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Brief Communication

The effect of multi-plate array spacing on grid-generated turbulence

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Abstract

This study compares measurements of the streamwise integral length scale, the root mean square (r.m.s.) of the streamwise component of velocity, and the r.m.s. of the normal component of velocity obtained at the exit of a plate array with measurements obtained at the same position for the "open pipe case". The "open pipe case" is defined as the empty tube, without the plates in place, i.e., the apparatus becomes grid flow entering an unobstructed pipe. In general, this study finds that the length scale in the streamwise direction decreases with increasing plate spacing while the r.m.s. velocity in the streamwise direction increases as the plate spacing increases for fixed values of x/M (i.e., the streamwise direction to mesh-spacing ratio). These measured trends are consistent with a simple model based on vortex elements and conservation of angular momentum.

1. Introduction

Curved or flat vanes are used in a variety of devices to condition the flow. For example, flat vanes in pumps are often used to straighten the flow while curved vanes in a turbine combustor are often used to create a swirl stabilized reaction zone. In most flow conditioning applications, the flow upstream of the vane arrays is turbulent. While vanes usually produce their desired conditioning goals, they also alter the turbulent properties of the flow which in turn can affect combustion and heat transfer downstream of the vane array.

There is a dearth of studies on the effect of multi-vane arrays on turbulent flow. However, several studies have focused on the interaction of a single plate with grid-generated turbulence. For example, Courchesne and Laneville (1982) show that an increase in the turbulent intensity leads to a drag increase but that variation of turbulent length scales only has a minor effect on drag. As with most studies of plates in turbulent flows, Courchesne and Laneville focus on the effect of turbulence on the drag or the vortex-shedding behavior of a flat plate. The present study focuses on examining the effect of vane array spacing on integral length scale, turbulent intensity and isotropy on a flow that, upstream of the plates, is nearly homogeneous and isotropic.

Flow between plates has some similarity to flow through a contracting channel or duct. Thus, another useful family of studies that is related to turbulence and plate arrays is those that determine the effect of contracting and expanding ducts on turbulence. This geometry has been thoroughly studied for use in windtunnel design and development. Uberoi (1956), for example, analyzes the flow using vortex elements and conservation of angular momentum. He shows that the longitudinal component of fluctuating velocity decreases, and the lateral component of fluctuating velocity increases as the flow accelerates through a contraction section.

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2. Background

A thorough literature review has found that there is a lack of studies that explore the interaction of turbulence with plates arrays. The studies that have been completed focus on the effect of turbulence, specifically the intensity and integral length scale, on the drag coefficient of a single plate. For example, Courchesne and Laneville (1982) study the effect of grid turbulence on the drag coefficient of two-dimensional plates. They find that the drag coefficient decreases as the turbulent intensity is increased when $c/t > 0.5$. Conversely, for plates with $c/t < 5$ the drag coefficient initially increases and then decreases as the turbulent intensity increases.

Similarly, Nakamura and Ohya (1984) study the effect of turbulent intensity and integral length scale on the drag coefficient, the rate of growth of the shear layer, and the vortex-shedding frequency. They show that an increase in the turbulent intensity leads to a drag increase and that small-scale turbulence is found to increase the growth rate of the shear layer, while large-scale turbulence is found to enhance the roll up of the shear layer.

For most practical vane applications, the spacing between vanes is greater than one vane thickness. Miau et al. (1996) give results of special phenomena that occur when the spacing is about equal to or less than one vane thickness. They use a two-vane array with closely spaced vanes to study a specific bi-modal wake behavior called "flopping". However, based on studies of the flow downstream of cylinder arrays (cf. Zdravkovich (1977)), for spacings more typical of vane applications, flopping is not expected to occur.

The flow between vanes is qualitatively similar to flow passing through a contracting duct. Specifically, the formation of the leading edge separation zone and the growth of the boundary layer on the upper and lower surfaces of the channel formed between adjacent vanes leads to an acceleration of the flow in the center region. Uberoi (1956), Tsuge (1984), Hussain and Ramjee (1976), and Ramjee and Hussain (1976) use qualitative arguments based on vortex elements and conservation of angular momentum to describe the changes in integral length scales and turbulent intensities due to the effect of contraction sections. In general, all these studies find that the combination of a vortex element with conservation of angular momentum is a model that is consistent with measured turbulent intensity and integral length scale trends.

