VORTEX ENHANCEMENT OF PARALLEL PLATE HEAT AND MASS TRANSPORT

by

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LIST OF FIGURES

NOMENCLATURE

a = slot separation
C_f = Dimensionless skin friction coefficient $= (\frac{2g_c\ \tau_w}{\overline{\rho}\ \overline{U}^2})$
d_e = effective slot diameter = (2a)
D = diffusion coefficient
g_c = gravitation constant
N_w = Mass flux at wall
p_s = static pressure
Re = Reynolds number $(\frac{\overline{U}\ d_e}{\nu})$
Sc = Schmidt number $= (\frac{\nu}{D})$
St_m = Mass-transfer Stanton number

$$= (\frac{N_w}{(\omega_w - \overline{\omega})\overline{\rho}\ \overline{U}})$$

U = local velocity
$\overline{U}$ = average velocity
x = longitudinal coordinate along duct
y = vertical coordinate across duct
ν = kinematic viscosity
ρ = density
τ_w = wall shear stress
ω_w = wall mass fraction
$\overline{w}$ = average mass fraction

ABSTRACT

An experimental measurement of the effect of mechanically generated vortices on the mass transfer rates for turbulent flow in the entrance region of a parallel-plate channel has been made. The purpose of these measurements was to determine if the insertion of such vortex generators would substantially increase drying rates for moistened films, lumber, or paper products. Data are obtained by measuring weight loss for sublimation mass transfer of a napthalene surface. The experimental results indicate that there is a significant increase (30 - 90 percent) in mass-transfer Stanton number in the presence of the vortices.

INTRODUCTION

An experimental study has been made of vortex generator augemented heat and mass transfer in the entrance region of a parallel-plate duct flow. Heat and mass exchange designers have aggressively searched for methods to improve convective transfer coefficient without increasing pumping power. Many efforts have been directed toward shortening overall drying time in handling moistened films, lumber, or paper - one of the predominant factors in the economics of dried product manufacture. Some authors have accomplished this by mechanically altering the subject surface with roughness, grooves, dimples, or corrugations (Kays and Chien, 1971; Kidd, 1970). Others have inserted twisted tapes into pipes to make "vortex" tubes (Sephton, 1971). Some have suggested the deliberate puslation of the circulating air to develop an agitated constantly reforming boundary layer; however recent experiments suggest any improvement may be traced to reduced transition Reynolds numbers (Miller, 1969).

If one is constrained from surface alteration or extensive redesign, the alternatives are considerably reduced. The use of simple vortex-generating inserts discussed herein may be a practical solution. The mass transport intensifier considered involves the insertion of an array of small vortex generators between parallel plates. A possible design might be a series of small sheet metal delta wings. Properly oriented these delta wings should produce strong tip vortices which would scour the parallel walls and increase transport. Vortex motion is extremely stable and once produced would maintain itself for considerable slot depth. In addition, it is expected that the pressure drop across such flow impedances for a given increase in mass transport should be less than the pressure drop required to obtain equivalent mass transport with an increase in velocity. Since fan power increases with the cube of circulation velocity the economy might be considerable.

Review of Vortex Dynamics

Thus, the objectives of the research were to

1) Determine if vortex inserts made any substantial increase in local drying rates,

2) Examine the value of alternative arrangements of inserts, and

3) Measure mean field velocity and turbulence response in the channels to the presence of such inserts.

Enhancement of heat, mass, and momentum transport by longitudinal vortices aligned with the flow have been recorded previously. Görtler vortices generated in laminar flow over curved surfaces are known to increase transfer by up to 100-150 percent (McCormack, et al., 1969). When a uniform flow approaches a two-dimensional stagnation region formed by a cylinder, inherent flow instability or vortex amplification may produce a regularly distributed system of counter-rotating vortices which increase heat transfer by 20 - 40 percent in the stagnation region depending upon Prandtl number (Kestin & Wood, 1970; Sadeh, et al., 1970). Vortex generators placed symmetrically on either side of a circular cylinder at 50° in cross flow augmented average heat transfer from 7 to 17.5 percent. Locally the Nusselt number increased over 200 percent in some positions (Johnson and Jaubert, 1968). In general it is accepted, however, that merely increased free stream turbulence does not significantly augment turbulent flat plate boundary layer transport (Kestin, 1961; Büyüktür, 1964); hence, any insert must do more to organize the flow than agitate it.

It is well known that conical vortices are created along the edges of delta wings as shown in Figure 1a. These vortices are steady in character, and when they do decay, they can create pressure pulsations from three to six times the dynamic pressure of the mean velocity depending upon the density of wing units placed in the slot. These pulsations are transmitted into an intense turbulence field with strong vertical and horizontal components (Kuchemann, 1953; Thwaites, 1960; (Ostrowski, 1960).

There are two possible mounting configurations for such vortex generators in a slot. If the wings are mounted as in Figure 1b the rotational velocity components will become accentuated. This secondary flow should be strong enough to transport fluid from the wall to the central stream and back, which would greatly increase heat and mass transport. If the wings are positioned so that the vortices generated are in opposition, as in Figure 1c, then the flow will decay quickly, creating intense turbulence.

Exploratory Experiments in Stacked Lumber

A review of wood drying practice (Meroney, 1969) encouraged a search for a means to mechanically enhance the removal of moisture from green lumber stacked in drying kilns. An exploratory experiment was performed in a drying kiln utilizing a simple set of vortex generators (Meroney and Ostrowski, 1967). The lumber stacks consisted of six layers of Engleman Spruce ten to twelve boards deep. Each board was rough cut lumber 1 inch thick by 8 inches wide and 6 feet long. The layers were separated by 5/8" by 3/4" stickers. The separating stickers were so notched that a set of six test boards could be removed for weighing during drying. Two boards were positioned downstream from a set of delta-wing vortex generators. The delta-shaped generators were manufactured from 1/32" thick sheet metal and soldered at a uniform spacing to a small diameter positioning rod which was driven firmly into the board upstream of the test boards. (See Figure 2). For each test board affected by vortex intensified flow, there was a second board cut from the same piece of lumber in a geometrically similar position in the stack to act as a control.

