ON INTERACTION OF T-S WAVES AND 3-D LOCALIZED DISTURBANCE IN A DIVERGENT FLOW UNDER ZERO PRESSURE GRADIENT

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(Received: April 18, 1999 - Accepted: March 14, 2000)

Abstract To simulate the effect of free stream turbulence on turbulent spot formation, experiments were conducted on the interaction of localized three-dimensional disturbances with the harmonic waves in a laminar boundary layer on a flat plate. Experiments conducted in three-dimensional diverging flow (but zero pressure gradient) show, while individually the disturbances decay downstream, their interaction leads to amplification of three-dimensional disturbance leading to formation of the turbulent spot. Also flow divergence show the least effect in the interaction process.

Key Words T-S Waves, 3-D Flow, Turbulence Spot, Transitional Boundary Layer

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INTRODUCTION

It is believed that out of various possible routes to laminar-turbulent transition of boundary layer, the hydrodynamic stability approach and Emmons's theory of transition give the best justification for transition phenomenon.

Schubauer and Skramstad [1] convincingly confirmed the existence of linear waves postulated by linear stability theory of the boundary layer on a flat plate. When a small disturbance is applied to a laminar flow for which the Reynolds number exceeds a critical value, initially the disturbance grows exponentially with time. At the small disturbance the Reynolds stress generated by the disturbance is negligibly small. However, as amplitude of the disturbance increases the finite velocity fluctuations transport appreciable momentum and the associated Reynolds stress modifies the mean flow so that the transport of energy from the mean flow to the disturbance is modified and the disturbance growth rate is affected.

A second effect of the modification of the rate of transfer of energy to disturbance by the Reynolds stress is the extremely rapid increase in disturbance energy which initiates a turbulent spot. Emmons [2] reported the existence of turbulent spots and subsequent work by Dhawan and Narasimha [3] established a good phenomenological theory of a transition zone.

Emmons' theory is based on four assumptions: 1) point like break down, 2) a sharp boundary between the turbulent fluid of a spot and the surrounding laminar flow, 3) a

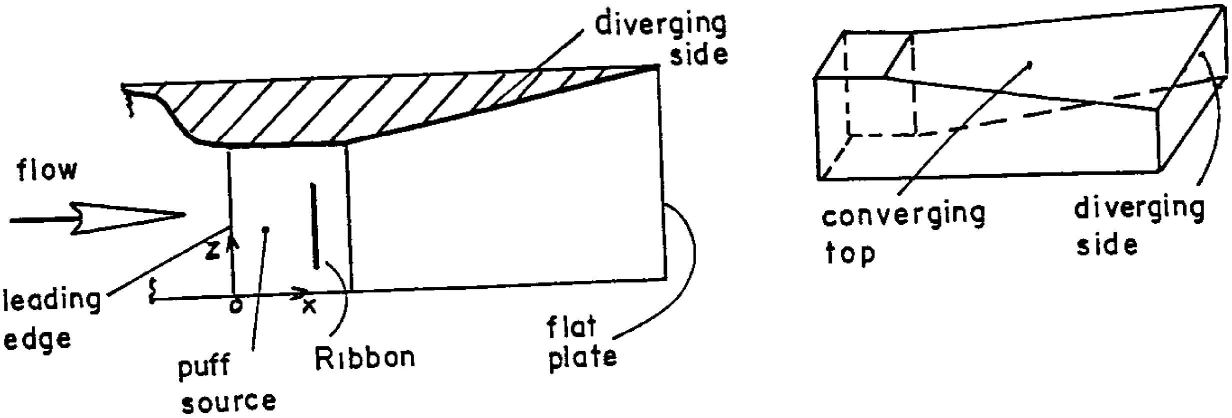

Figure 1. Schematic view of 3-D duct.

uniform rate of spot growth, and 4) no interaction between spots. These ideas were experimentally investigated in details by Schubauer and Klebanoff [4]. Emmons theory basically deals with the fluid behavior subsequent to break down while hydrodynamic stability approach throws some light on initial stages of transition prior to break down.

The word break down implies that the spot originates from a small volume and suggests the importance of the disturbance present immediately before break down to occur. It is important to note that it may be unjustified to neglect the character of flow far upstream of the break down point. The role of upstream flow is to produce and amplify disturbances which satisfy certain local conditions that cause break down to turbulence.

