test section. The freestream turbulence is about 1% at the maximum tunnel speed. This is large but as will be seen later is irrelevant to the flow under study.

Figure 1 shows the details and dimensions of the wake generator (referred to as an 'airfoil' henceforth) used for the experiments. It is a flat plate 45 cm x 90 cm x 2.5 cm with the last 15 cm of its length tapered to end in a pointed trailing edge. The airfoil is placed in the midplane of the tunnel working section. The boundary layers on both sides of the body are tripped by means of 2-mm dia wires glued to the surface at 12 cm from the leading edge.

II.2. Instrumentation

For mean-velocity measurements a total head tube of 0.71 mm outer diameter was used. Hotwire anemometry was used for turbulence measurements. Two Disa 55 M01 anemometers were used in conjunction with a P51 cross-wire probe. A thermistor probe connected to a calibrated digital thermometer with an accuracy of .01°C was used to measure the tunnel temperature. The mean and fluctuating temperatures in the wake were measured differentially (with respect to the 'freestream') using resistance thermometry. A pair of Disa P31 probes were used as 'cold-wire' probes for this purpose. The frequency response of the temperature instrumentation (about 2KHz) is more than adequate for the study of large scale structure. The data acquisition system consisted of an HP1000 minicomputer and a Preston Analog to Digital Converter. Instantaneous voltages from the temperature bridge and the two cross-wire probes were simultaneously sampled, digitized and stored on disk. These data were processed to obtain the mean and fluctuating quantities, double and triple correlations and conditionally averaged results.

II.3. Heating Technique

Conditional sampling requires that one of the boundary layers be tagged by heating it. At first this heating was accomplished by a method similar to that used by Andreopoulos and Bradshaw [2]. This method proved to be unsatisfactory for studies in the intermediate wake and in the outer part of the near-wake. This is because this method of heating does not result in a region of uniform high temperature beyond the wake. A modified heating technique which would provide a reasonably 'constant-high-temperature' region on the heated side of the airfoil was therefore to be developed. After several trials, the heating configuration shown in Fig. 1. was arrived at. Twelve nichrome resistance wires of 0.5 mm diameter, extending over the span of the airfoil and spaced 6 mm apart were placed on each side of the airfoil at about 20 cm from the leading edge in a plane perpendicular to its surface. All the wires were spring-loaded so that they would remain straight when heated. The wires on one side of the airfoil were heated electrically. The wires on the other side merely served to provide flow symmetry. The heating wires were connected in 3 parallel branches with each branch having 4 wires in series. Each wire had a resistance of approximately 5 ohms. Thus, this arrangement would draw a power of about 1.7 kW at 110 volts. With this arrangement, a temperature difference of nearly 1.2 C was obtained between the heated and unheated streams at the trailing edge at a tunnel velocity of 13 m/sec. This amount of heat was found to be sufficiently large to provide the required discrimination between "hot" and "cold" fluid, yet small enough not to introduce buoyancy effects. The drag on the wires resulted in a 'wake' behind each wire. However, these individual wakes merged with one another and the flow at the trailing edge [about 900 wire diameters downstream] was found to be 'well mixed' with regard to temperature distribution. Figure 2 shows schematically the flow conditions at any station in the wake and explains the wake nomenclature used henceforth. Note that the 'freestream' for the airfoil wake has a slightly smaller velocity than the undisturbed flow in the tunnel. It was found that even at the last measurement station in the wake, there was a 'freestream' of about 3 cm in width in which the velocity U_{fs} was constant. U_{fs} remained practically constant in the x-direction. The turbulence level in the 'freestream' was about 1.2%. This is high and is one of the shortcomings of the present design. However, the shear stress in this stream was almost zero (in fact, it could not be detected). It is also to be noted that since the wake is not surrounded directly by the rest of the tunnel fluid, the tunnel turbulence characteristics are irrelevant to the behavior of the wake. The half-width, 'b', velocity defect 'W' and the momentum deficit thickness θ of the wake are all defined relative to the freestream velocity U_{fs}. Thus

$$\theta \equiv \int_{-\infty}^{\infty} \frac{U}{U_{fs}} (1 - U/U_{fs})\, dy$$

The value of θ at the trailing edge was about 2.6 mm.

The experimental set-up, instrumentation, and the design of the heating system are discussed in detail in the M.S. thesis of Kalale [3] and also in Ramaprian, Kalale and Kaushik [4].

II.4. Experimental Procedure

Initial experiments were performed to determine whether the presence of the wires placed perpendicular to the airfoil affected the behavior of the wake. These experiments were conducted first by measuring mean velocity profiles at eight stations in the wake [$0 < x \lesssim 670$ mm or $0 < x/\theta \lesssim 260$] using a total heat tube, and later the turbulent properties using the x-wire probe. In these experiments, the resistance wires were not heated. Next, the wires on one side of the airfoil were heated and the experiments repeated to determine whether any changes were measured. Since the temperature increase in the wake is too small to cause any changes in the flow, agreement between the two sets of experimental results is a verification of the accuracy of the calibration and data processing procedure. In the experiments to measure turbulence properties in the 'cold flow', signals from the three sensors were sampled simultaneously at the rate of 50 samples per second to obtain 2560 samples per channel. This corresponds to a record length of 51 seconds for each channel. In the experiments with the wires heated, the number of samples were increased to 5120 per channel. In both the cases, the signals were not low-pass filtered.

The final set of experiments were conducted at the same x-locations as the previous experiments. These data were stored on tape and were later used for estimating conditional averages. In these experiments, the voltage output from the three channels were first low-pass filtered at 1000 Hz using sharp cut-off (32 db/octave) analog filters and were then sampled by the computer at the rate of 2000 samples/sec. These 'low' sampling rates are required in order that the low-frequency end of the energy spectrum can be studied in detail (so that information on the large eddies can be obtained). However, low-pass filtering unavoidably results in some loss of information because of the removal of the higher frequencies in the signal. But, such loss of information was found to be less than 5% of the mean square value. This is not serious especially since the interest is primarily in the larger eddies. The data were acquired in 8 batches of 5120 samples per channel per batch. The samples in each batch were continous (i.e., with no break) while there was a record gap of about 6 secs between two successive batches. The overall length of the 8-batch record (including gaps) was about 60 secs.

III. RESULTS AND DISCUSSION

III.1. Results of Initial Experiments

As already mentioned, the initial experiments were conducted to study the behavior of the wake and the performance of the instrumentation. The behavior of the wake in the presence of the wires is documented in detail in Ramaprian, Kalale and Kaushik [4].

Figures 3(a) and 3(b) show as typical examples, the variation of the half-width b and the maximum velocity defect, W_o along the wake. The results are compared with those of Sastry [5]. The lines with slopes corresponding to the asymptotic growth rate are also shown. It is seen that the present wake behaves 'normally' and that it has not quite reached full development (as expected) at the last station, namely $x/\theta \approx 260$. The nondimensional defect velocity distributions shown in Fig. 4 (obtained from total head tube) indicate that the wake is symmetric and is almost 'fully developed' in terms of the mean velocity beyond $x/\theta \approx 20$. Thus, it can generally be concluded, that the presence of the wires has not disturbed the mean flow properties in the wake in any significant manner.

The behavior of the turbulent properties in the wake is seen typically from Fig. 5. The data shown in this figure refer to the Reynolds shear stress ($-\overline{uv}$) and were obtained from the first set of experiments with the heating turned on. Note that negative y corresponds to the unheated side and positive y corresponds to the heated side. The gradual increase of the magnitude of the nondimensional shear stress, $|\overline{uv}/W_o^2|$ along the wake towards the universal far-wake value is as expected. Any lack of antisymmetry noticed in the distributions are due to inadequate correction for temperature sensitivity of the hot-wire sensors. This is most probably due to the physical separation between the hot-wire and temperature sensors (note that the temperature measured by the temperature sensor approximates to the air temperature at the hot-wire sensor location only if the two sensors are 'very close' to each other). These discrepancies, however, are generally not large. For example, the departure for symmetry of $\overline{uv}/W_o^2$ in Fig. 5 is about 10%. This is considered to be not serious for the purpose of the present study. It may also be noticed that there is no significant shear stress in the free stream and that the "freestream" turbulence level is not very large. The average value of $|\overline{uv}/W_o^2|_{max}$ for the two sides at the last station is about 0.045 which can be compared with the asymptotic value of about 0.048. After insuring from the initial experiments that the behavior of the flow and the performance of the instrumentation were both acceptable (even if not ideal), the final set of experiments were performed.

