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Comparing the flow on the bounded and unbounded sides of a plate

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Abstract

A two-plate array is used to compare the flow characteristics between the side of a rectangular plate that is bounded by an adjacent plate and the side of the plate that is unbounded. For $c/t = 3$, flow visualization shows that the thickness of the recirculation bubble is slightly thinner on the bounded side, but the distance from the plate's leading edge to the point of reattachment is nearly the same on both the bounded and the unbounded sides of the plate. For $c/t = 6.67$ and $c/t = 16$, the flow reattaches in a shorter downstream distance from the leading edge of the bounded side of the plate than the unbounded side of the plate. On the bounded side of the plate, the recirculation zone formed by the reattached flow is less than half as thick as the recirculation zone formed on the unbounded side of the plate.

Vane arrays are often used to condition flowfields. For example, swirl vanes produce a vortical motion that is used to aerodynamically stabilize reactions within combustors. Besides altering the flow in the desired manner, vanes also affect the dynamics of the flow field. The flow around and downstream of a single-plate exhibits significant differences than that observed around and downstream of a plate in a plate array. Some of these differences can be described by the Strouhal number, $St = \ell \cdot f/U$, where ℓ is the characteristic length, f is the frequency associated with the vortex shedding and U is the characteristic velocity. For $St(c)$ and $St(t)$, the characteristic length is the chord or thickness respectively and the characteristic velocity is the freestream velocity. The characteristic length and velocity for the Reynolds number used in this study is the chord of the plate and the freestream velocity.

Many studies focus on the flow characteristics around and downstream of single plates. For example, Okajima [1], with $1 \leqslant c/t \leqslant 4$ and $70 \leqslant Re \leqslant 2 \times 10^4$, presents a study of the relationship between c/t, Reynolds number, and vortex shedding frequencies of single flat plates. As the Reynolds number is varied from 70 to 2×10^4, he finds an abrupt change in both the calculated and visualized downstream flow pattern and in the vortex shedding frequency at critical Reynolds numbers for each c/t studied. Okajima [1] suggests that the abrupt flow change at the critical Reynolds number is due to the reattachment of the separated flow. Above the critical Reynolds number, he observes that the flow that separates at the leading edge of the plate always reattaches to the side of the plate. Below the critical Reynolds number, the flow only periodically reattaches to the side of the plate.

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Nomenclature

ℓ	characteristic length for the Strouhal number	St	Strouhal number
c	chord length of the plate	$St(c)$	Strouhal number based on plate cord length
f	frequency	$St(t)$	Strouhal number based on plate thickness
Re	Reynolds number	t	thickness of the plate
		U	Freestream air velocity

Parker and Welsh [2], with $0.055 \leqslant c/t \leqslant 52.00$ and $1.48 \times 10^4 \leqslant Re \leqslant 3.11 \times 10^4$, and Stokes and Welsh [6], with $c/t \leqslant 16.0$ and $8 \times 10^3 \leqslant Re \leqslant 4.43 \times 10^4$, describe the flow in the near wake as a function of c/t. Specifically, they define four flow regimes based on c/t. Regime 1 corresponds to $c/t < 3.2$. The flow separation occurs at the leading edge of the plate and never reattaches. A vortex street is not formed. Regime 2 corresponds to $3.2 \leqslant c/t \leqslant 7.6$. The shear layer formed by the separation at the leading edge periodically reattaches, permitting the formation of a regular vortex street. Regime 3 corresponds to $7.6 < c/t \leqslant 16$. The shear layers formed at the leading edge always reattach upstream of the trailing edge and form a leading-edge recirculation zone. The recirculation zone grows and divides in a random manner to produce irregular shedding. No vortex street forms. Finally, Regime 4 corresponds to $c/t > 16$. The recirculation zones always reattach but fluctuate in length similar to the behavior in Regime 3. For this regime, the recirculation zone reattaches far enough upstream from the trailing edge so that the vortex street formed behind the plate is not influenced by the leading-edge recirculation zone.

Nakamura et al. [3], with $3.0 \leqslant c/t \leqslant 16.0$ and $1 \times 10^3 \leqslant Re \leqslant 3 \times 10^3$, confirm the existence of these regimes. They show that the dominant shedding frequency varies for different ranges of c/t. At a c/t where an abrupt transition in $St(c)$ occurs, two characteristically different large scale structure shapes are observed which produce two different non-harmonic shedding frequencies. One of these frequencies corresponds to the lower, pre-transition, Strouhal number while the other corresponds to the higher, post-transition, Strouhal number. Each of these transitions represents a change in magnitude of $St(c)$ of about 0.6.