The detailed analysis of nonlinear breakdown of a laminar boundary layer had been carried out in the fundamental experimental investigation of Klebanoff, P.S. et al. [5]. It is concluded that the actual breakdown of the wave motion into turbulence is a consequence of a new instability which arises in the 3-D wave motion (a strong amplification of three - dimensionality, a sudden appearance of "spikes" and high frequency oscillations etc.).

It is indeed the aim of this paper to highlight the effect of the interaction of unstable wave and localized 3-D disturbance on break down of laminar flow to turbulence prior to spot formation (which is analogous to that introduced by the free-stream turbulence) based on aforementioned experiments performed by Klebanoff and his co-workers. A preliminary results of this work has already been published, see Dey et al. [6].

EXPERIMENTAL SET-UP

The 3-D low turbulence (freestream turbulence was less than 0.05%) wind tunnel (see Figure 1 and for details refer to Jahanmiri et al. [7] with zero pressure gradient at the Dept. of Aerospace Engg., Indian Institute of Science, Bangalore) was used for this investigation. The x-z coordinate system is shown in Figure 1 with y-axis perpendicular to the surface of the flat plate. The free stream velocity was chosen in some part of the experiments to be 10m/s to study the behavior and growth of T-S wave and later lowered down to 5m/s to investigate the effect of T-S wave on 3-D localized disturbance (velocity variation along the streamwise direction was about 2%). The alumium flat plate with elliptic leading edge was mounted in the center of the tunnel and spanned fully across the wind tunnel test section.

To excite boundary layer oscillation, a ribbon of 2.5mm wide, 0.05mm thick, 306mm long was installed at 200mm from leading edge of the flat plate . At a distance of 60mm from each side of the tunnel wall, two spacers were laid to keep a height of 0.2mm from the surface. Also a strip of scotch cellulose were laid on the surface on either end for insulation and another strip of tape was then laid on the ribbon to hold it firmly.

To establish the resonant frequency and for the stability purpose a certain amount of tension is applied to the ribbon.

The 186mm long ribbon at the center was driven in and out from the surface by passing through it a small amount of current (0.6 amp.) of the desired frequency by a power oscillator (SI-28), generating a sinusoidal wave in the presence of a strong permanent magnetic field installed on the opposite side of the plate. The input frequency to the ribbon was chosen to be 94Hz primarily to study the behavior of T-S waves and then lowered to 72Hz in interaction mode with puff.

An artificial localized three-dimensional disturbance (turbulent spot or a puff) was introduced by a loud speaker driven by a rectangular pulse generator through a 1mm static hole at a distance 100mm from the leading edge of the plate at a frequency of 1Hz. The Reynolds number based on the displacement thickness at the localized disturbance source was 318.

Measurements were made using constant temperature hot wire anemometer for measuring fluctuation and mean streamwise velocity component with the help of 0.0005 inches Pt-Rd silver coated wire etched to desired resistance of 1.8 Ohms and overheat ratio of 2.8 and soldered to the pronges of the probe facing to the flow and mounted on an indigenous three coordinate moving traverse.

B&K signal analyser was used for ensemble averaging of the signal on time enhancement mode, which was triggerd by either the loud speaker pulse or power oscillator signal during the experiment.

A dual beam oscilloscope also was incorporated to monitor the signal traces. This instrument also triggered by either loud speaker pulse or power oscillator signal.

The development of the disturbances was studied individually as well as in the interacting mode. Ensemble averaging was carried out to enhance and measure the signal characteristics. Experimental conditions were chosen such that the development of the two-dimensional (hydrodynamic) wave as well as the localized three-dimensional wave from the puff were such that they were eventually damped downstream, individually.

RESULTS AND DISCUSSION

Mean velocity profiles at x= 550mm amd z= 150mm for three different cases of introduction of disturbances are shown in Figure 2. There is a similarity in these profiles, which implies that nonlinearity is not strong enough to distort the mean profiles.

Figure 3 illustrates the spanwise variation of mean flow velocity inside and outside of the boundary layer for two cases of both with and without T-S wave. As can be seen, there is no appreciable effect of T-S wave on the mean flow along z-direction. The distribution is almost constant (specially outside the boundary layer) along the span. Within the boundary layer (at y= 1mm) in the central region of flat plate (between z= 100 and 200mm) where most of measurements was carried out except for small irregularities (due to the noise in the system), the constancy of variation is sensible within measurement accuracy. This figure is comparable to figure 1 of Klebanoff et al.