III.2. Cold-hot Intermittency

The instantaneous velocity and temperature data obtained during these experiments were stored and later used to obtain the 'cold-hot' intermittency in the wake and hence several conditionally averaged properties. Figure 6 shows a schematic sketch of the temperature-time record. In principle the probe location can be considered to be occupied by the (unmixed) cold fluid if $\Delta T = 0$ and by the (unmixed) hot fluid if $\Delta T = \Delta T_{max}$. If neither of these conditions is satisfied, it is occupied by the mixed or 'warm' fluid. In practice, however, the presence of noise in the 'cold' stream and turbulent fluctuations in the 'hot' stream necessitate that a 'low' threshold level $\Delta T_L > 0$ and a 'high' threshold level $\Delta T_H < \Delta T_{max}$ be set as shown in the figure. Hence if $\Delta T < \Delta T_L$ the fluid is considered to be 'cold' and if $\Delta T > \Delta T_H$, it is considered 'hot'. The fluid is 'warm' during the remaining instants. A computer program was developed to analyze the recorded temperature data and sort them into 'cold', 'hot' and 'warm' categories for specified values of ΔT_L and ΔT_H. If f_c, f_h, and f_w are respectively the fractional number of 'cold', 'hot', and 'warm' samples collected, one can define a mixing intermittency Ω_{nc} as

$$\Omega_{nc} = \frac{1-f_c}{f_h+f_w+f_c} = (1-f_c).$$

Ω_{nc} is a measure of the fractional period for which the fluid is <u>not cold</u>. $\Omega_{nc} = 1$ represents that no uncontaminated fluid from the cold side reaches the probe; while $\Omega_{nc} = 0$ means that the probe is within the cold fluid all the time. A complimentary intermittency Ω_c, which is a measure of the fractional period for which the fluid is <u>cold</u> can be defined as

$$\Omega_c = 1 - \Omega_{nc} = f_c$$

Corresponding definitions, Ω_{nh} and Ω_h can be introduced for <u>not hot</u> and hot fluid in the following way

$$\Omega_{nh} = \frac{1+f_h}{f_h+f_w+f_c} = 1 - f_h$$

$$\Omega_h = 1 - \Omega_{nh} = f_h$$

Note that Ω_{nc} depends on ΔT_L and Ω_{nh} depends on ΔT_H. Figure 7 shows some typical results for intermittency Ω_{nc} obtained with different threshold settings (ΔT_L) at four different locations across the wake at x = 670 mm. Obviously the 'correct' threshold level should be around 0.25 in this figure since, the intermittency has to be zero at the 'cold' edge of the wake. There is some subjectivity involved in the selection of a specific value for ΔT_L and this results in some uncertainty in the value of Ω_{nc} estimated. In the typical illustration in Fig. 7, it is seen that this uncertainty is small at $y/\theta = -16$ but rather large at $y/\theta = -6.5$. After several trials, it was decided to set $\Delta T_L = 3t_c$ where t'_c is the rms "turbulence" intensity of temperature fluctuations in the cold "freestream". Similarly, ΔT_H was set equal to $3t'_n$ where t'_h is the rms turbulence intensity of temperature fluctuations in the hot freestream.

Figures 8 and 9 show typical distributions of the intermittencies Ω_c and Ω_{nc} as well as the various conditionally, and conventionally averaged turbulence properties. The results are shown for the 'cold' side of the wake only. These results can be reflected suitably for the 'hot' side. Results are shown for 4 x/θ locations. Also shown in Figs. 8(a)-8(f) are the mean temperature excess distributions across the wake. It was found that there was a slight error in the location of the wake axis (y = 0 line). This error was of the order of 1 to 2 mm. Figures 8 and 9 have been drawn by assuming the y = 0 line to coincide with the point where $\Delta T/\Delta T_{max} = 0.5$. There is thus an uncertainty of about 1-2 mm ($y/\theta = 0.4$-0.8) in the y-location of the data points.

The intermittency distributions clearly show how the 'hot' fluid continuously encroaches into the cold fluid as the wake develops. It is seen that the "cold-not cold" interface is very sharp at $x/\theta = 17$, indicating very little large-scale mixing at this station. On the other hand, there is a wide region of partially mixed fluid in the downstream locations. The value of $\Omega_{nc} = 1$ indicates that mixed fluid is present all the time. It is seen that the width of this region continously increases as x/θ increases. The distance from the wake axis at which Ω_{nc} goes to zero at a given x-location, is approximately a measure of (half) the largest size (L_W) to which the eddies in the wake have evolved from the trailing edge upto that location. On the other hand, the distance (L_{bL}) from the edge of the wake (detected preferably from the turbulent shear stress profile) to the point where $\Omega_c = 0$ is a measure of the largest eddies present in the unmixed fluid. This fluid can be regarded as belonging to the upstream boundary layer or as being entrained from the ambient by the outer part of the wake.

III.4. Conditional Averages

Conditionally averaged values of the Reynolds stresses u'^2, v'^2 and $\overline{uv}$ are defined in the same way as in Andreapoulos and Bradshaw [2]. Thus, for example, $\overline{uv}_c$, $\overline{uv}_{nc}$ are defined as the contributions to the total shear stress $\overline{uv}$ from the 'cold' and 'not cold' (hot plus warm) fluid respectively. On the unheated side of the wake, these correspond respectively to unmixed and mixed fluid. In these definitions, u and v refer to fluctuations from the conventional mean velocities $\overline{U}$ and $\overline{V}$. Hence $\overline{uv}_c + \overline{uv}_{nc} = \overline{uv}$, etc.

Figures 9(a)-9(f) show, as typical examples, the distributions of the conditionally averaged Reynolds shear stress across the wake at four x-locations. While the intermittency distributions indicate the time-sharing between the 'boundary-layer' and the 'wake' fluid, the distributions of the conditional averages provide additional information such as the contributions to the time-averaged shear stress from these two sources. The area under $\overline{uv}_c$ distribution, for example, can be regarded as the strength of the boundary-layer-like component of the flow while twice the area under the $\overline{uv}_{nc}$ - distribution represents the strength of the wake-like component in the flow. Normalizing both areas by $\overline{uv}/w_o^2$ will yield nondimensional length scales l_b^* and l_w^* which can be regarded as the weighted integral length scales for the two flow components. On the other hand, the overall widths of these two distributions are measures of the large eddy scales L_b and $L_{w/2}$ of these flow components.

Based on the above experimental observations one can visualize the developing wake as qualitatively schematized in Fig. 10. Notice the overlap between the boundary-layer-like and wake-like regions. The quantitative evolution of the eddy scales L_b and L_w are shown in Fig. 11. The large eddy scale L_b starts from the obvious value L_δ corresponding to the upstream boundary layer and grows until $x/\theta \approx 150$, beyond which it ceases to grow. The scale L_w however continuously grows with x/θ. The dotted line represents the length scale of the largest eddies in the flow. These eddies belong to the boundary-layer like region in the region $x/\theta \lesssim 50$ and to the wake-like region for values of $x/\theta \gtrsim 150$. It is necessary to recognize this fact while attempting to model the developing wake. These data are still being carefully analyzed at this time. Also no attempt has so far been made to model the flow. Work will proceed in this direction in the coming months.

IV. CONCLUSIONS

The present investigation has provided interesting details about the time-sharing between the outer boundary-layer-like region and the inner wake-like region of the developing wake behind a streamlined body. The study has shown that the effective largy eddy scale evolves from a size appropriate to the boundary layer flow to that appropriate to a wake as the wake develops in the downstream direction. It may be necessary to incorporate this information into the turbulence model, in order to obtain an accurate prediction of the wake behavior. This research effort is continuing and more detailed results will be reported in forthcoming publications.

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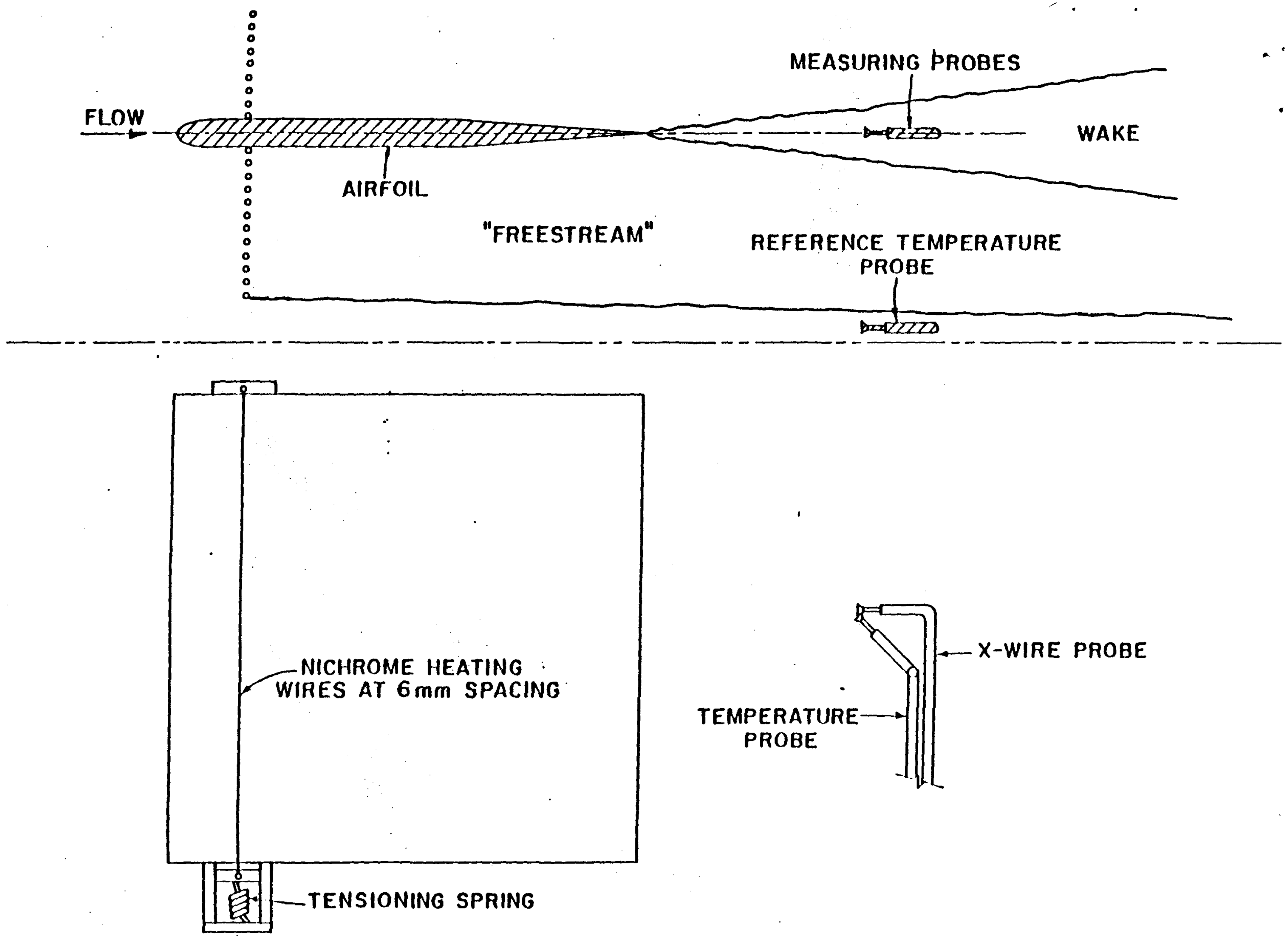