As a result of the wide variations in moisture content, thickness, variation in internal moisture distribution through the samples, and nonuniform wetted surface areas a wide variation was observed in the absolute magnitude of the drying rate in the constant rate regions for the various samples. However, it was felt that there was a consistent improvement in drying rate with vortex generators beyond mere statisitcal chance (perhaps as high as 200%, see Fig. 3). It was concluded the following more detailed and controlled measurements were justified.

EXPERIMENTAL APPARATUS & TECHNIQUES

Local rates of mass transfer from one side of a parallel plate wall to an air stream were obtained by measuring the rate of weight loss of a layer of cast napthalene slabs inserted flush with the exposed surface of the plate. Developing velocity and turbulence intensity profiles were measured across the slot width the length of the tested section. Static pressure changes the length of the section were recorded.

The arrangement of the equipment used in the experimental part of the study is shown in Figure 4. Two one-quarter inch aluminum plates 36" long by 22.5" wide were mounted with a separation of 15/16 inch. The leading edge of each plate was sharpened to an angle of 30°. Ten 3/16 inch diameter holes were drilled on the plate centerline. These provided access for pitot tube and hot wire anemometer instruments, and they were also the location for static pressure measurements.

Before each test run crystal-grade napthalene ($C_{10}H_g$ molecular weight 128.2, melting point 79-81°C) was melted in a covered flask in an electrically heated oven at about 120°F. The molten napthalene was then cast into three 1/8" x 2 7/8" x 36" plates. One plate was sectioned into thirty-six one inch long slabs. These smaller plates were inserted into a slot in the parallel plate duct wall while the two remaining longer plates were mounted on either side as buffers. The casting process left the surface of the plates extremely smooth and with care no bubbles formed during casting; therefore no further surface preparation was required.

Having pre-weighed each small plate the flow in the duct was set at an average velocity of 10 ft/sec and the napthalene allowed to sublimate for several hours in place. The plates were then removed and reweighed on a Mettler K-5 electronic balance (± .005 grams). All test runs were of such duration (2-7 hours) that natural convection losses between weighing and mounting, and between dismounting and reweighing were small.

Mass-transfer data are conveniently presented as mass-transfer Stanton numbers. This is properly thought of as the ratio of the mass flux to the rate of transfer needed to increase the free stream flow to the same weight fraction of diffusing substance as exists at the wall. The Stanton number utilized herein is then defined by:

$$St_m = \frac{N_w}{(\omega_w - \overline{\omega})\overline{\rho}\ \overline{U}} \tag{1}$$

where N_w is the mass flux, ω represents the weight fraction, and the superscript bar refers to average duct conditions. Inasmuch as the rate of transfer is extremely slow $\overline{\omega} \cong 0$. The weight fraction ω_w is evaluated from the vapor pressure of napthalene at the surface temperature, which was not actually measured. However, as discussed by Kreith, (1959), the surface temperature depression by cooling due to sublimation is at most of the order of 0.1°F. The physical properties used in the reduction of the experimental data were taken from Christian & Kezios (1959) and Sherwood (1960).

Two delta-wing vortex generators styles were examined as proposed in Figure 1. Each element was an equilateral triangle 5/8" on a side, 1/32" thick, set at 45° to the flow stream, and spaced at an average of 3/4" laterally. Figures 5 and 6 display the generators and their position in the parallel plate duct.

A single-wire constant-temperature anemometer was used to measure velocity and turbulent intensity. In addition, pitot-static tube measurements were made at each section on centerline. The sensing element of the anemometer circuit was a .00035 inch diameter tungsten wire, approximately .187 inch long. The bridge circuit utilized was a DISA, type 55D00, Universal Solid-state Anemometer, and the pitot tube output was processed by a Transonic Model A, Type 120, electronic pressure meter. Measuring instruments were tranversed across the slot utilizing a vernier rack and pinion system (±.004 inch).

EXPERIMENTAL RESULTS AND DISCUSSION

Clean Duct Performance

A number of runs without vortex generators were conducted to calibrate the channel flow. Figure 7a displays the sequence of developing profiles typical of an entrance geometry. Since it requires $0(50\ d_e)$ for the turbulent velocity profiles to develop in a channel, the profiles are not fully developed even at the end of the test channel ($\sim 20\ d_e$). However the exit profile is very similar to that measured by Nikuradse at an equivalent Reynolds number ($\sim$10,000). Since the entrance length for heat, mass, and momentum wall fluxes is $\sim(10\text{-}15\ d_e)$ the length of the duct was considered adequate, (Mori & Uchida, 1966).

A series of turbulent intensity profiles for a clean duct is shown in Figure 8a.

Static pressure variation along the duct is displayed in Figure 9. Longitudinal variation of the pressure is compared with the analytical prediction of Deissler (1953). The static pressure gradient at the end of the duct was utilized to calculate the local skin friction from

$$C_f = \frac{2 g_c\ \tau_w}{\bar{\rho}\ \bar{U}^2} = a\ (-\frac{dp}{dx})/\bar{\rho}\ \bar{U}^2 \quad . \qquad (2)$$

A value of $C_f = .007$ compares favorably with the magnitude of $C_f = .008$ projected by Deissler (1953) for $Re = 10{,}000$.

Napthalene sublimation losses have been converted to mass-transport Stanton numbers. The data in Figure 10 are compared with the analytically predicted values obtained from

$$St_m (Sc)^{2/3} = \frac{C_f}{2} \qquad (3)$$

where C_f was taken from Deissler (1953), and $Sc = 2.43$ for a napthalene-air mixture. The results are also in close agreement with values projected for thermal transport by Hatton and Quarmby (1963).

Vortex Generator Performance

The vortex generators tend to disturb the velocity profiles that develop in the slot entrance. Figure 7b displays the typical unsymmetric profile shape which occurs. Similar profile distortions were measured by Mori and Uchida (1966) when longitudinal vortexes developed in slot flow as a result of Rayleigh instabilities. Figure 8b depicts the resulting distortions in typical turbulent intensity profiles.