In many vane applications, turbulence levels and scales must be controlled in order to produce a desired effect. No past work has been found that examines the effect of an array of plates of vanes on turbulence. Thus, the goal of this study is to determine the effects of plate or vane arrays on turbulent intensity and integral length scales.

3. Experimental apparatus

The flow facility (Fig. 1) used for all experiments in this study consists of a flow conditioning section comprised of honeycomb and dampening screens, a contraction section with a contraction ratio of 11.4, and an 8.89 cm internal diameter by 0.5 m long acrylic tube which functions as the test-section. The test-section is followed by an aluminum tube that also has an 8.89 cm internal diameter and a 0.5 m length. Slots of 0.4 cm center-line-to-center-line spacing are machined into the sides of the tube 22.9 cm from the contraction exit which allow the flat plates to be inserted or removed. The flat plates have a chord of 2.54 cm and a thickness of 0.13 cm. The streamwise coordinate, x, has its origin

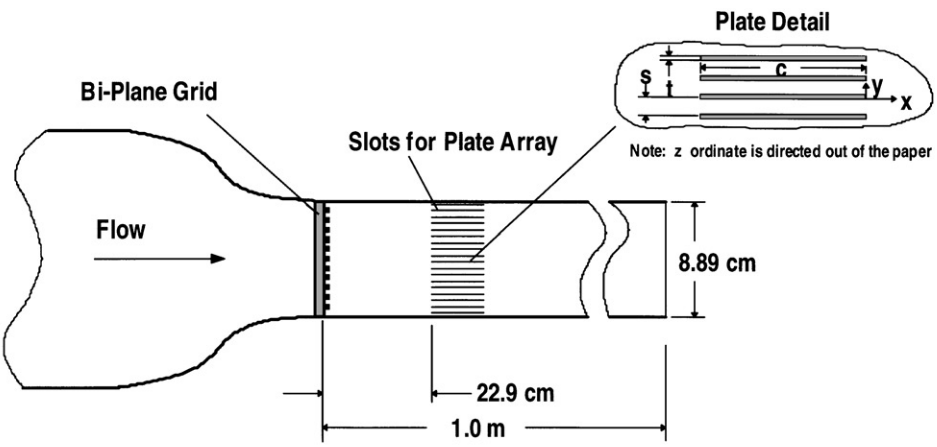

Fig. 1. Schematic diagram showing the test configuration and defining the nomenclature used for the study.

at the trailing edge of the plate; the spanwise coordinate, y, has its origin at the centerplane of the plate that is positioned closest to the test-section center-line; and the depth coordinate, z, originates from the measurement plane and travels normal to the x and y coordinates and outward. The spacing is varied by adding and removing plates from the slots while keeping the spacing between the plates equal. The unused slots are sealed. Thus, the average measured spacing, s, is the distance between the centerplanes of adjacent plates and can be set to 0.32, 0.79, 1.23, 1.67 or 2.54 cm.

To determine the effect of freestream turbulence on the flow downstream of the plate array, a bi-plane grid composed of flat plates with mesh spacing of 0.92 cm (M), a thickness of 0.16 cm, and a depth of 1.27 cm is placed at the contraction exit. The leading edge of the plates is located 22.9 cm from the downstream side of the grid.

The x-wire probe that is used to obtain the velocity, turbulence intensity, and integral length scale consists of 2 mm long, 0.00508 mm diameter, platinum wire that is silver soldered to a TSI-1241 sensor holder. The probe holder is connected to a traverse support that is located 28 cm downstream of the sensors. The sensors are connected to TSI Model 1050 constant temperature anemometers, to low-pass filters, to a Computer Boards Inc. (CBI) SSH-16 sample and hold board, and a CBI CIO-AD16F 12 bit analogue-to-digital converter which is controlled by a PC clone. At 12 m/s, the frequency responses of the sensors, based on the square wave test, are about 15 kHz. The x-wires are operated at an overheat ratio of 1.7. The data are collected at 10 000 samples per second for a period of 81.9 s and then low-pass filtered at 5 kHz.

4. Results

The x-wire probe is placed on the center-line between the third and fourth plates from the bottom, at the trailing edge of the plate array to obtain measurements of the streamwise velocity, u, and the transverse velocity, v, i.e., the component normal to the plates. The streamwise integral time scale is calculated by using the trapezoidal rule to numerically integrate the normalized autocorrelation from zero time shift to the time shift where the autocorrleation first crosses zero. The streamwise integral length scale, L, is then calculated by multiplying the integral time scale by the streamwise mean velocity, i.e., Taylor's hypothesis (Tennekes and Lumley, 1972).