Figure 1. Final heating arrangement.

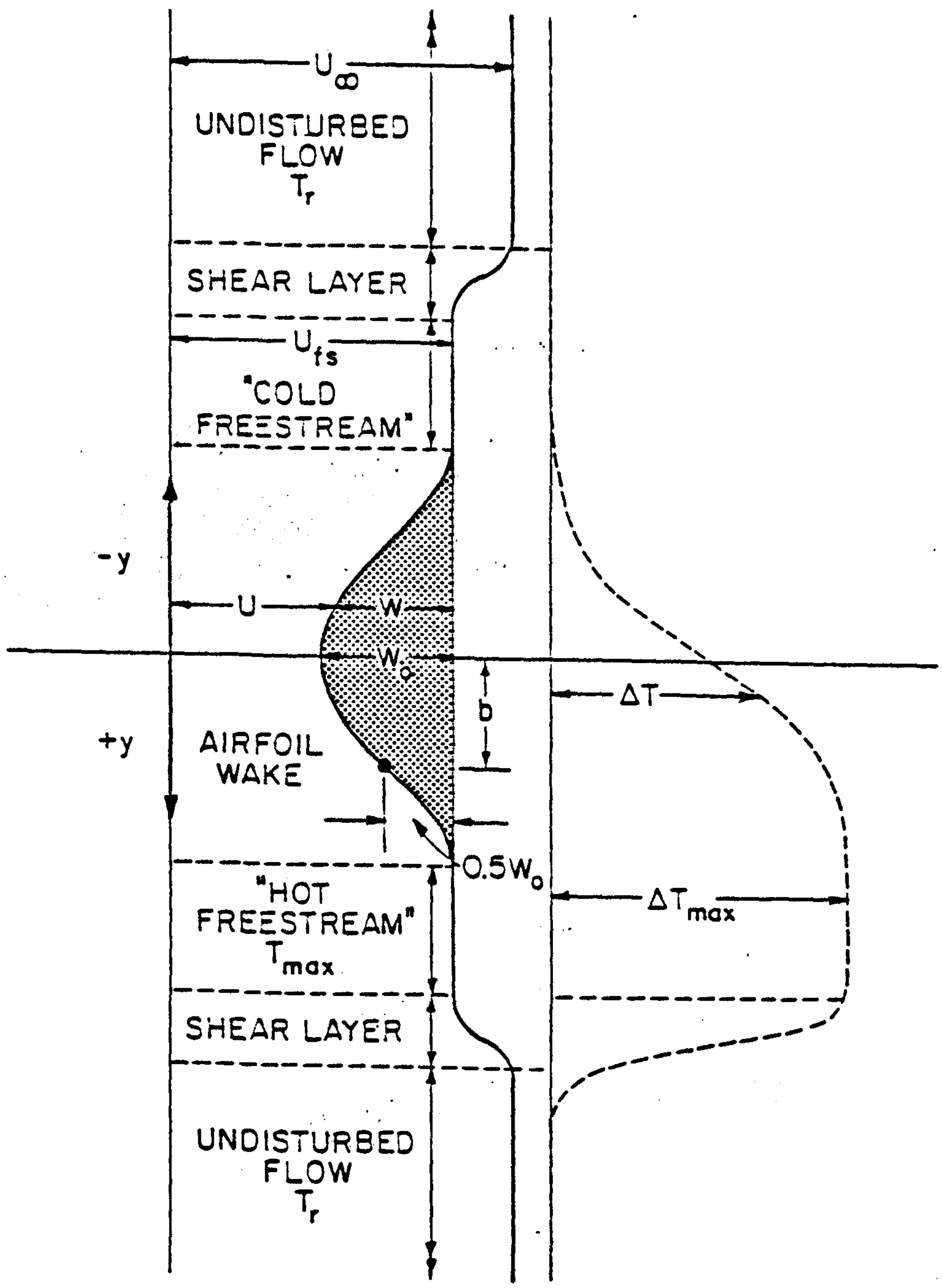

Figure 2. Flow configuration and nomenclature.

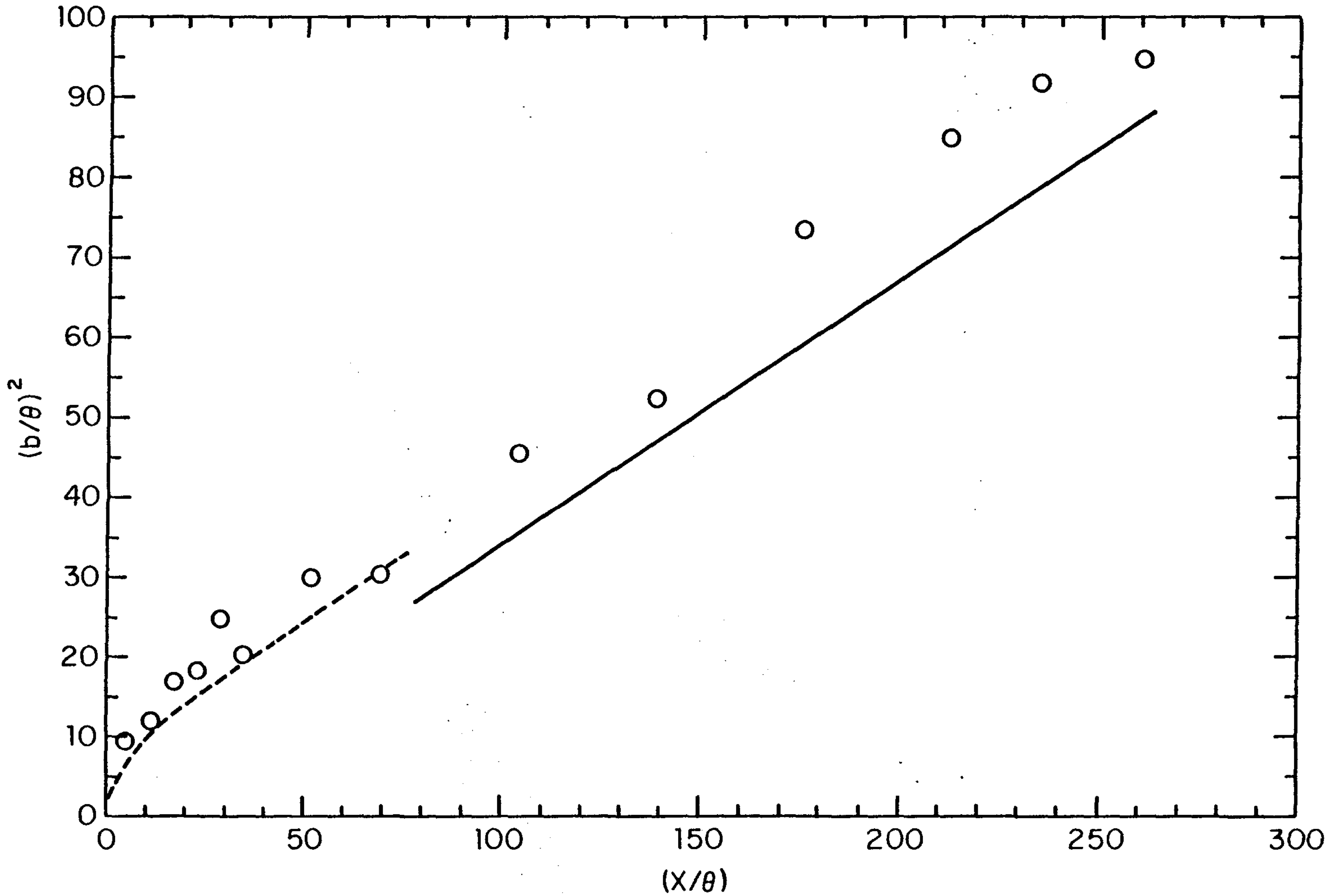

Figure 3(a). Growth of the wake half-width ---, data from Sastry[5], ——, asymptotic far-wake; O, present experiment.