The vortex generators result in marked static pressure gradient variation along the duct length. Figure 9 displays the effect of single and double ranks of vortex generators. Surprisingly the secondary motions created do not appear to appreciably alter the pressure gradients downstream.

The napthalene sublimation tests were more promising. Actual mass transfer rates for five configurations is shown in Figure 10. Entrance lengths for the mass flux range from 8-15 d_e as expected. The wide variance in the data is indicative of accumulating measurements errors and local surface inhomogeneity due to imperfect slab fit.

Table 1 compares the average mass transport losses for the five configurations. Since the entrance length is short the ratios of average transport with generators to average transport for a clean duct should

Table 1. Total Evaporation on Napthalene Slabs

Case	$\dot{m}$ (gm/hr)	St_m	$(St_m)/(St_m)$ Clean duct
1	1.540	.0020	1
2	2.900	.0039	1.88
3	1.990	.0027	1.29
4	1.980	.0027	1.29
5	2.475	.0033	1.61

be typical of fully developed flow. Class 5 vortex arrangement performed better than class 4; this was unexpected since the vortexes generated were not expected to reinforce one another. An attempt was made to evaluate the lifetime of the secondary motion by comparison of single and double runs of generators. In this case however little to no improvement is apparent from the second row of generators. Hence the effective range of the generators was at least 20 d_e for this study.

Conclusion:

An effort has been completed to evaluate the effectiveness of vortex generator inserts to stimulate drying rates, especially in the aerodynamically controlled portions of a drying cycle. It was found that such inserts produce a significant increase (30 - 90%) in mass transfer Stanton number for at least twenty slot diameters. These generators have a significant influence on the dynamic and kinematic behavior of turbulent channel flow. The performance of these inserts over an idealized surface suggest examination of similar generators in full-scale lumber kiln operation may be fruitful for selected purposes where long drying times are economically limiting.

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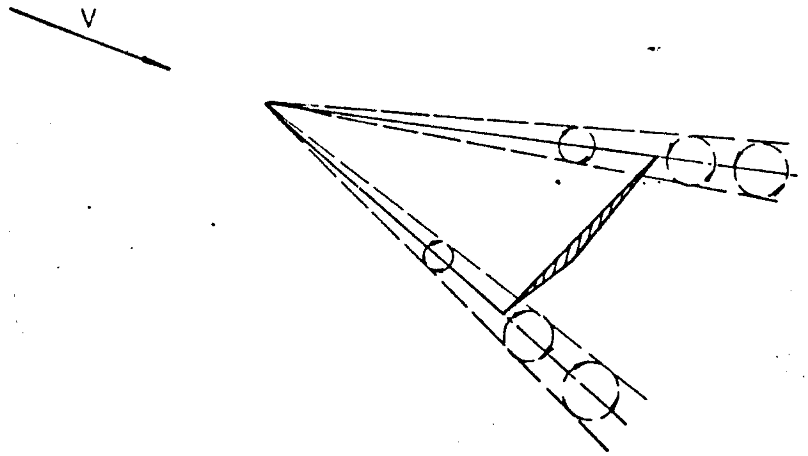
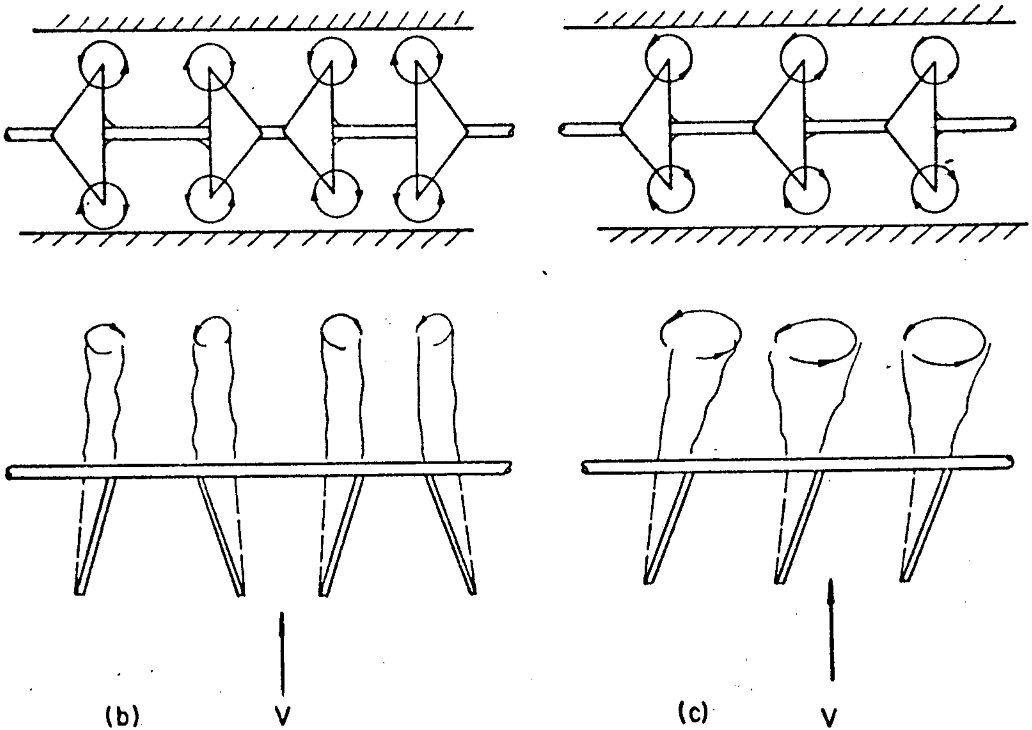


(a) Delta Wing



(b) (c)

Figure 1. Vortex Generators.