Figure 4 shows the spanwise distribution (up to z= 200mm from the straight wall since

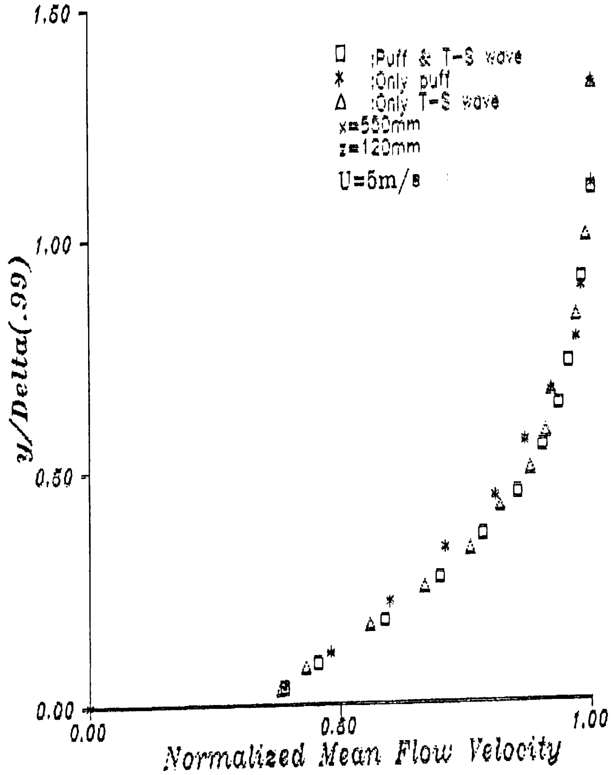

Figure 2. Mean velocity profiles.

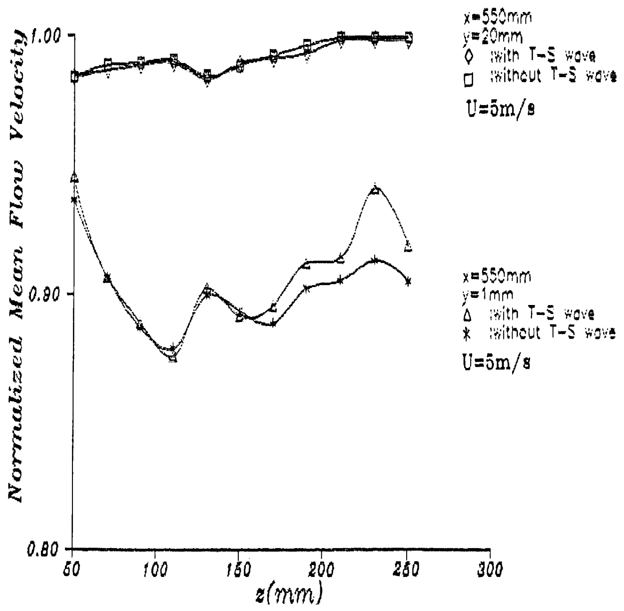

Figure 3. Spanwise variation of mean flow velocity.

beyond this point due to divergent wall effect the turbulence level was quite high) of the phase shift of the propagating waves (T-S waves) at different streamwise direction (x=550, 600mm) and y=1mm normal to the flat plate. It is seen that the spanwise phase shift of propagating waves at any of these streamwise locations is almost constant. This implies that the T-S waves propagate without any distortion, i.e. same as 2-D flow, and it is obvious to say that T-S waves are not perpendicular to streamlines. The position of constant time phase of T-S waves are found at two flow conditions as shown in Figure 5 by moving the hot-wire probe at x-z plane.

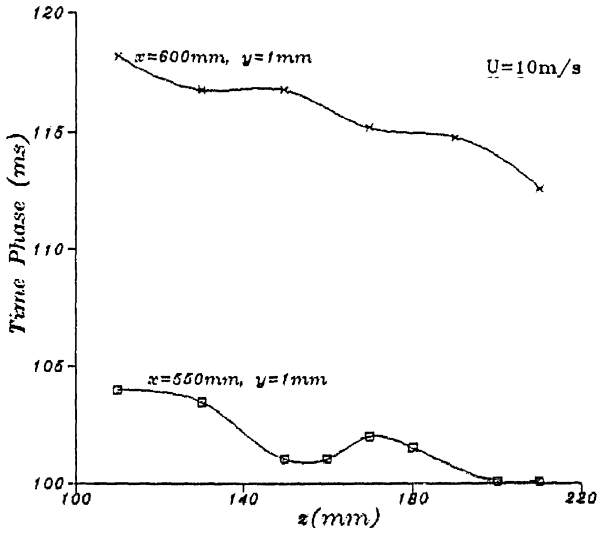

Figure 4. Spanwise variation of time phase.