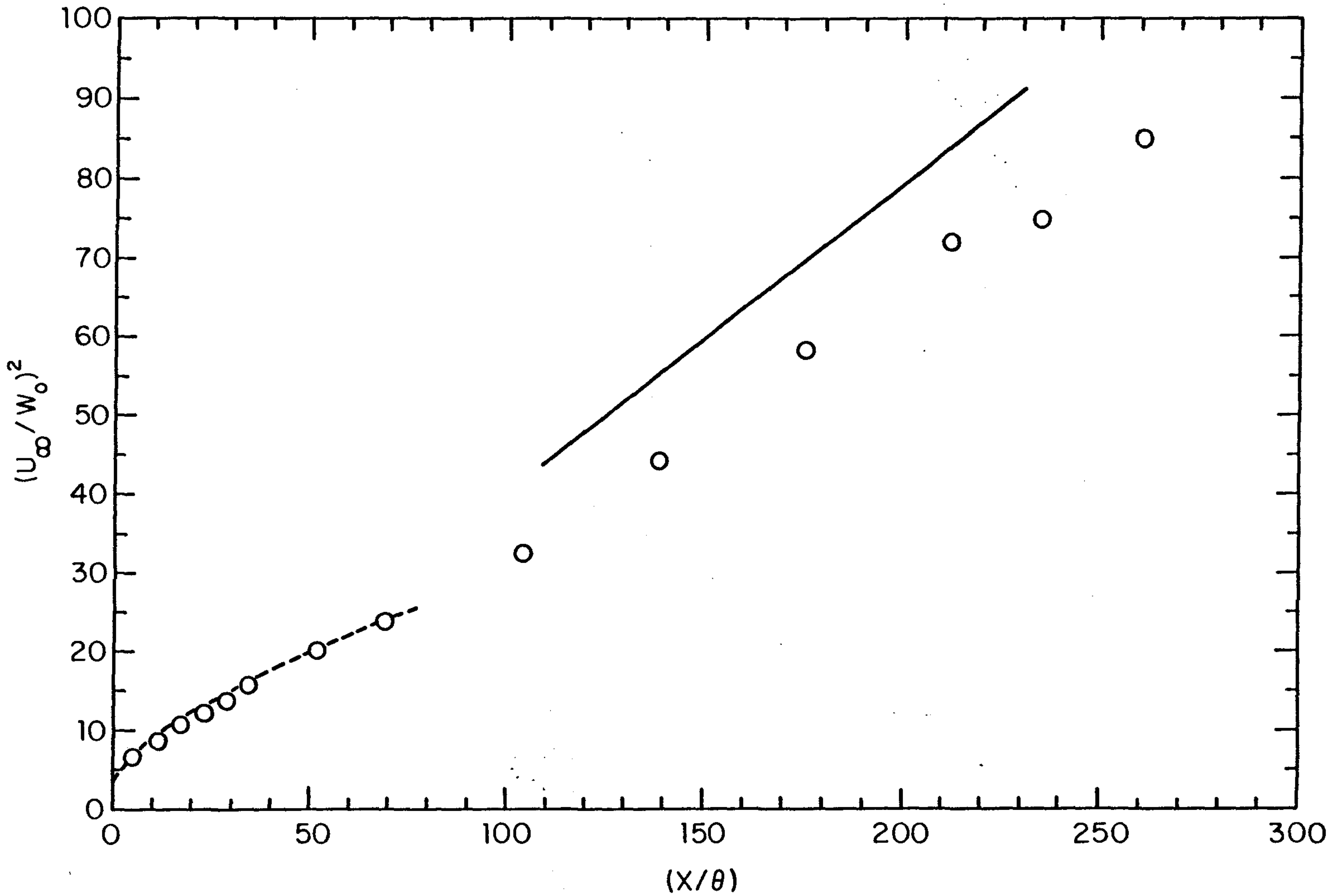

Figure 3(b). Decay of the maximum wake defect ---, data from Sastry [5], ——, asymptotic far-wake; O, present experiment.

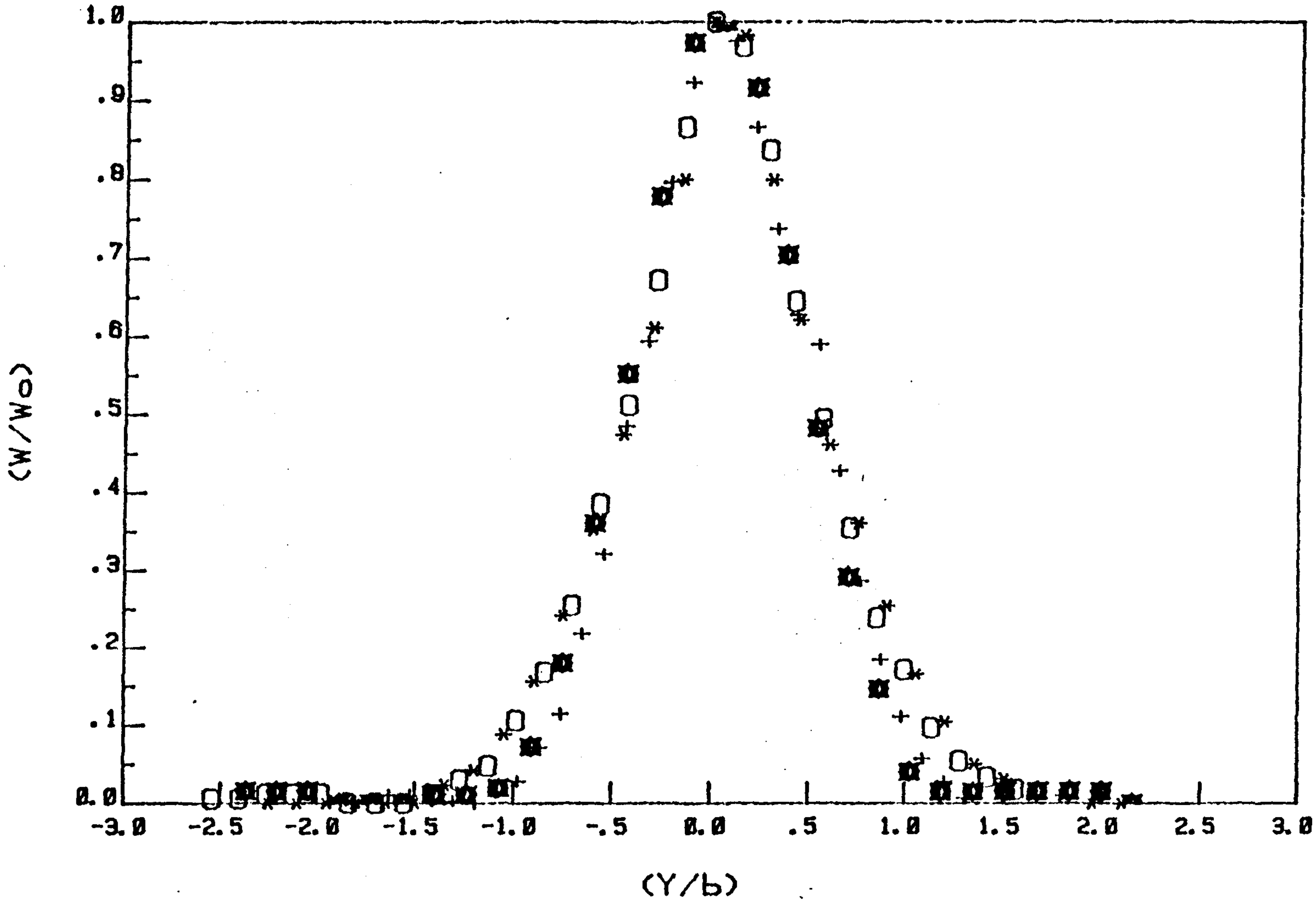

Figure 4. Distribution of velocity defect across the wake. Symbol, x/θ : *, 5; ▢, 10; +, 20; ∇ , 35; Δ , 70; ◇ , 140; ●, 210; 0, 260.

