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# Vortex Shedding: A Review on Flat Plate

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**Abstract**—Flat plates, both single and in tandem or side by side arrangement, are widely used in many engineering applications. Despite vast investigations of the flow structures and wakes downstream of these bluff bodies, this unsteady phenomenon yet remains a fundamental issue in many industrial applications. This paper reviews the state of the art concerning the flow over flat plates in different arrangements focusing on plates normal to the flow. Turbulent wake regions are discussed for the flat plates in side by side or tandem arrangement. Numerical studies are reviewed with emphasis on the realized turbulent models. The effect of the chosen turbulence model on the prediction of the wake region is discussed.

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Flow structures behind bluff bodies have been widely investigated in the past three decades due to their importance in various fields of industry, civil engineering, and wind engineering. A flat plate and circular and square cylinders are among the most employed geometries in engineering. These simple geometries generate complex wake structures which resemble turbulent wakes behind industrial objects, such as cooling towers, bridges, and wind turbines.

The shedding of the Kàrmàn vortices from these structures can be the cause of unsteady loads keading to the failure. For this reason, in view of the above-mentioned applications, numerous studies have been conducted in order to identify the wake structures. Sumner [1], Zdravkovich [2], Zdravkovich [3], Zdravkovich [4], and Matsumoto [5] presented comprehensive reviews concerning circular and square cylinders. However, the absence of a similar review concerning the vortex shedding from flat plates instigates to fill this gap. Thus, the purpose of this review is to discuss different arrangements of the normal and inclined flat plates. Moreover, the influence of the chosen turbulence model on the parameters of the calculated turbulent wake behind a flat plate is considered.

## 1. SINGLE FLAT PLATE

The topic of the flow over a flat plate was always an important matter of discussions; many researchers have investigated the flow past a single flat plate normal to main flow. The researchers, such as Mazharoğlu and Hacışevki [6], Kiya and Matsumura [7], and Bearman [8], conducted experimental studies, while Narasimhamurthy and Andersson [9], Saha [10], and Najjar and Vanka [11] investigated the wake structures behind a single flat plate numerically.

Kiya and Matsumura [7] and Mazharoglu and Hacışevki [6] reported that a maximum of the turbulent kinetic energy takes place at the center of a coherent structure corresponding to the edges of the flat plate. A remarkable observation of Mazharoglu and Hacışevki [6] revealed that a coherent shear stress alternates twice per cycle, as a result of the transverse coherent velocity lagging behind the streamwise coherent velocity. Moreover, Kiya and Matsumura [7] reported that the shear stress contributes mainly to incoherent fluctuations with frequency half the shedding frequency. Table 1 summarizes the data of selected experimental investigations of flow past a single flat plate and presents the measured results.

On the other hand, in numerical studies different turbulent models were used to investigate the accuracy of these models in simulating the wake structures behind a flat plate. Table 2 summarizes various

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**Table 1.** Selected experimental studies of flow past a single flat plate

| Researchers | Re | TI | BR | AR | IA | Technique | Measurements |
|---|---|---|---|---|---|---|---|
| Kiya and Matsumura [7] | $2.3 \times 10^4$ | 0.20% | 6.70% | 15 | 90 | CTA | St, U |
| Wu, Miau [45] | $1.8 \times 10^3$– $2.7 \times 10^4$ | 0.70% | 21% | 4.7 | 90 | FV, CTA | St, U |
| Leder [46] | $2.8 \times 10^4$ | 0.50% | 7.30% | 10.2 | 90 | LDA, CTA | St, U |
| Mazharoğlu and Hacışevki [6] | $3.2 \times 10^4$ | 0.5–0.8% | 6% | 14 | 90 | CTA | St, U |
| Bearman [8] | $4.8 \times 10^4$– $2.14 \times 10^5$ | 0.20% | – | Various | 90 | CTA | $C_P$, $C_D$, U |
| Lam and Leung [17] | 5300 | 0.01% | 3.70% | 33 | 20–30 | PIV, CTA | St, U |
| Deri, Braza [47] | 200 000 | 1% | 7.40% | 2 | 10 | PIV | U |
| Lam [48] | 30 000 | 1% | 5% | 11 | 30 | LDA, CTA | St, U |
| Chen and Fang [49] | $3.5 \times 10^3$– $3.2 \times 10^4$ | 0.50% | 13% | 7.6 | 0–90 | FV, CTA | St, U |

Re, Reynolds; TI, Turbulence intensity; BR, blockage ratio; AR, Aspect ratio; IA, Inclined angle; CTA, Constant temperature anemometry; FV, Flow visualization; PIV, particle image velocimetry; LDA, Laser Doppler anemometry; St, Strouhal number; $C_D$, Drag coefficient; $C_P$, Pressure coefficient.