Guillaume and LaRue [4] compare the shedding behavior around and downstream of a single plate with the shedding behavior around and downstream of the same plate positioned in an array of six identical plates. The shedding frequencies and corresponding values of $St(c)$ and $St(t)$ are obtained using a hot-wire anemometer. For the single plate, they find step changes in $St(c)$ of about 0.6 at $c/t \approx 6$, 8 and 11 that correspond to abrupt changes in the shedding behavior at the trailing edge of the plate. In contrast to the single-plate results, only one abrupt transition, i.e. at $c/t \approx 4$, is observed downstream of a plate positioned in a plate array. Above $c/t \approx 4$, increasing c/t leads to an increased $St(c)$, but there are no abrupt transitions. The goal of this current study is to investigate the lack of abrupt transitions above $c/t \approx 4$.

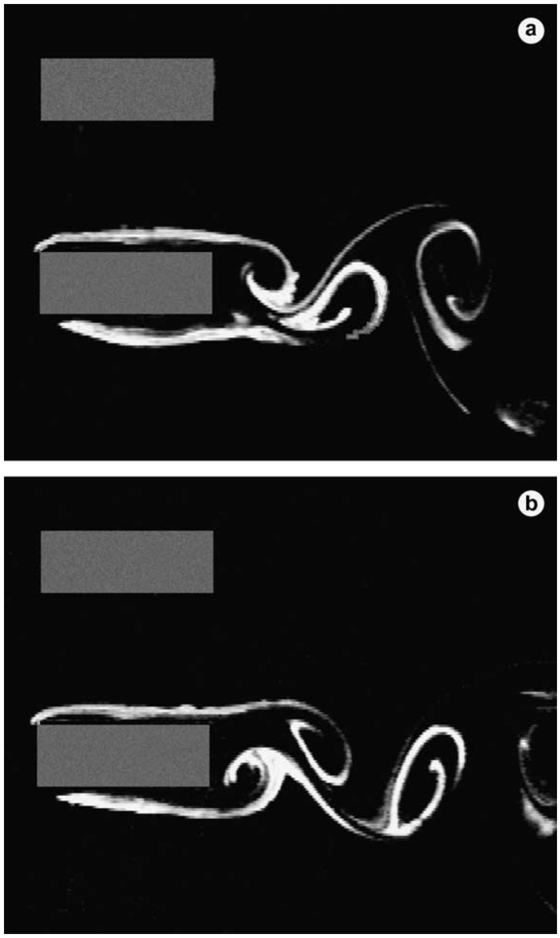

Fig. 1. Smoke visualization of the flow around and downstream of a two-plate array with $Re = 500$ and $c/t = 3$. (a) shows the vortex shed from the trailing edge on the side of the plate nearest the adjacent plate while (b) shows the vortex shed from the side of the plate farthest from the adjacent plate.

The windtunnel that is used for all the experiments has a test section length of 6.71 m, a cross-section of 61 by 91 cm, and is preceded by a contraction section with an area reduction from 5.15 m^2 to 0.55 m^2 (a contraction ratio of 9.36). A two-plate array is used in this study so that a comparison of the flow separation characteristics can be made between the side of the plate that is bounded by an adjacent plate and the side of the plate that is unbounded. For all test plates, the separation between plates is 2.54 cm, t = 1.27 cm, and the length in the spanwise direction is 0.30 m. Thus, there is 15.5 cm of clearance between the edge of the plates and the wall of the windtunnel on both sides. The plates are mounted at one end to a 1.27 cm diameter, 0.62 m high rod that is attached to a chemistry stand. The vertical rod passes vertically through the center of the chord of the plate at the far spanwise end of the plates. The two-plate arrays are mounted parallel to the floor of the tunnel and centered between the floor and the ceiling of the tunnel. The base of each stand has an approximate width of 16 cm, a length of 27 cm, and a height of 2.54 cm.

Smoke that is illuminated with a laser light sheet is used to visualize the flow. The nominal 0.8 mm thick laser sheet is produced by passing a 2.5 W argon-ion beam through a cylindrical lens. The smoke is injected at the leading edge of the plate through three equidistant holes located in the plane of the laser sheet. Images are collected with a video camera at a shutter speed of 1/10 000 s and are digitized with frame-grabbing hardware and software.