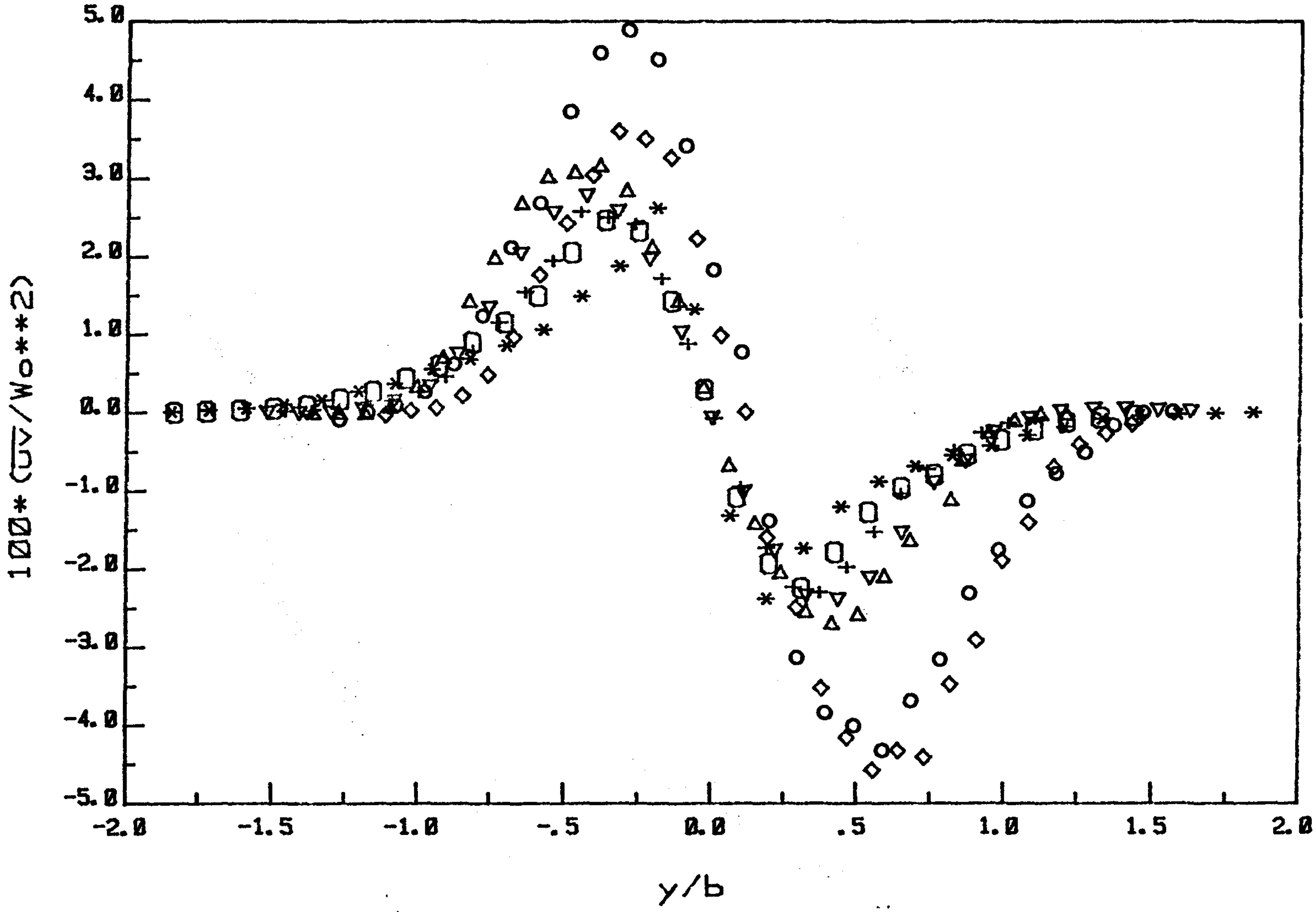

Figure 5. Distribution of conventional Reynolds shear stress across the wake. Symbols, x/θ: *, 5; O, 10; +, 20; ▽, 35; △, 70; ◇, 140; **O**, 260.

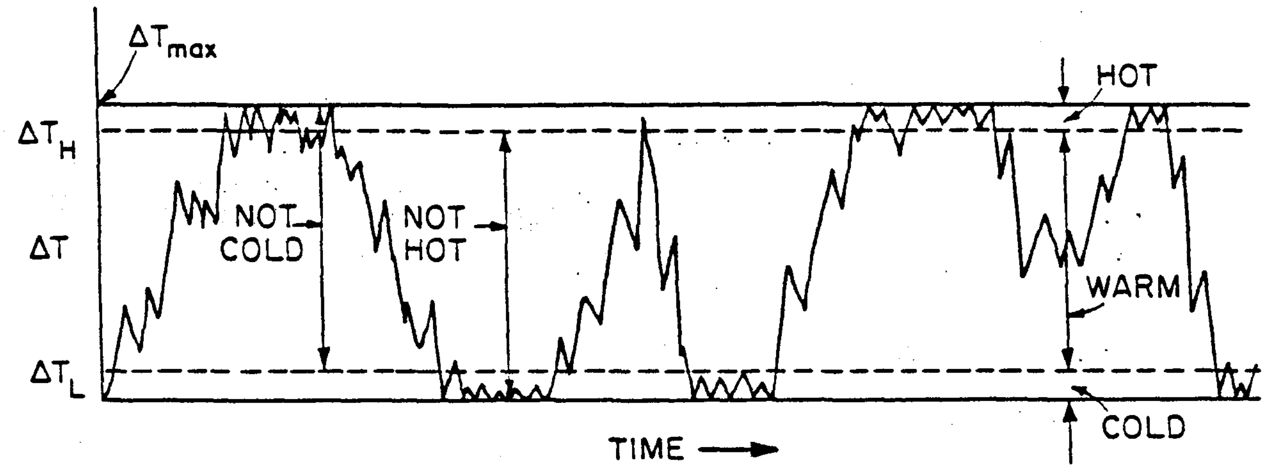

Figure 6. Threshold-setting for hot-cold discrimination.

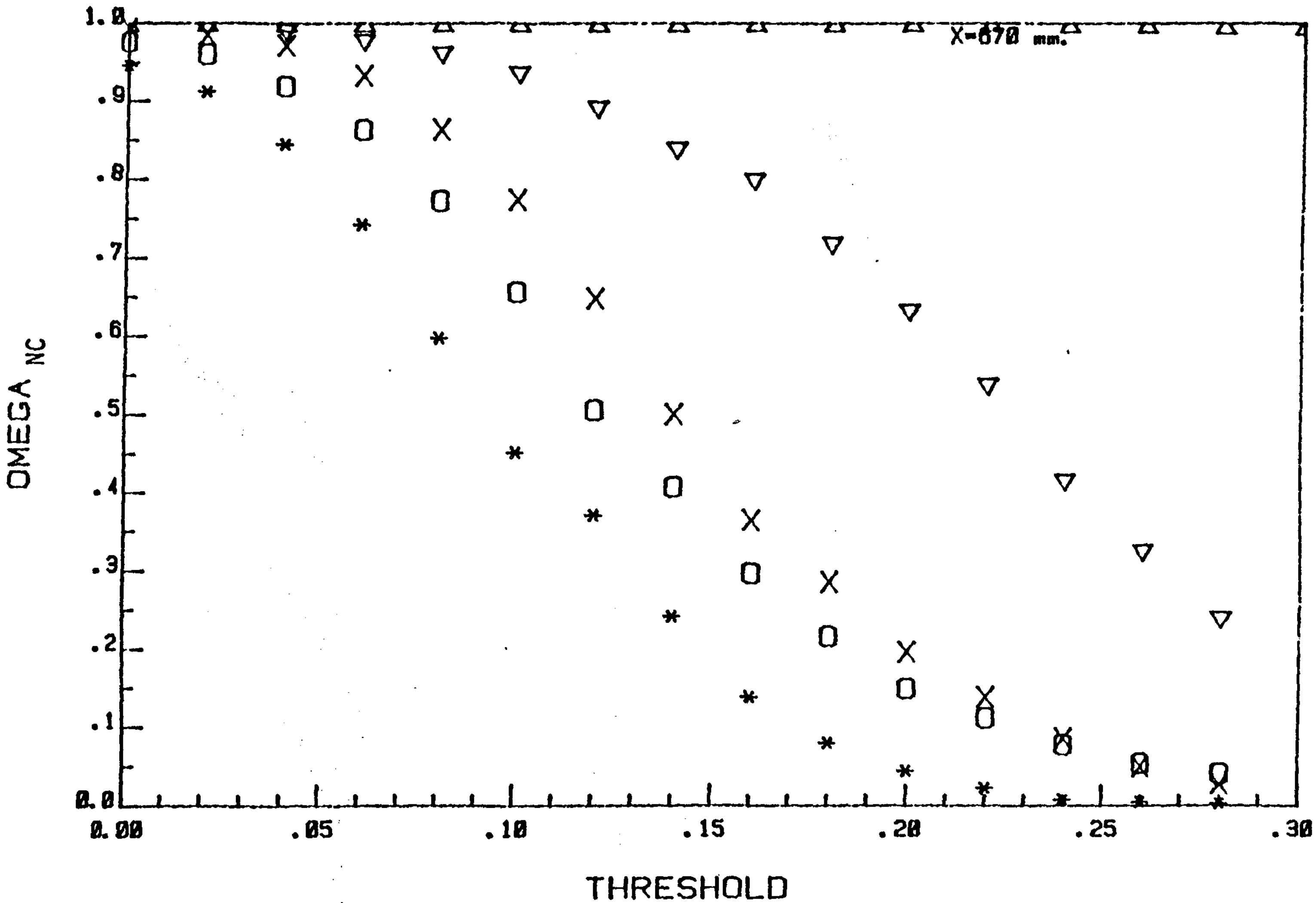

Figure 7. Effect of the threshold-level ΔT_L on the intermittency Ω_{nc}.
Symbol, y/θ : *, -16; ◻, -13; x, -9.5; ▽, -6.5; △, -3.5.