**Table 2.** Numerical studies of flow past a single flat plate

| Researchers | Reynolds number | Numerical solution | Inclination angle(s) | Solution | Measurements |
|---|---|---|---|---|---|
| Narasimhamurthy and Andersson [9] | 750 | DNS | 90° | 3D | St, $C_D$, $C_P$ |
| Najjar and Vanka [11] | 1000 | DNS | 90° | 3D | $C_D$, $C_P$ |
| Huang et al. [50] | $7.2 \times 10^5$, $2 \times 10^4$ | RNG $k-e$ | 7°, 15° | 2D | $C_L$, $C_M$, |
| Yang and Abdalla [12] | 6500 | LES | 90° | 2D | U, $C_P$ |
| Taira and Colonius [51] | 300 | N.M | 30° | 3D | $C_L$, $C_D$ |
| Lasher [52] | 32 200 | $k-\varepsilon$ | 90° | 2D | $St_t$, $C_D$ |
| Yang, Pettersen [19] | 1000 | DNS | 20°, 25° & 30° | 2D, 3D | St, $C_L$, $C_D$, U, $C_P$ |
| Han, Sagaut [53] | 125–165 | DNS | [−12°, 12°] | 2D | St, $C_L$, $C_D$, U |
| Khaledi, Andersson [54] | 750 | DNS | 90° | 3D | St |
| Yang, Pettersen [55] | 750 | FVM | 30° | 2D | St, $C_L$, $C_D$, U, $C_P$ |
| Lam and Wei [18] | $2 \times 10^4$ | RNG $k-\varepsilon$ | 20°–45° | 2D | St, $C_L$, $C_D$, |
| Saha [10] | 30–175 | DNS | 90° | 2D | St, $C_L$, $C_D$ |
| Khaledi, Barri [56] | 100, 200, 300 | DNS | 90° | 3D | St |
| Chen and Fang [57] | 100 | FDM | 90° | 2D | St, $C_D$ |
| Tian, Ong [58] | $1.5 \times 10^5$ | LES | 90° | 3D | St, $C_D$, $C_L$, $C_P$, U |
| Julien, Ortiz [59] | 220 | DNS | 90° | 2D & 3D | St, U |
| Kiya and Arie [60] | 200 | N.M | 60° | 2D | St, $C_D$, $C_L$, U |
| Marquet and Larsson [61] | 40–150 | DNS | 90° | 3D | $C_D$, U |
| Najjar and Balachandar [62] | 250 | FDM | 90° | 3D | $C_D$, $C_L$, $C_P$ |

DNS, Direct numerical solution; LES, Large eddy simulation; FVM, Finite volume method; FDM, Finite difference method; St, Strouhal number; $C_D$, Drag coefficient; $C_P$, Pressure coefficient; $C_L$, Lift coefficient; N.M, Not mentioned.

available numerical studies on flow past a single flat plate. From these data it can be concluded that direct numerical simulation (DNS) is the most employed method in these studies. .Narasimhamurthy and Andersson [9] observed that a decrease in the base pressure leads to an increase in the Strouhal number and a shortening of the recirculation bubble. It was reported that the wake was distinctly turbulent downstream of the plate, where the transverse velocity fluctuations were more intense than the streamwise velocity fluctuations and, thus, made the major contribution to the fluctuating kinetic energy. Saha [10] showed that at low Reynolds numbers the unsteady flow in the near and far wakes became unsteady and steady in the near wake and the far wake, respectively. The results indicate that, as the Reynolds number increased up to 145, the far wake flow experienced transition with the formation of secondary vortices. Moreover, an increase in the Reynolds number leads to the transition point displacement from the high-frequency wake to the low-frequency wake, nearer to the plate. It was also found that the transition has only a slight effect on such parameters as the drag coefficient and the Strouhal number.

Yang and Abdalla [12] investigated the influence of freestream turbulence (FST) on the transitional separated-reattached flow over a blunt flat plate using large eddy simulation (LES) turbulence model. The results obtained show that a 2% freestream turbulence level leads to a 14% decrease in the mean reattachment length, as compared with the no freestream turbulence (NFST) case. The results also show that an increase in the FST level can result in the arrearance of some new, more rapid transition mechanisms. On the other hand, in the case of a less than 2% FST level, the characteristic shedding frequency value would be the same as in the NFST case.

Ohya et al. [13] found that the impinging-shear-layer instability is the reason for shedding from flat plates with square leading and trailing edges. In particular, the numerical results show that an increase in the plate chord causes an increase in the Strouhal number and, as a consequence, in the number of vortex formations on any side of the plate.

## 2. INCLINED FLAT PLATES

As shown above, the periodic vortex shedding phenomenon can lead to destructive loads on the bluff bodies. Some studies have been performed with inclined rather than normal to flow bluff bodies in order to address and tackle more specific engineering problems.

The wake flow structure and the vortex shedding phenomenon behind inclined rectangular and circular cylinders were studied by Norberg [14], Hogan and Hall [15], and Snarski [16]. It was observed that the wake flow behind an inclined cylinder exhibited a more disordered vortex shedding into the wake region [15]. Moreover, multiple shedding frequencies were observed by Norberg [14] in the wake region of a rectangular cylinder at small angles of inclination.