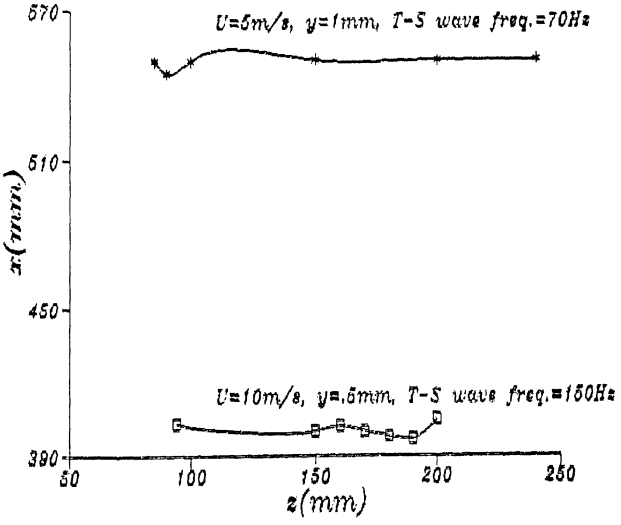

Figure 5. Lines of constant phase.

Similar experiments were performed when

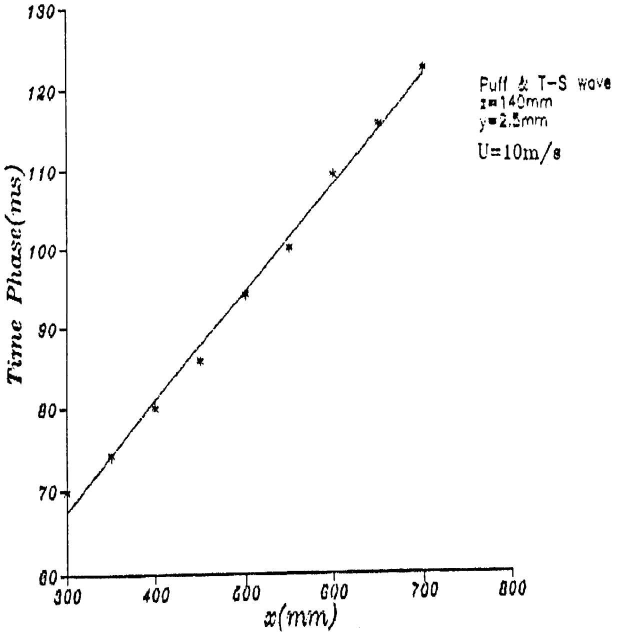

Figure 6. Streamwise variation of time phase.

there was an artificial turbulent spot. From the oscilloscope traces, it was found out that contrary to T-S waves, which are propagating in 2-D manner, the turbulent spot was turning along the streamlines. Though the turbulent spot was not at a constant angle, (also refer Jahanmiri, et al. [7]) it followed different paths with respect to T-S waves.

It was found out that the turbulent spot was

because of the influence of T-S wave and no effect on leading and trailing edge velocity of turbulent spot was noticed. However, there was a difference on spot amplitude with and without T-S wave.

Streamwise distribution of time phase at z=140mm, y=2.5mm and freestream velocity of 10m/s are seen in Figure 6. The curve shows a linear trend, slope of which gives phase velocity of the propagating waves , and is found to be 0.8 times of freestream velocity. This is almost the same as the speed of the leading edge of the turbulent spot (see Jahanmiri et al [7]). Hence it implies that the interaction of T-S wave and puff could be the cause for inception of the turbulent spot.

Distribution of intensity of u-fluctuation across boundary layer at three different x-locations and z= 150mm for two wave propagation conditions are shown in Figure 7. These curves are quite similar to those in Figure 5 of Klebanoff for 2-D flows. There is an apparent increase in the intensity of puff magnitude due to the effect of T-S wave interaction across the boundary layer where the maximum value is seen at about y=1.5mm.