Fig. 2 shows the effect of plate spacing in the array on integral length scale, in the streamwise direction, for $x/M = 20$, 40 and 80 and for the open pipe case, i.e., measurements with the plate array removed. For all three x/M locations the integral length scale in the streamwise direction decreases with increasing plate spacing. Further, at $x/M = 20$, the integral length scale for the widest spacing, $s = 2.54$ cm, is approximately the same size as for the open

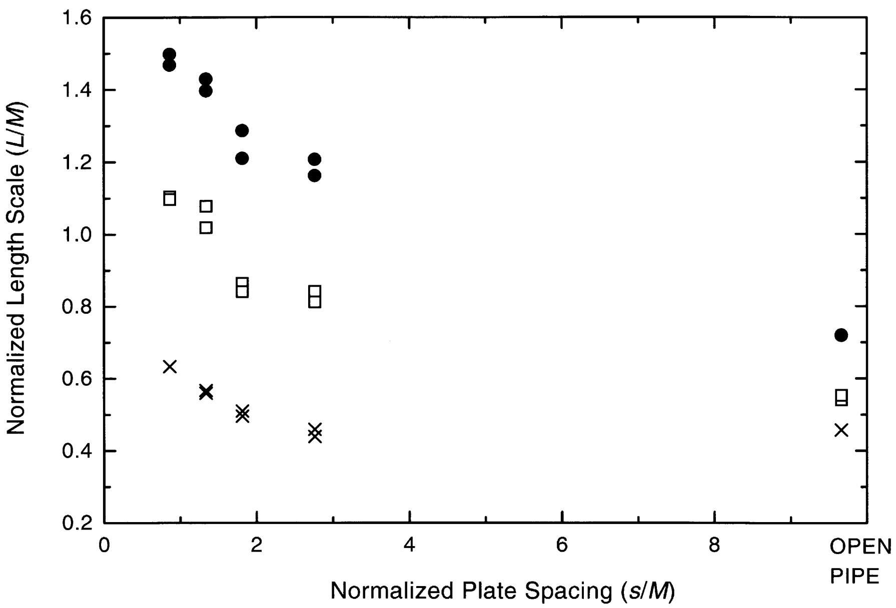

Fig. 2. Graph of the center-line, streamwise integral length scale versus plate spacing. Symbols: $x/M = 20$, $\times$; $x/M = 40$, $\square$; and $x/M = 80$, $\bullet$.

pipe condition. Conversely, the integral scales at $x/M = 40$ and 80 with $s = 2.54$ cm are, respectively, factors of approximately 2 and 3 times larger than for the open pipe.

Fig. 3 shows the effect of plate spacing on the root mean square (r.m.s.) of the streamwise and normal components of velocity. With the exception of the smallest plate spacing, i.e., $s = 0.79$ cm, the r.m.s. velocity in the streamwise direction increases as the plate spacing increases for fixed values of x/M. Although the values of the normalized r.m.s. are much higher closer to the array, the same trend is found at all three x/M positions. The large increase in r.m.s. velocity in the streamwise direction at $s = 0.79$ cm is probably due to the merging of the boundaries forming on the side of the plates.

Fig. 3 also shows that, except for at $s = 0.79$ cm, the r.m.s. velocity in the normal (v) direction remains relatively constant as the spacing is changed and is approximately equal to the r.m.s. velocity in the normal direction for the open pipe. Again, the large jump in r.m.s. velocity in the normal direction is probably due to the merging of the boundary layers.

By considering conservation of angular momentum applied to a vortex element, the trends observed in Figs. 2 and 3 can be qualitatively explained. We characterize the vortex element as cylinders exhibiting solid body rotation. Under this assumption, the cross-sectional area of a vortex element multiplied by its rotational velocity ($\Omega = A \cdot \omega$) is equal to the circulation and is proportional to the angular momentum. Thus, an increase in A results in a decrease in ω while a decrease in A results in an increase in ω.