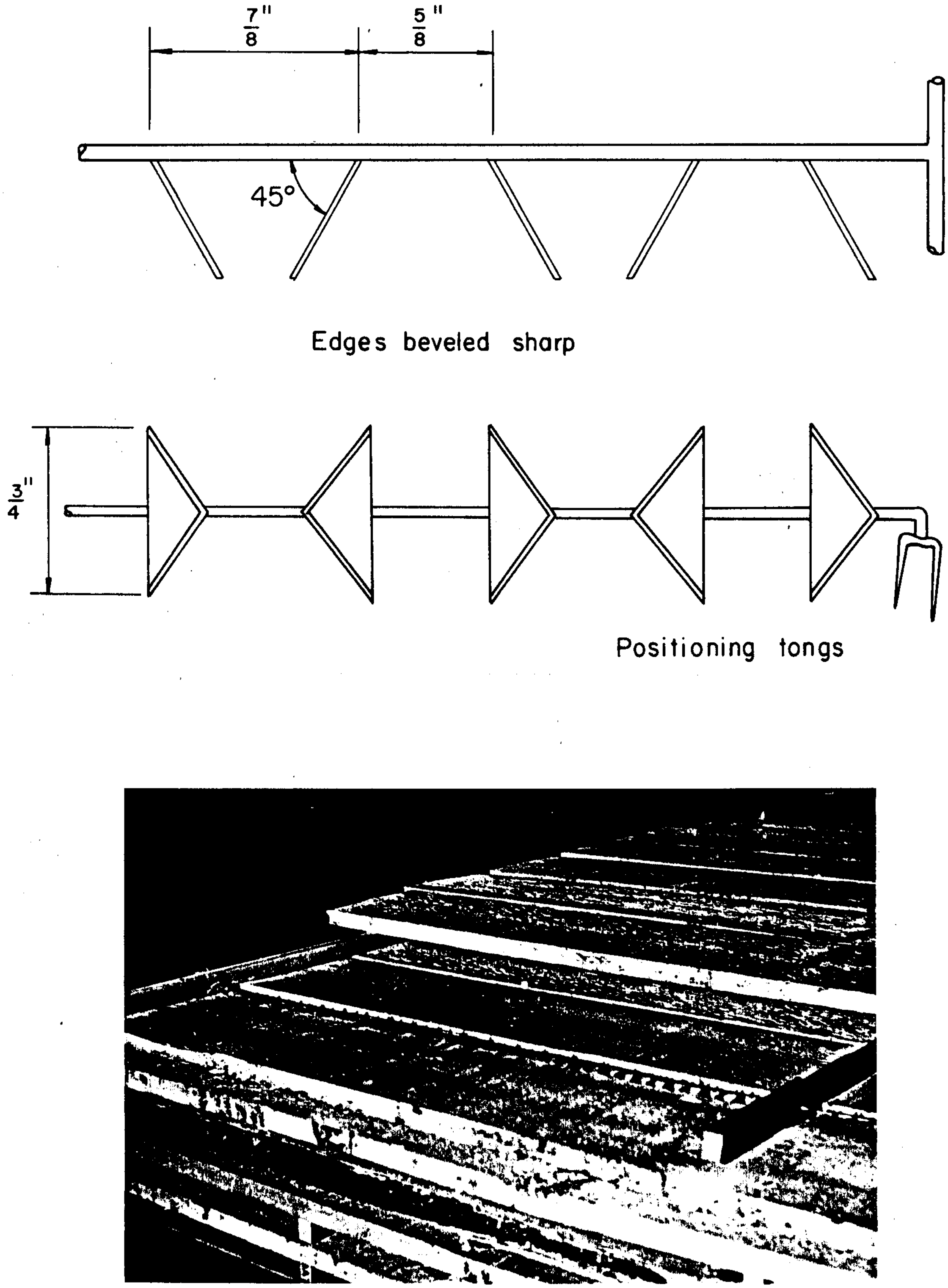


Figure 2. Delta Wing Vortex Generators in Stacked Lumber.