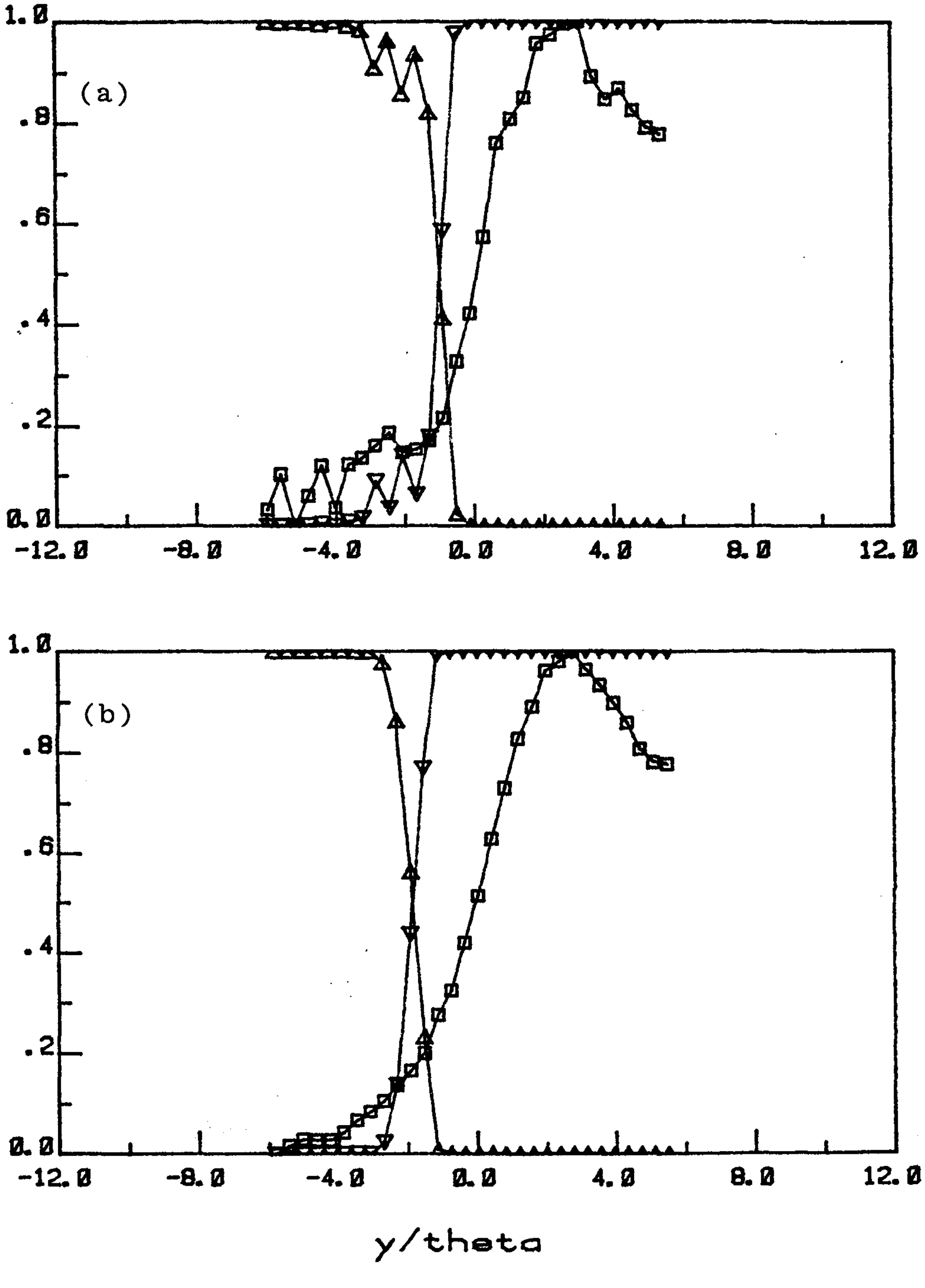

Figure 8. Distribution of intermittency and mean temperature across the wake. (a) x/θ = 17, (b) x/θ = 29. ▽, Ω_c; △, Ω_{nc}; □, $\Delta T/\Delta T_{max}$.