A series of flow channels is formed between each adjacent plate in the array. As the boundary layers form on each side of the channel, the velocity near the centerplane of the passage is increased. As vortex elements with axes aligned in the z-direction pass through the channel, the increased velocity increases the length of the element in the x-direction and changes the shape of the cross-sectional area of the element from a circle to an ellipse. This increases the cross-sectional area of the elements in the $x-y$ plane. Due to conservation of angular momentum, as A increases, ω of the element in the $x-y$ plane decreases. When the side of the element that is moving at ω is aligned with the flow, it adds a positive fluctuation. Conversely, as the side of the element that is moving at ω is opposed to the flow, it adds a negative fluctuation. Thus, as ω in this plane decreases, the r.m.s. velocity in the streamwise direction decreases.

As vortex elements with axes aligned in the y-direction pass through the channel, the growth of the boundary layer on the sides of the channel decreases the length of the elements in the y-direction and increases and the cross-sectional area of the elements in the $x-z$ plane. Due to conservation of angular momentum, an increase in A corresponds to a decrease in ω. As ω of the element in the $x-z$ plane decreases, the r.m.s. velocity in the streamwise direction decreases. Thus, vortex elements with axes aligned in either the z- or y-directions lead to increases in the r.m.s. velocity in the u-direction. This interaction of the plates with the vortex elements is shown in the schematic of Fig. 4.

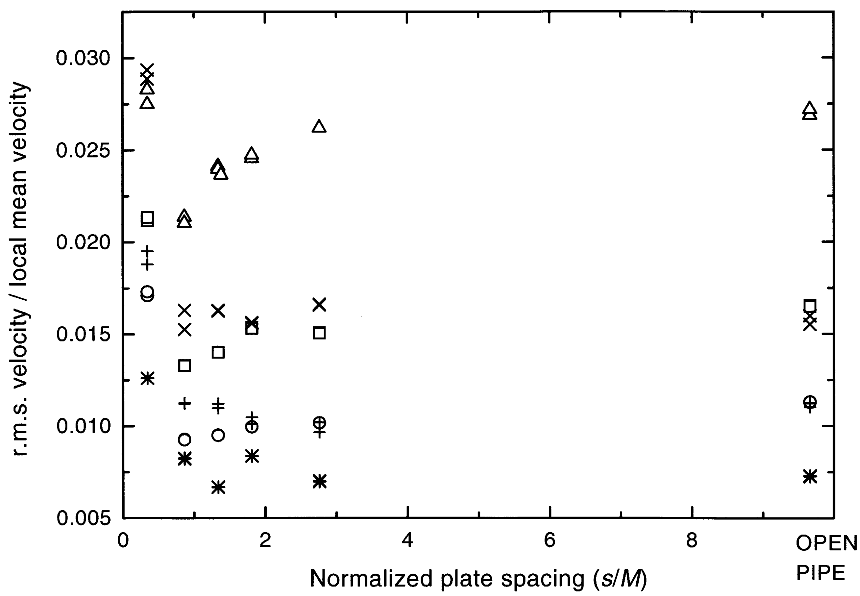

Fig. 3. Plot showing the normalized r.m.s. velocity versus plate spacing. Symbols: streamwise direction at $x/M = 20$, △; streamwise direction at $x/M = 40$, □; streamwise direction at $x/M = 80$, ○; normal direction at $x/M = 20$, ×; normal direction at $x/M = 40$, $*$; normal direction at $x/M = 80$, +;

In order to qualitatively describe the trends in the r.m.s. velocity in the direction normal to the plates in the array, vortex elements with axes aligned in the z-direction are again considered. From the previous discussion, passage of these vortex elements through the channels in the arrays leads to decreases in ω of the elements in the $x-y$ plane. As ω in this plane decreases, the r.m.s. velocity in the direction normal to the plate array decreases.

Further, as vortex elements with axes aligned in the x-direction pass through the channel, the velocity increase leads to an increase in the length of the elements in the x-direction which leads to a decrease in the cross-sectional area of the elements in the $y-z$ plane. Since a decrease in A corresponds to an increase in ω, the r.m.s. velocity in the direction