The positions of the maximum in the

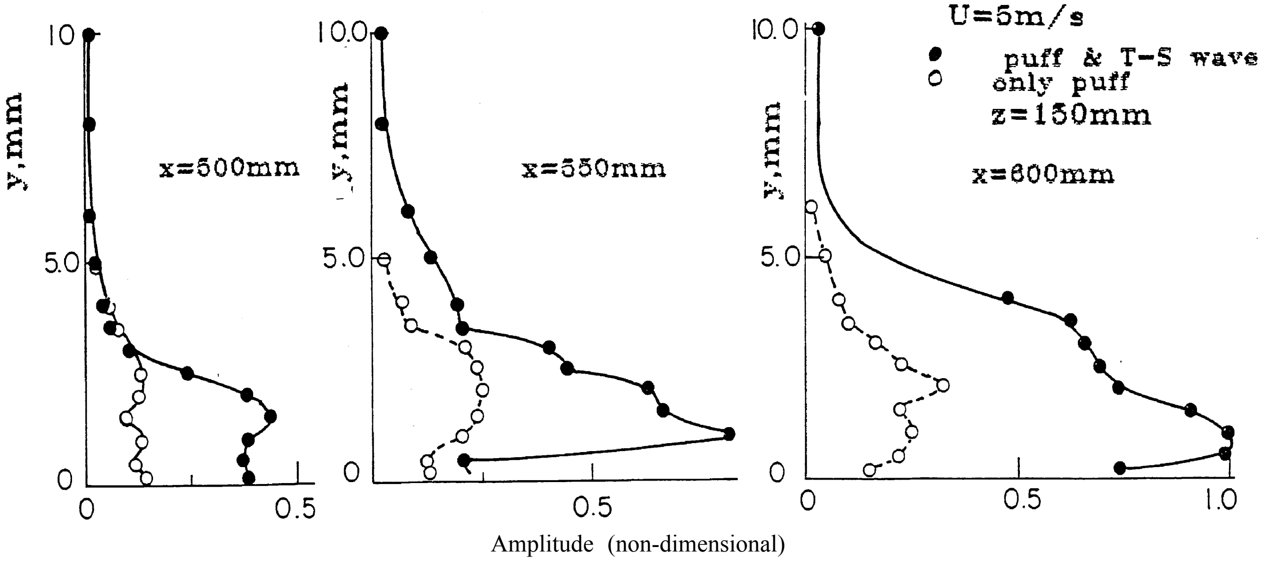

Figure 7. Distribution of intensity of u-fluctuation across boundary layer.

theory is at 0.2 times the boundary layerthickness, but in the non-linear range, is at a spanwise location which corresponds to a peakmoving away from the surface as breakdown is approached, and at breakdown it is about 0.4times the boundary layer thickness which is consistent with present results (i.e y=1.5mm).

Keeping y= 1.5mm (position of maximum puff amplitude) constant, at streamwise locations x=400mm, x=500mm, x=600mm, and x= 700mm the amplitude variation was measured along spanwise direction (see Figure 8) and again it was found out that due to interaction of puff and T-S wave the amplitude magnitude of wave quite extensively increased and the trend was progressively enhanced along the streamwise direction.

Streamwise variation of intensity of u-fluctuation is shown in Figure 9. As seen from the spanwise distribution, the unstable T-S waves and the puff have tendency to decay in x-direction. However, T-S wave, when propagating independently, seems to grow towards the last measuring station. The interaction of these two types of disturbances is found to cause a large amplitude, which is increasing in downstream direction. It is perceived that this process could finally end up with the production of turbulent spot.

CONCLUSION

These experiments indicate that interaction of harmonic waves and localized three dimensional disturbances may lead to the formation of the turbulent spot as seen in 2-D flows (see also Dey et al [6]). These results could be used for modelling the boundary layer transitional flow region.