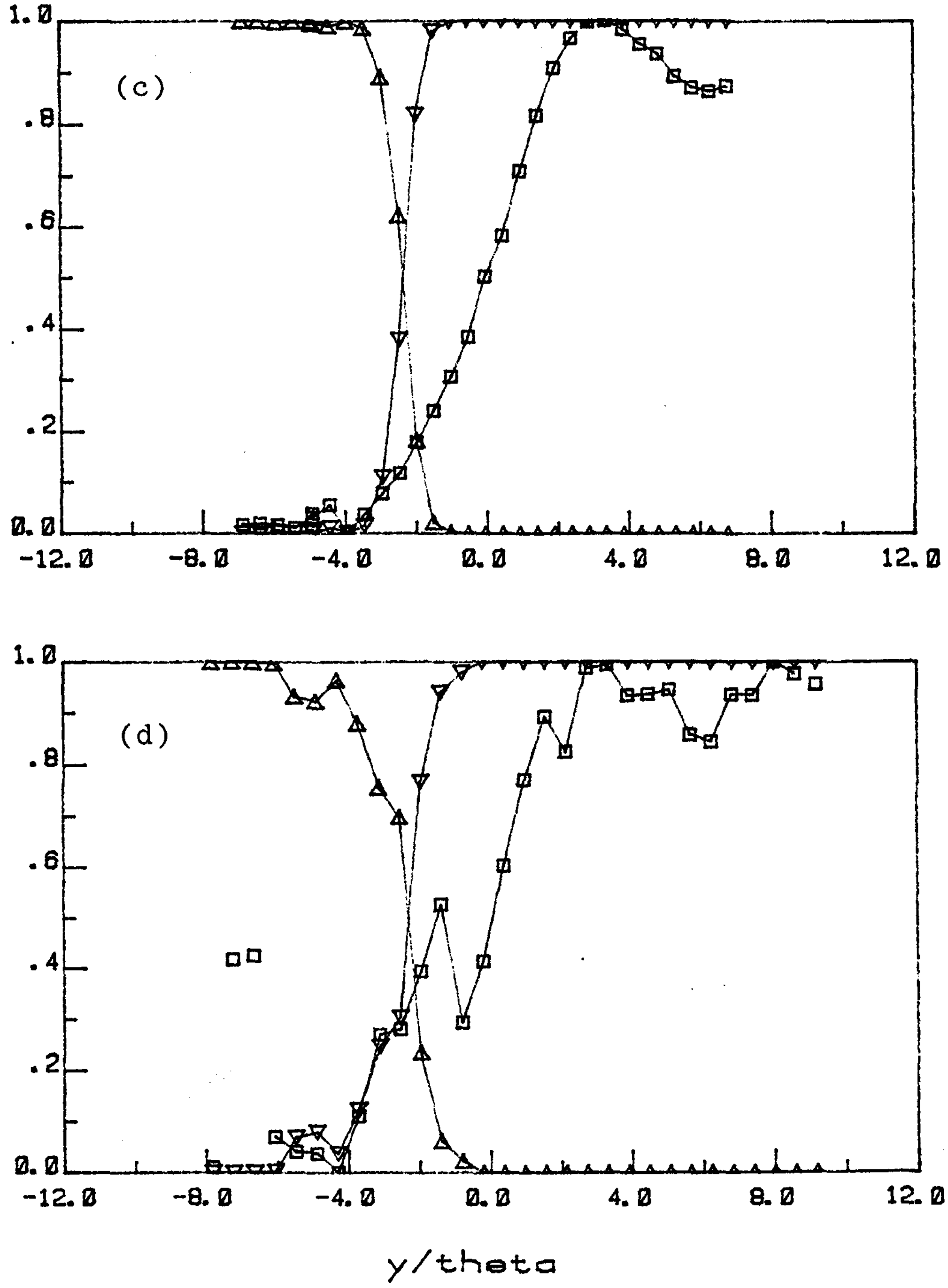

Figure 8 (Continued) (c) x/θ = 52, (d) x/θ = 104

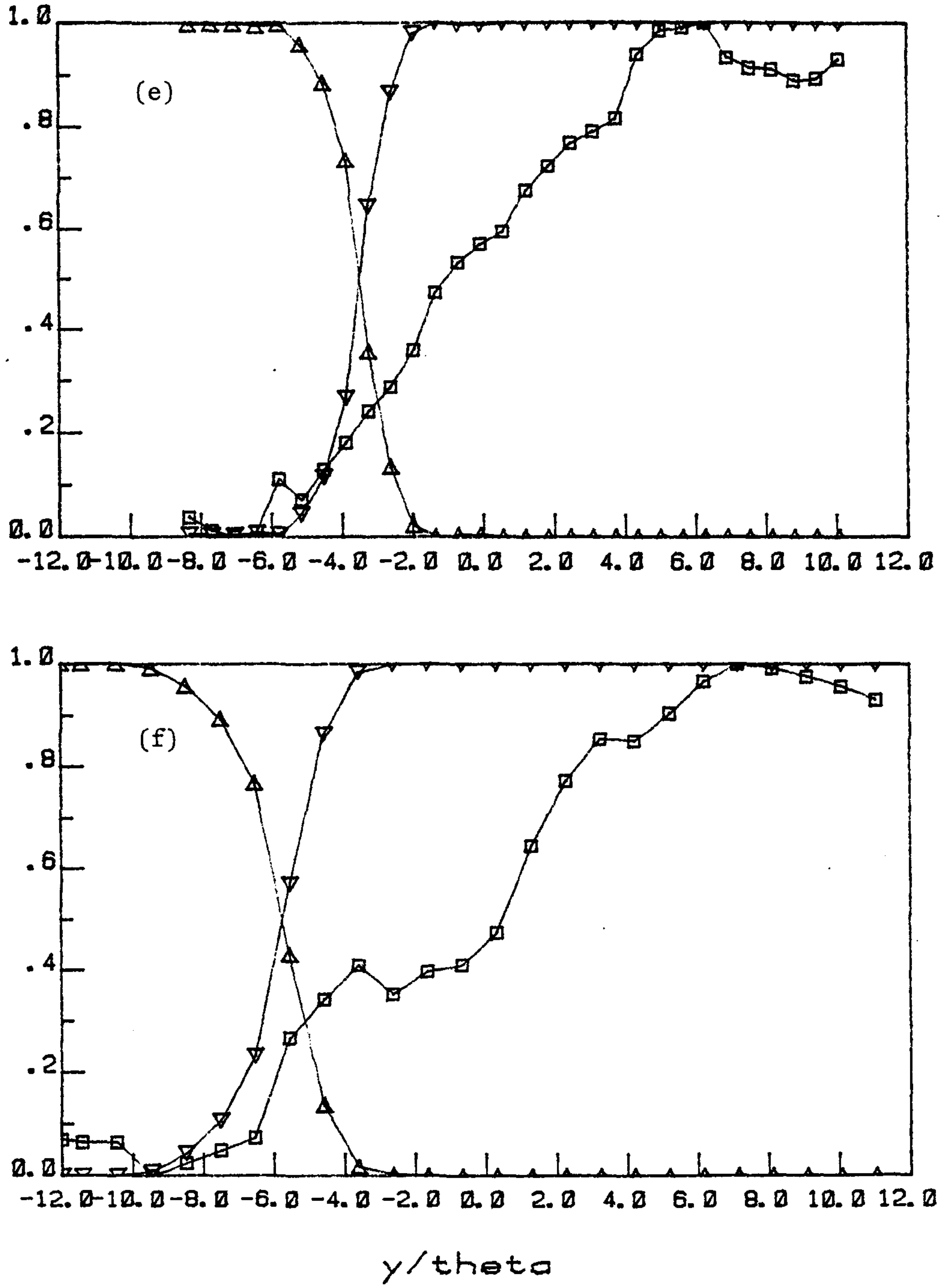

Figure 8 (Continued) (e) x/θ = 140, (f) x/θ = 260.

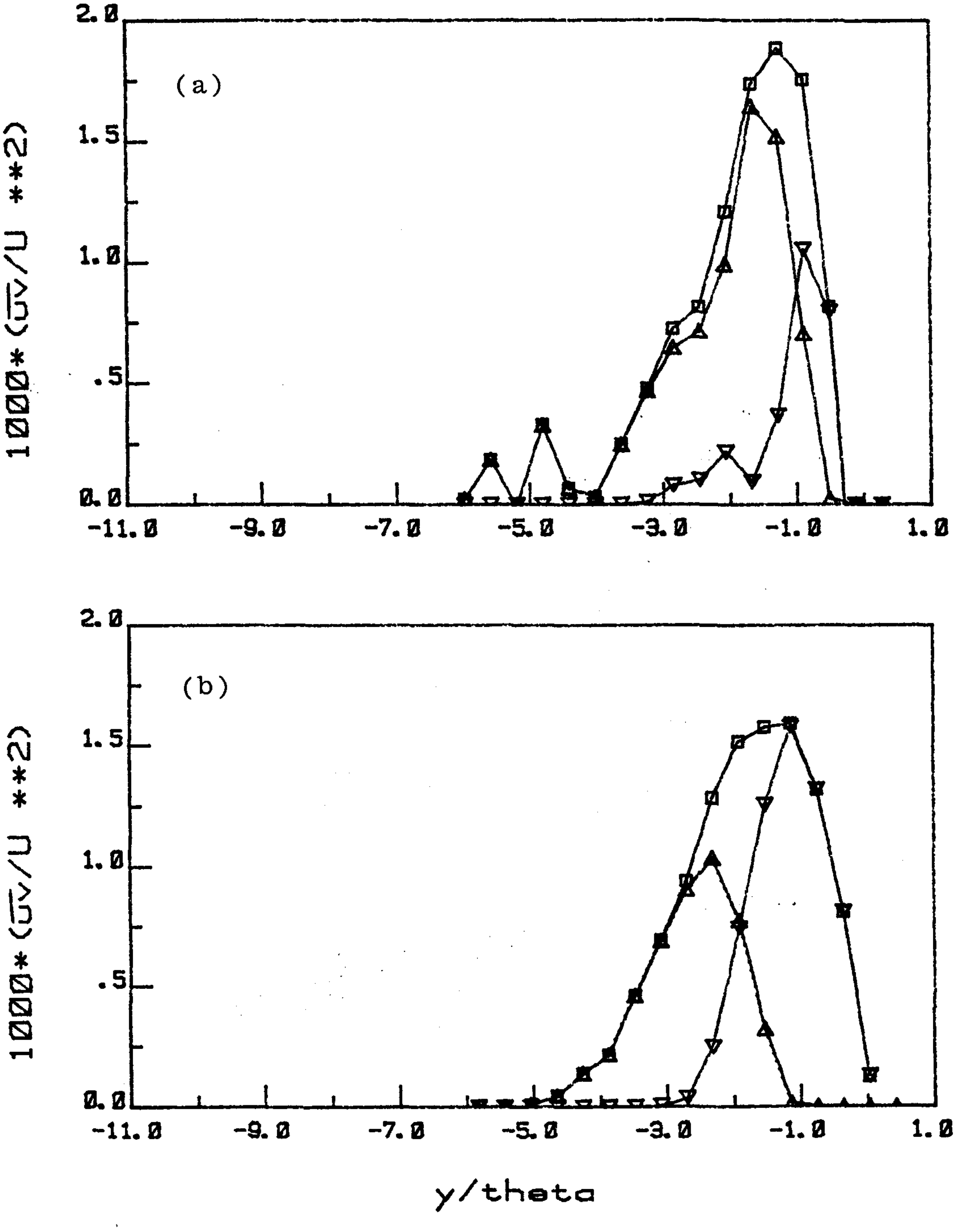

Figure 9. Conventional and conditional averages of Reynolds shear stress $\overline{uv}$. (a) $x/\theta = 17$, (b) $x/\theta = 29$. Symbols, Δ, $(\overline{uv})_c$; ∇, $(\overline{uv})_{nc}$; $\square$, $\overline{uv}$.