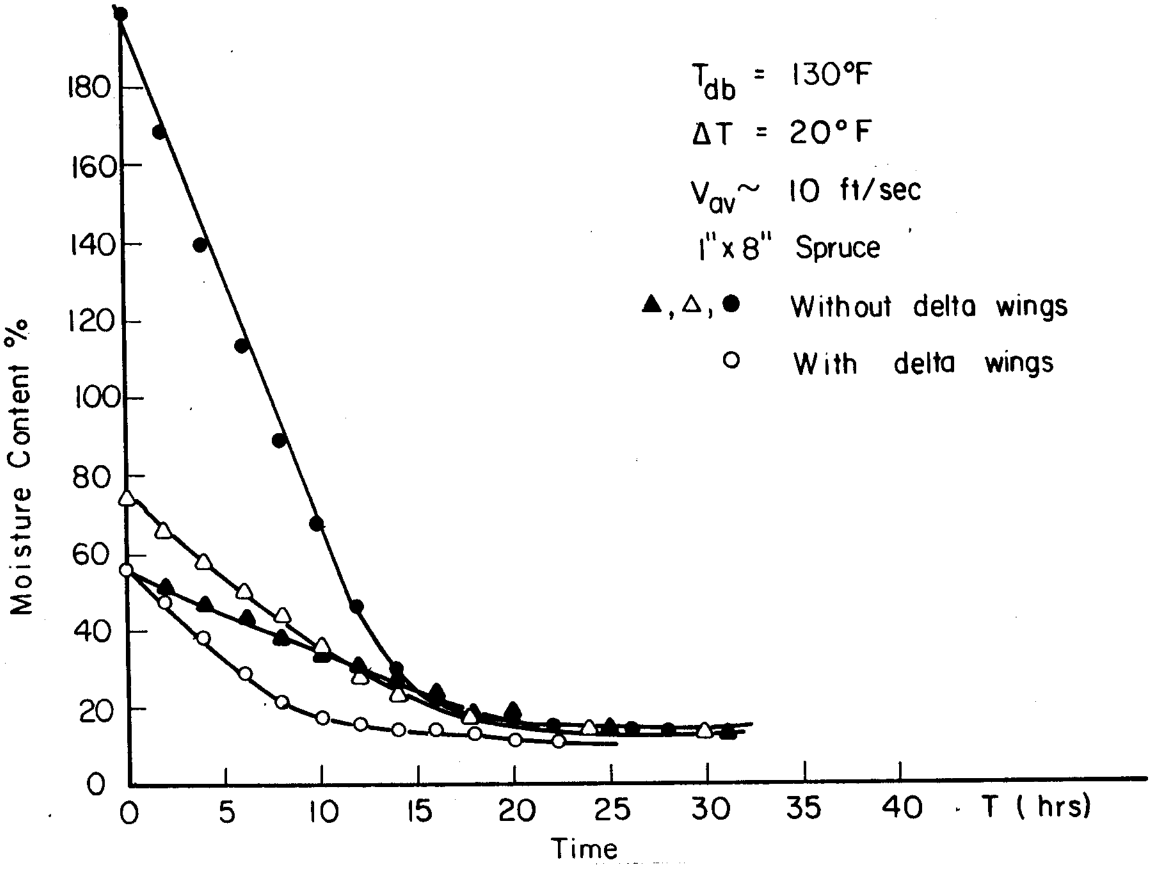
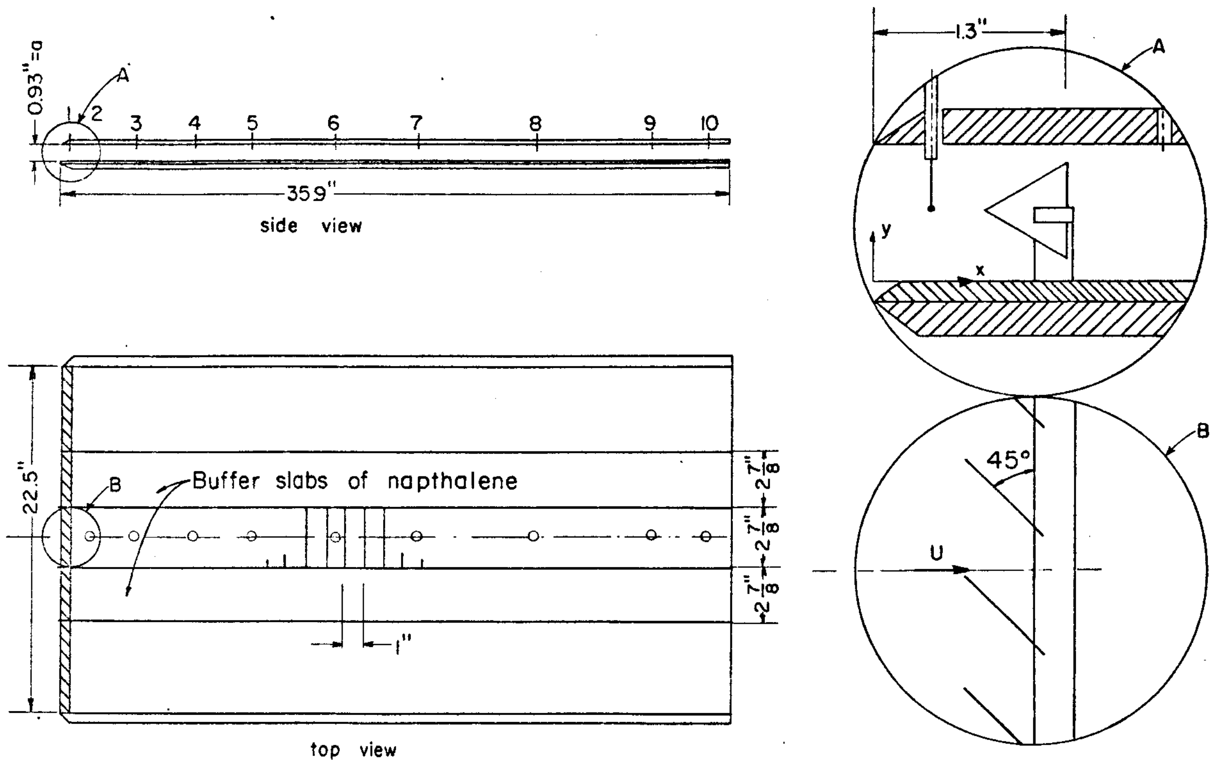


Figure 3. Moisture Loss Curves for Lumber Drying Experiment.



case 1 clean
case 2 ⫽ at entrance
case 3 ⋎ at entrance
case 4 ⋎ at entrance
⋎ at centre
case 5 ⫽ at entrance
⫽ at centre

station	Position (x)
1	0.43"
2	1.1"
3	3.37"
4	6.42"
5	9.5"
6	14.1"
7	18.7"
8	24.8"
9	30.8"
10	33.9"

Figure 4. Experimental Arrangement.

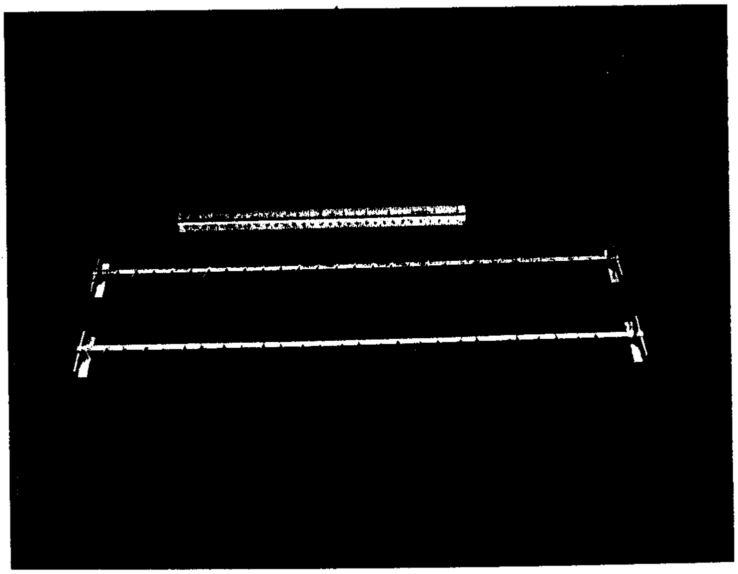


Figure 5. Vortex Generator Inserts.