Fig. 1 shows a smoke visualization image of the flow around and downstream of the plate array with Re = 500 and c/t = 3 (Regime 1). Consistent with the single-plate observations of Parker and Welsh [2], flow separation occurs at the leading edge of the plate and never reattaches. However, the thickness of the recirculation bubble is slightly less on the bounded side of the plate than on the unbounded side. This decrease in thickness is due to the favorable pressure gradient in the channel formed between adjacent plates. The distance from the leading edge of the plate to the point of reattachment is the same on both the bounded and unbounded sides of the plate. Therefore, at c/t = 3, the plates in the array are nearly unaffected by neighboring plates and produce flow patterns and Strouhal numbers similar to those observed for single plates.

With Re = 500, Fig. 2a and b show smoke visualization of the flow around and downstream of two-plate arrays with c/t = 6.67 (Regime 2) and c/t = 16 (Regime 3), respectively. For both c/t = 6.67 and c/t = 16, the recirculation zone on the bounded side of the plate formed by the reattached flow is less than half as thick

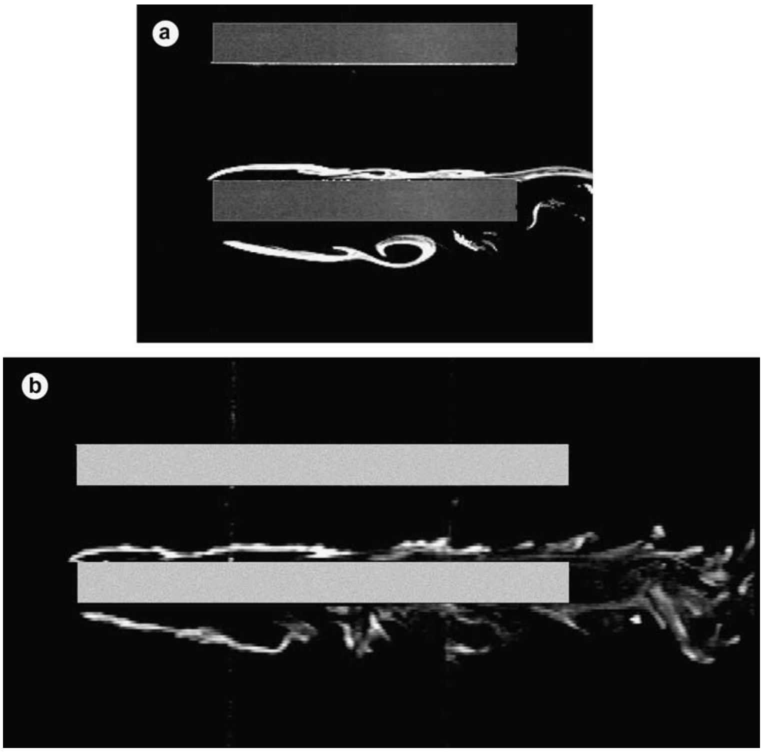

Fig. 2. Smoke visualization of the flow around and downstream of a two-plate array with Re = 500. (a) shows the characteristics of the vortices shed with c/t = 6.67 while (b) shows the characteristics of the vortices shed with c/t = 16.

as the recirculation bubble formed on the unbounded side of the plate. As with the plates with $c/t = 3$, the decrease in thickness is due to the favorable pressure gradient. However, because these plates are relatively longer, the pressure gradient is of sufficient strength to induce reattachment of the flow at shortened downstream distance than that observed on the unbounded side.

In summary, the adjacent sides of the neighboring plates create a channel that accelerates the flow and produces a favorable pressure gradient. If the chord is of sufficient length, e.g. for $c/t = 6.67$, the pressure gradient induces reattachment of the flow in contrast to the behavior of the flow on an unbounded surface [2]. For an unbounded surface, the flow is allowed to separate and produce a series of abrupt St transitions. The flow around a plate array (i.e. a bounded surface) behaves much differently than that observed around a single plate (i.e. an unbounded surface) and produces St characteristics that are inconsistent with the findings of researchers who have studied single plates [2]. When the separated flow at the leading edge of the plate always reattaches (i.e. as observed with the flow around an array), the shedding frequency and corresponding Strouhal number are only related to the trailing edge recirculation zone which increases linearly as velocity increases. Thus, for plates with $c/t > 4$, the characterizations of the vortex shedding behavior for single plate arrays stated by Parker and Welsh [2] are inconsistent because the flow separates at the leading edge and always reattaches. This is consistent with Guillaume and LaRue [5] who show that in a plate array with $c/t > 4$, the frequency of shedding increases linearly with velocity.

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