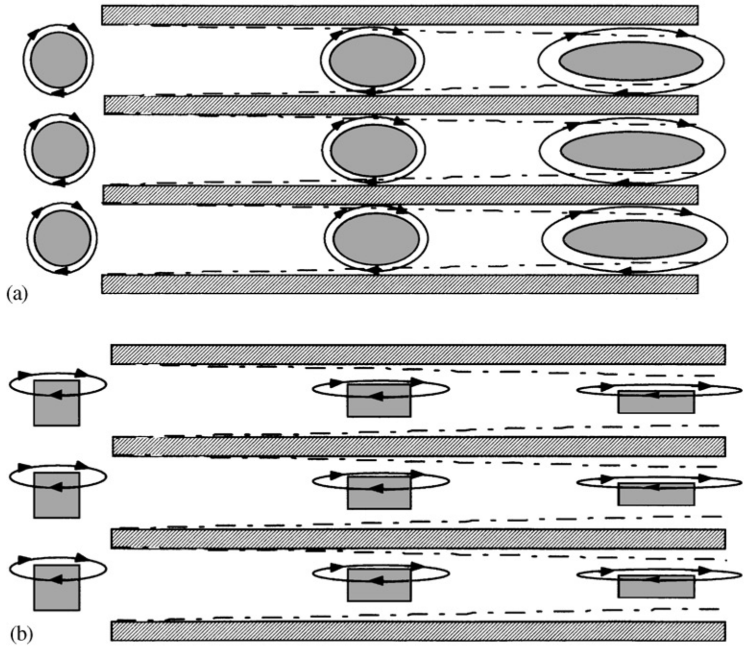

Fig. 4. Diagram illustration of how the flow through the plates alters the shape of the vortex elements and affects the r.m.s. in the streamwise direction. Fig. 4a and b indicate decreases in r.m.s. velocity.

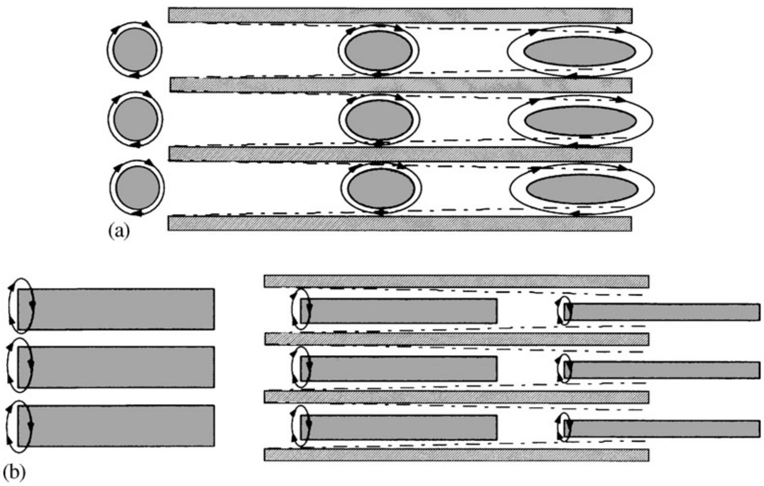

Fig. 5. Diagram illustration of how the flow through the plates alters the shape of the vortex elements and affects the r.m.s. in the normal direction. Fig. 5a indicates a decrease in r.m.s. velocity, while Fig. 5b illustrates an increase in r.m.s. velocity.

normal to the plate array is increased. Thus, vortex elements with axes aligned in the z-direction correspond to a decrease in r.m.s. velocity normal to the array while elements with axes aligned in the x-direction correspond to an increase in r.m.s. velocity normal to the array. Since it is very likely that approximately the same number of vortex elements exist that have axes aligned in the x-direction as elements that have axes aligned in the z-direction, the effect on the r.m.s. velocity of the elements aligned in one direction is countered by the effect of the elements aligned in the other direction. This is consistent with the trends observed in Fig. 3. This interaction of the plates with the vortex elements is shown in the schematic of Fig. 5.

5. Summary

At the exit of the plate array, for all three x/M (i.e., the streamwise direction to mesh-spacing ratio) locations, the length scale in the streamwise direction decreases with increasing plate spacing. As x/M increases, the effect of the array on the integral length scale decreases. This is demonstrated at $x/M = 20$. Here, the integral length scale for the widest spacing, $s = 2.54$ cm, is approximately the same size as for the open pipe. In contrast, the integral scales at $x/M = 40$ and 80 with $s = 2.54$ cm are significantly affected by the array since the integral scales are, respectively, factors of approximately 2 and 3 times larger than for the open pipe. In general, the r.m.s. velocity in the streamwise direction increases as the plate spacing increases for fixed values of x/M. Although the values of the normalized r.m.s. are much higher closer to the array, the same trend is found at all three x/M positions. These measured trends are consistent with a simple model based on vortex elements and conservation of angular momentum.

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