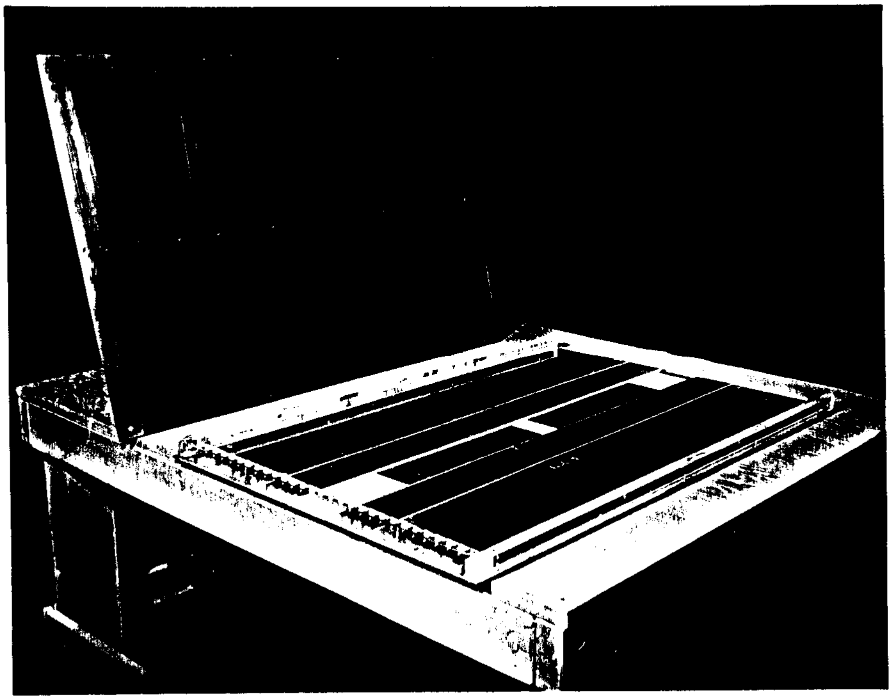


Figure 6. Duct Assembly - Vortex Generators in Place.