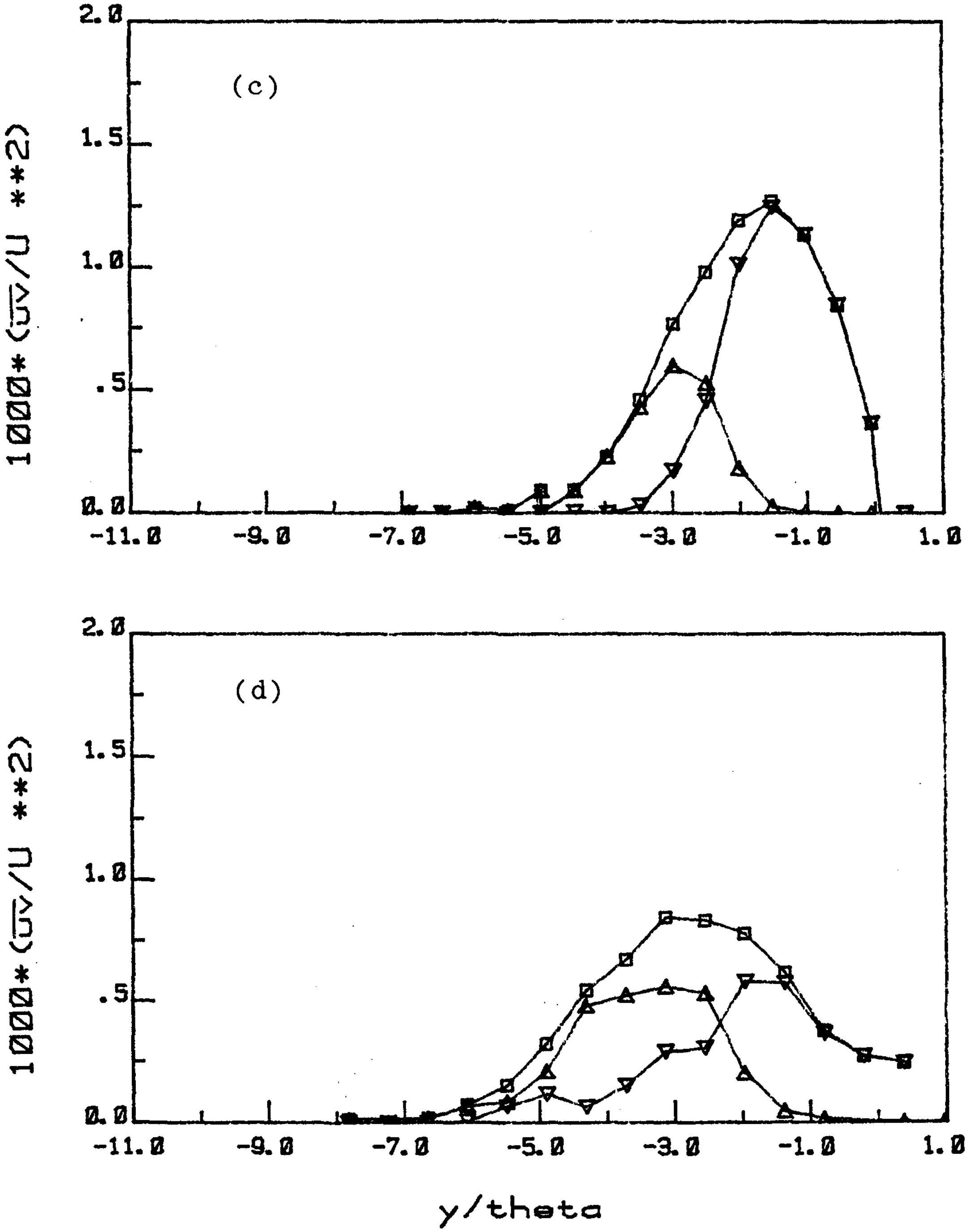

Figure 9 (Continued) (c) x/θ = 52, (d) x/θ = 104.

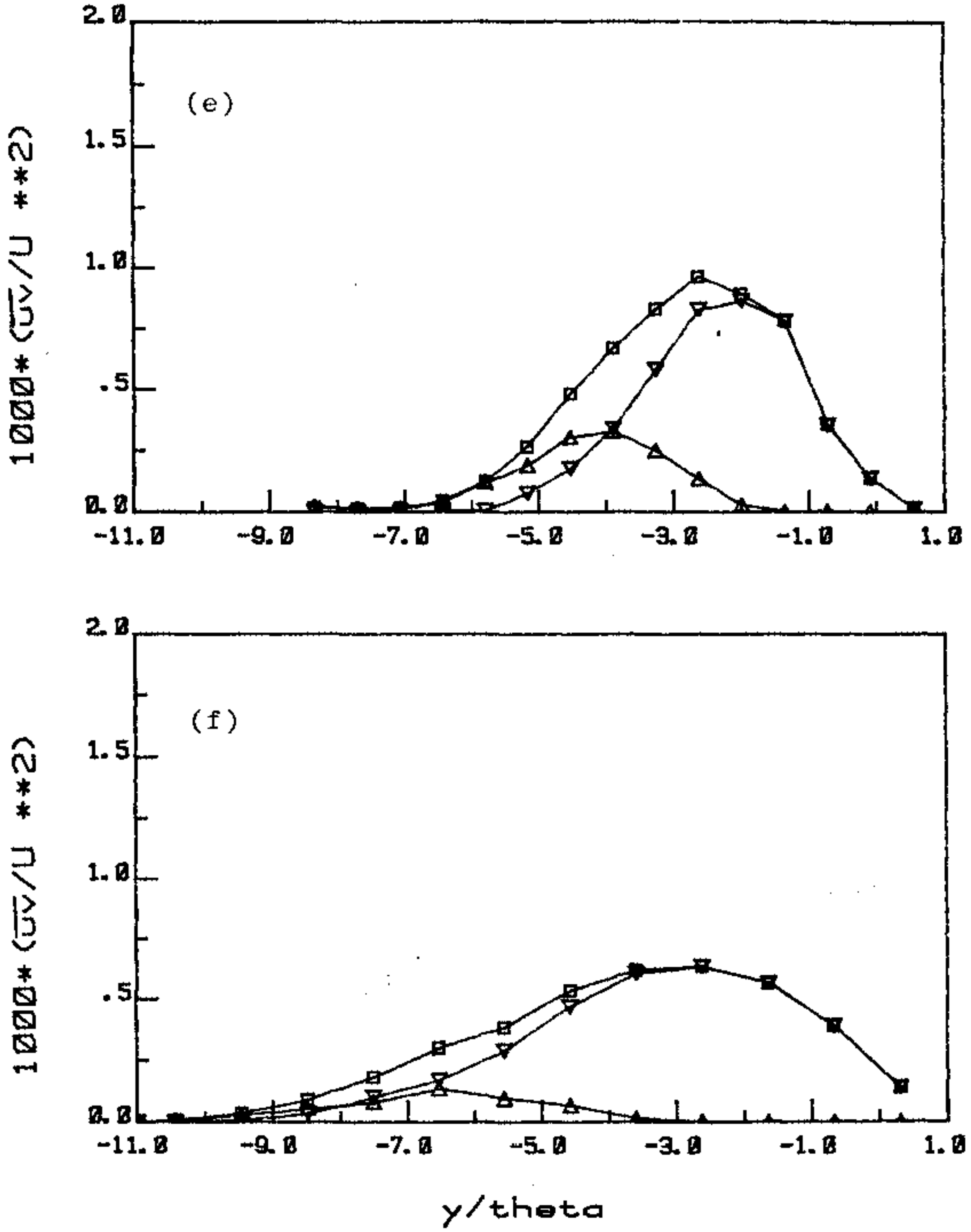

Figure 9 (Continued) (e) x/θ = 140, (f) x/θ = 260.

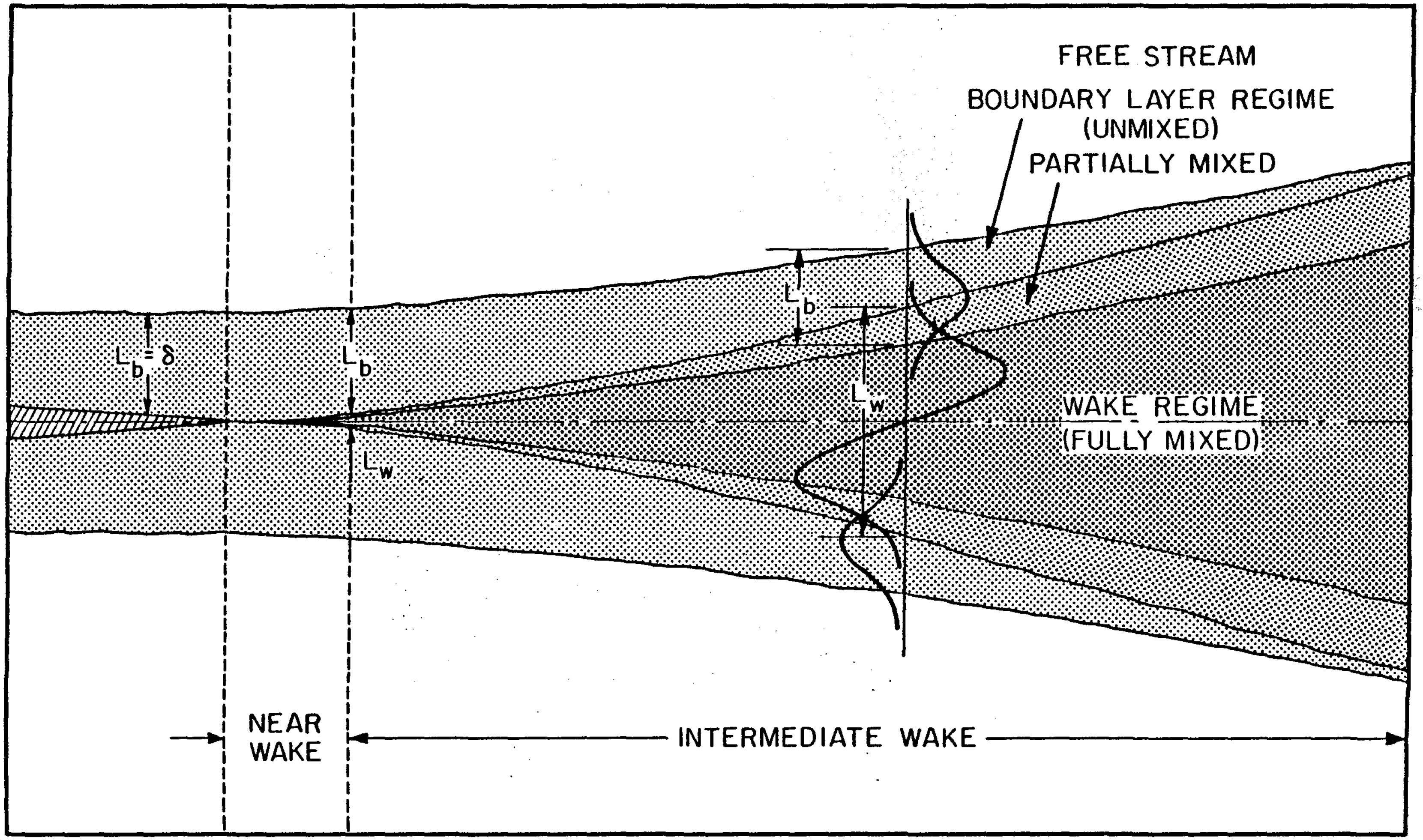

Figure 10. Schematic representation of the mixing process in the developing wake.

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