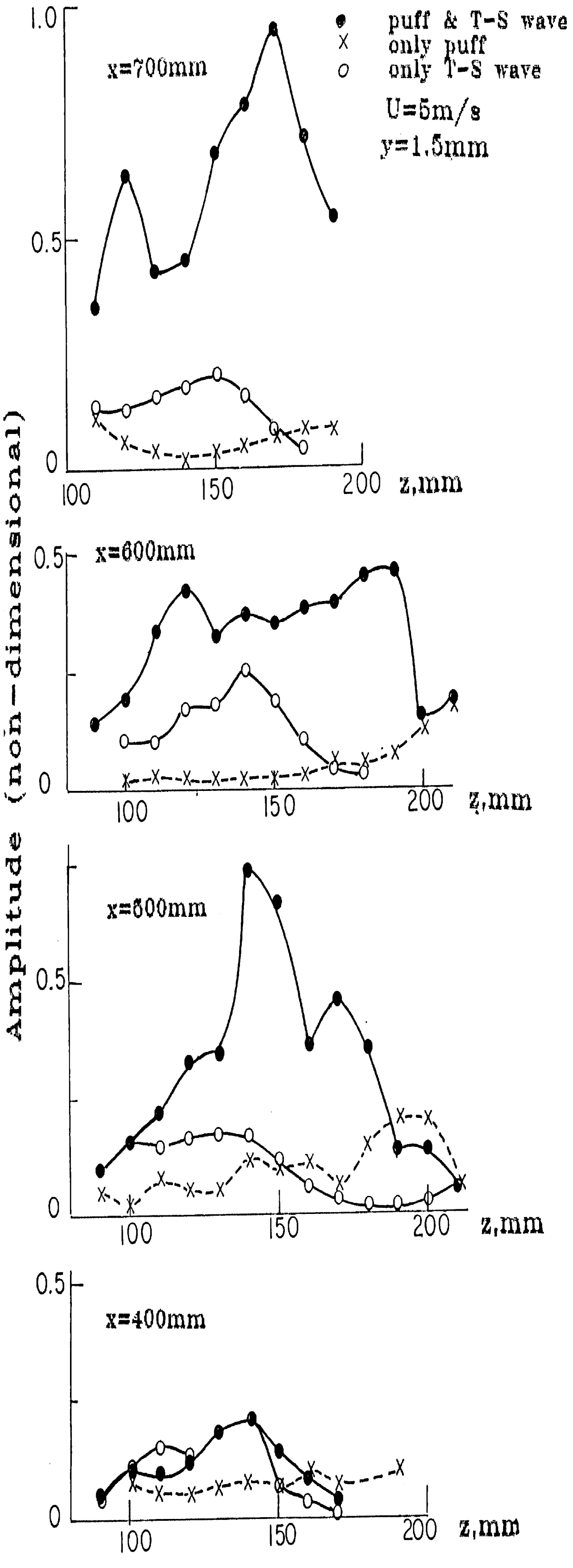

Figure 8. Spanwise variation of intensity of u-fluctuation.

ACKNOWLEDGEMENT

The author wish to thank Prof. R. Narasimha,

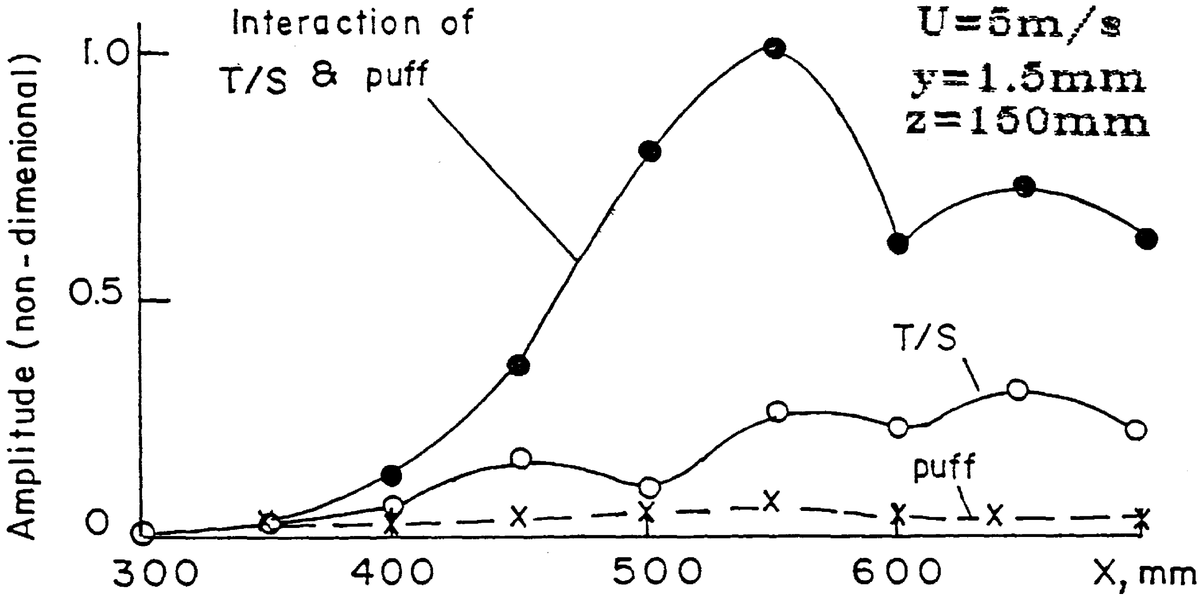

Figure 9. streamwise variation of intensity of u-fluctuation.

Prof. A. Prabhu, and Dr. J. Dey for their valuable scientific suggestion throughout the experiments.

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