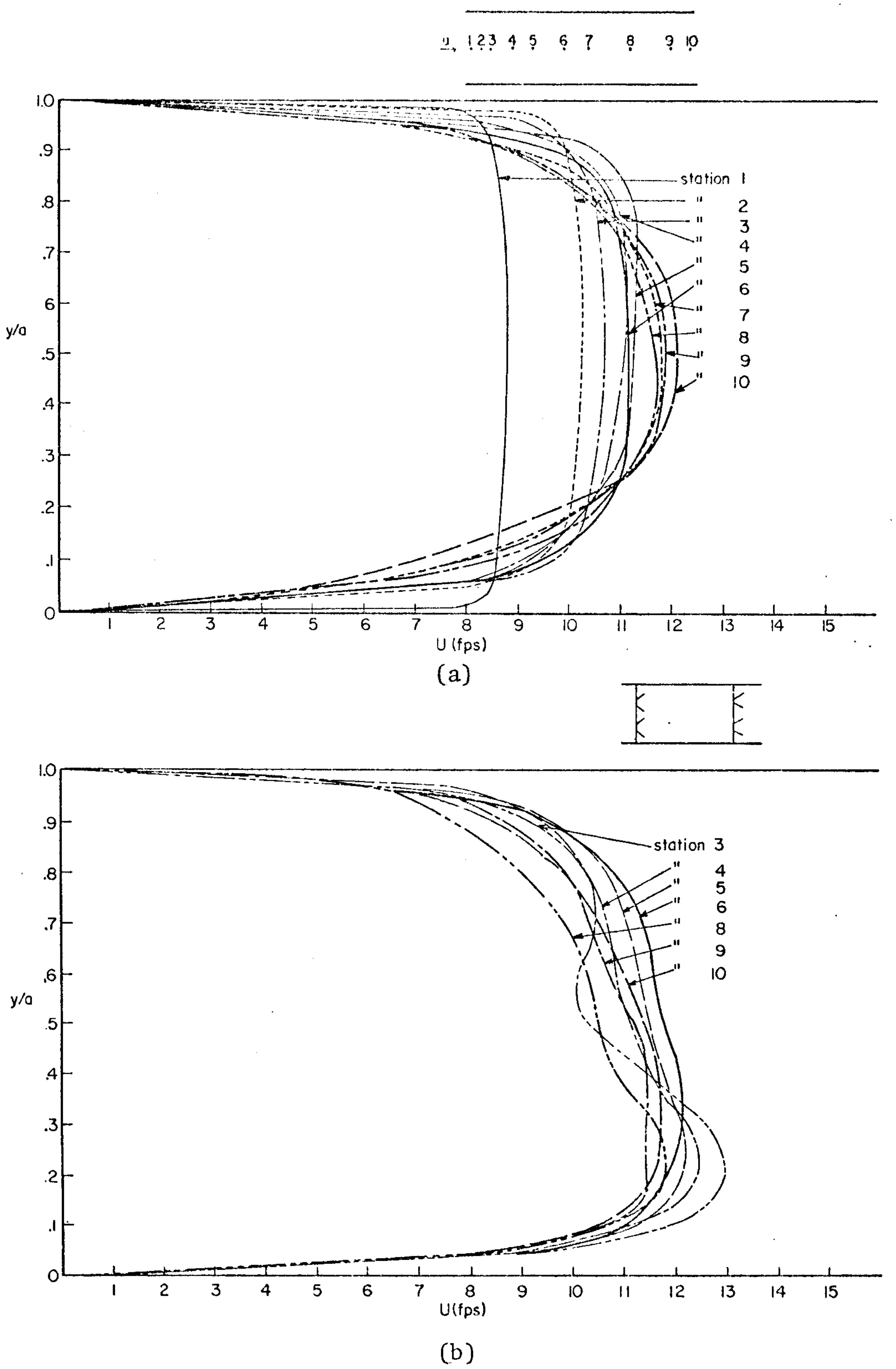
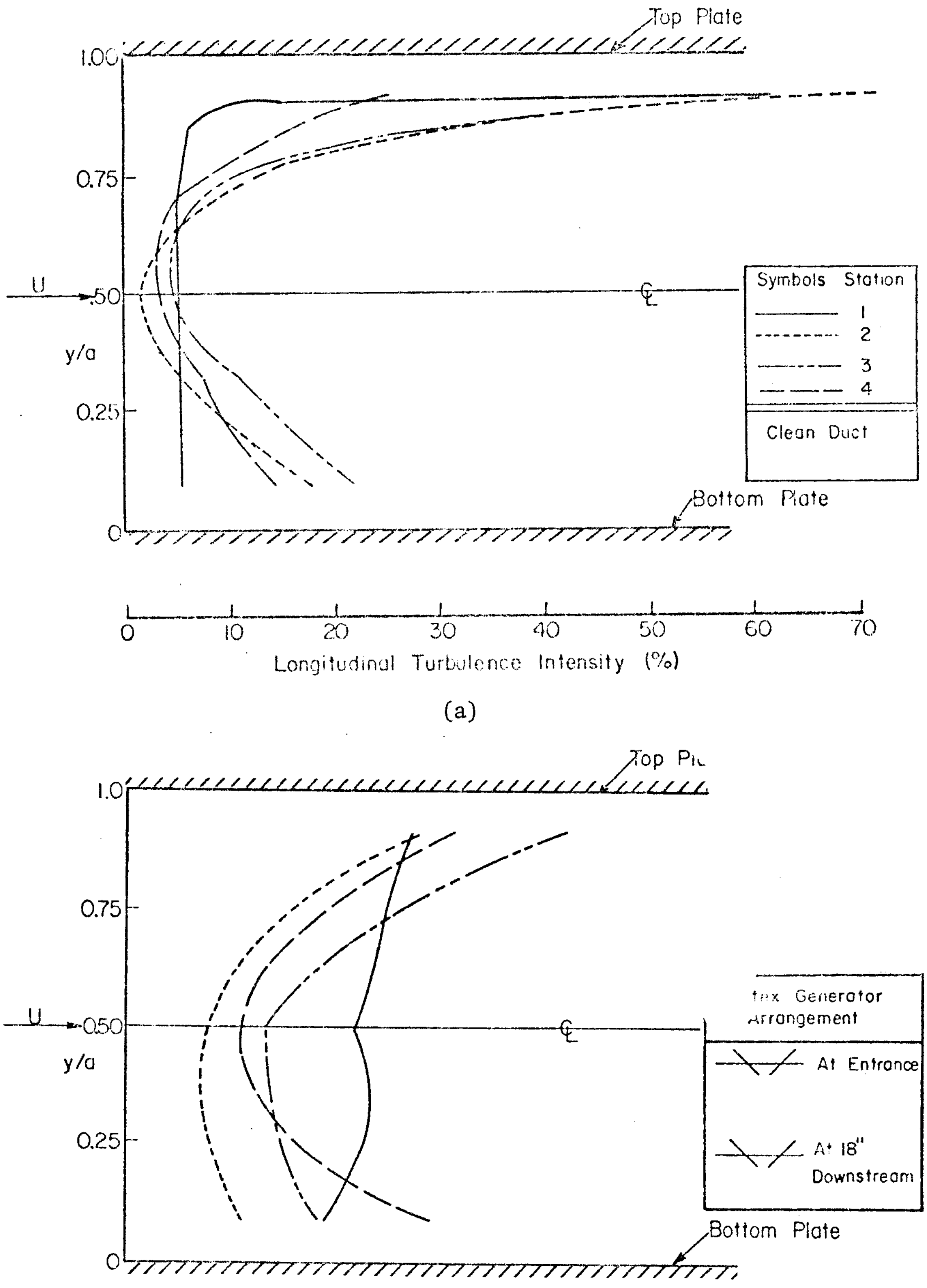


Figure 7. Velocity Profile with (a) Clean Duct (Case 1) and (b) Vortex Generators (Case 4).



(a)

(b)

Figure 8. Longitudinal Turbulent Intensity (a) Clean Duct (Case 1) and (b) with Vortex Generator (Case 4).

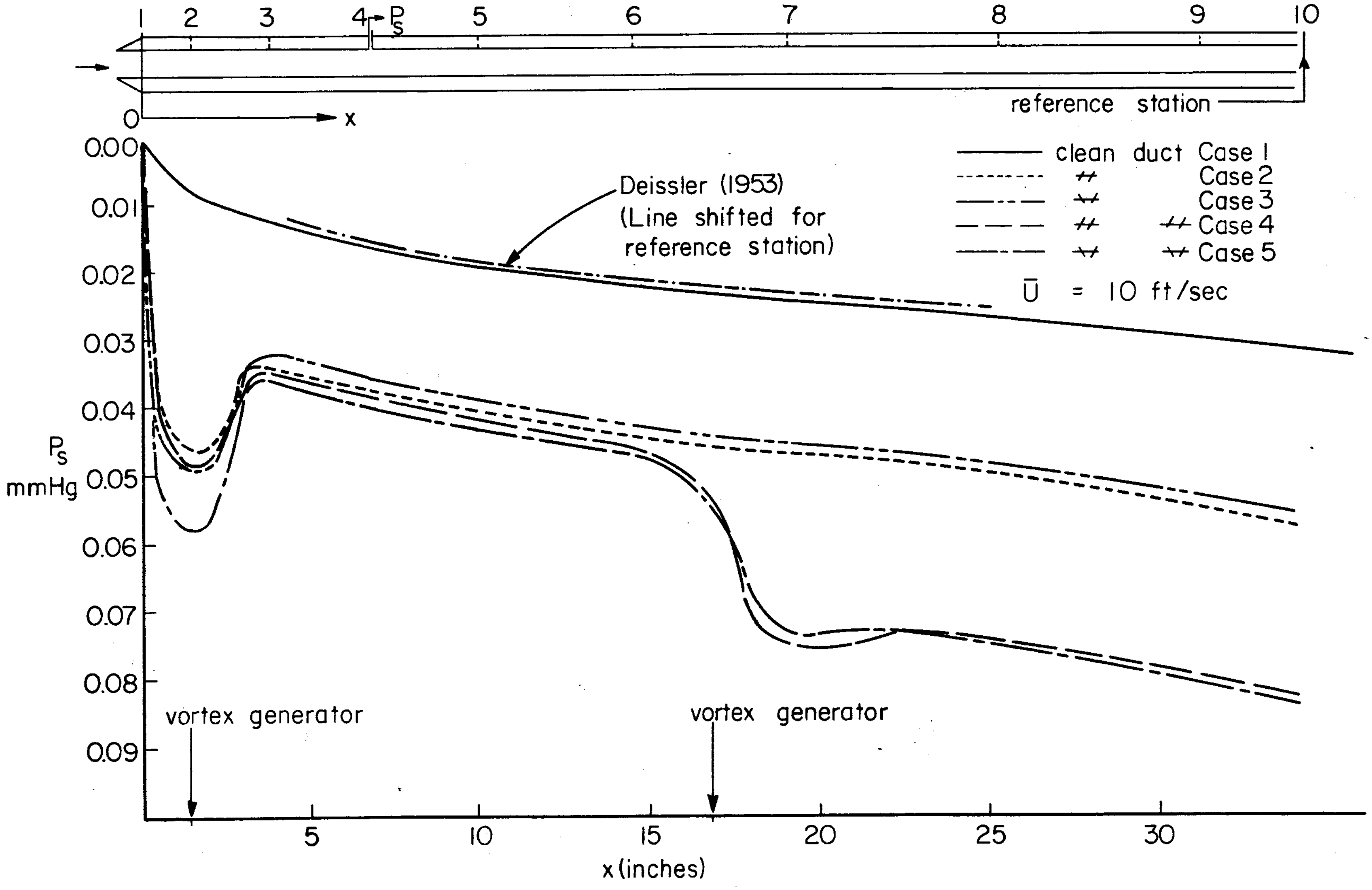


Figure 9. Static Pressure Difference.

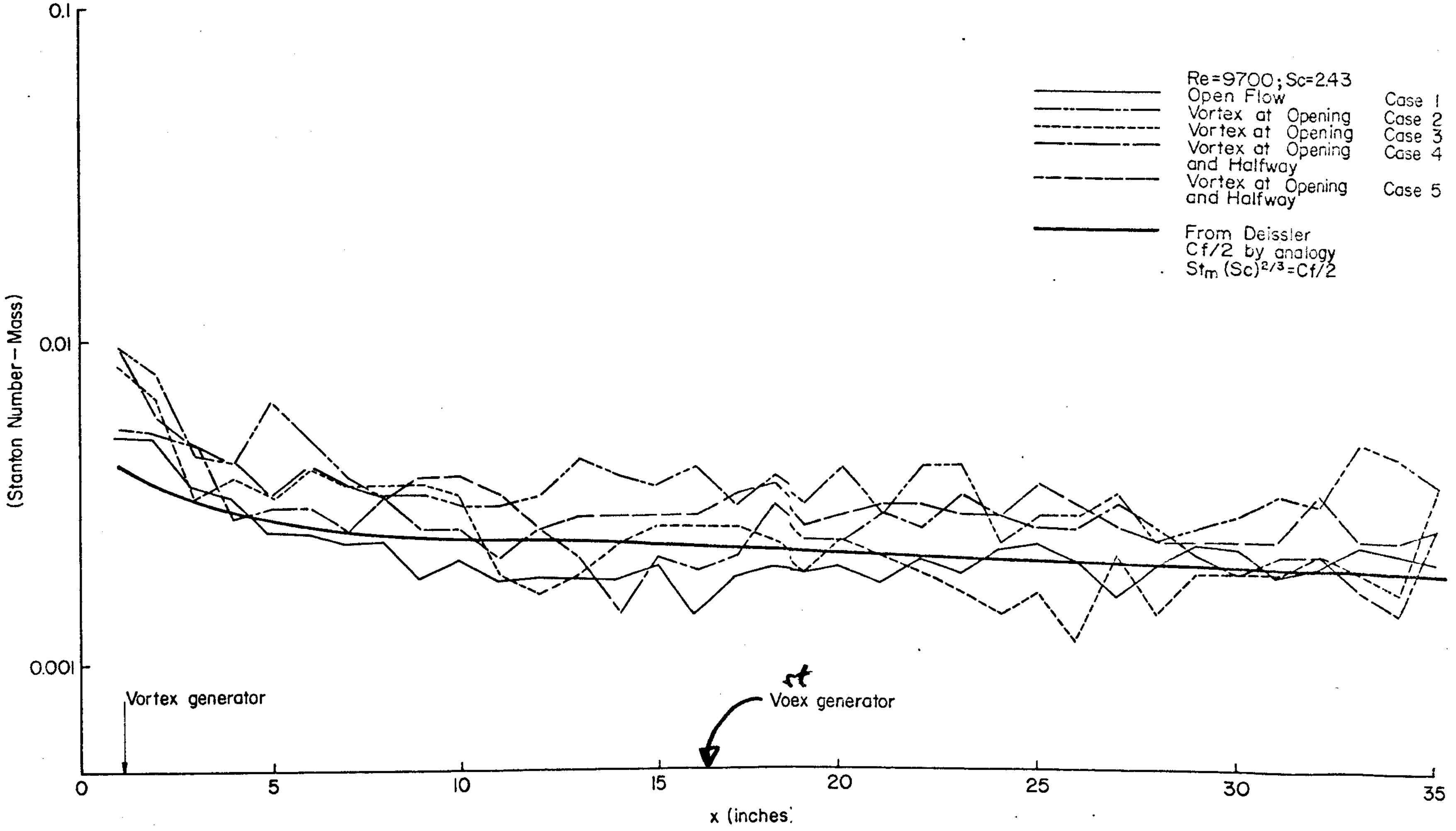


Figure 10. Relative Performance of Various Vortex Generator Configurations.