As for the flat plate, Lam and Leung [17] investigated the asymmetric vortex shedding phenomenon in the wake region of an inclined flat plate using PIV. The calculations of vorticity showed that the downstream motion of the vortex street occurs at a speed amounting to 80% of the freestream velocity. Figure 1 presents the schematic diagram of the vortex shedding from an inclined flat plate proposed by Lam and Leung [17]. Clearly visible in this figure are the Kelvin–Helmholtz instability and the trailing edge vortices. On the other hand, Lam and Wei [18] numerically simulated flow past an inclined flat plate using the $k-\varepsilon$ turbulence model. A similar train of vortices was observed, which contains vortices of different intensity.

Yang et al. [19] apllied direct numerical simulation to numerically investigate this phenomenon. As distinct from Lam and Leung [17], they noticed that the Strouhal number is independent of the angle of inclination. Moreover, the simulation revealed that the vortices shed from the trailing edge contain higher vorticity than those shed from the leading edge.

## 3. TANDEM CONFIGURATION

The interference between the wakes of bluff bodies in tandem arrangement is also connected with a lot of engineering applications. Zdravkovich [20], Bentley and Mudd [21], Baxendale et al. [22], and Pinarbasi et al. [23] investigated the bluff bodies in tandem arrangement to identify the flow patterns and the wake interference. Bentley and Mudd [21] conducted an extensive study to describe the vortex shedding mechanism and the gap flow effect on the detachment of shear layers for various bluff bodies in tandem arrangement.

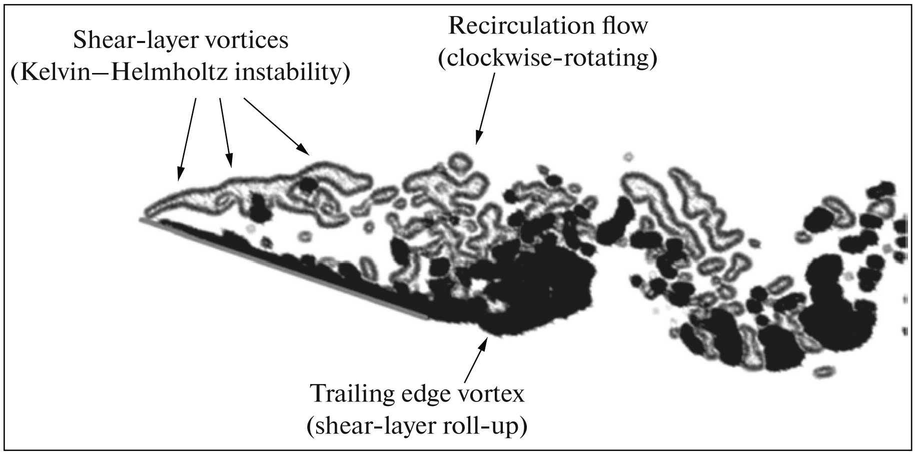


**Fig. 1.** Schematic diagram of vortex formation behind an inclined flat plate (figure taken from Lam and Leung, 2005).

Closely spaced bluff bodies behave as a “single body”, so that no vortices can roll inside the gap between the bodies. As a result, the shear layers shed from the upstream body flow past this dead flow region and form vortices behind the downstream body. However, as the gap between the bodies increases, vortices start rolling up inside the gap and in the case of a fairly large enough gap the vortices are shed from each body separately. Hangan and Vickery [24], Havel et al. [25], Martinuzzi and Havel [26], Zdravkovich [27], and Liu and Chen [28] described in detail the “single body” and “dual body” shedding modes.

As for the normal flat plates in tandem arrangement, the vortex shedding and the interference between the wakes of the upstream and downstream plates were investigated by Nakamura [29], Hacışevki [30], Auteri et al. [31], Auteri et al. [32], Dianat [33], Hacışevki and Teimourian [34], and Hacışevki and Teimourian [35].

At a low gap ratio between the plates, namely, $g/D = 0.9$, the recirculating flow in the gap region between the plates and downstream of the back plate was described by Auteri et al. [32]. In this configuration a weak recirculating flow in the gap region rotates in the opposite direction with respect to the downstream-plate wake flow, while the shear layer shed from the upstream plate flows past the gap between the plates. At such low gap ratios a wide wake is formed downstream of the back body. On the other hand, a narrower wake with a smaller recirculating region in the back body wake was observed at higher gap ratios, for example at 1.2. In this case, the vortices have enough space to roll up inside the gap region, the rotation direction being the same as in the wake region. The two above-mentioned flow fields correspond to the “single body” and “dual body” shedding modes, respectively. Nakamura [29] observed the features of the “single body” and “dual body” modes of vortex shedding at gap ratios $g/D = 0.5$ and 2.0, respectively.

The results of the numerical simulation conducted by Dianat [33] are also in agreement with the smoke visualization data obtained by Auteri et al. [31], Auteri et al. [32], and Nakamura [29]. In this study, the $k-\varepsilon$ turbulence model was used and it was shown that at low gap ratios vortices do not roll up inside the gap between the plates. However, as the gap ratio between the plates increases, the vortices start to roll up in the gap.

Since two identical tandem plates are similar in shape with a rectangular body without definite upper and lower boundaries, Hacışevki and Teimourian [36] attempted to establish the similarity between the wake structures of two tandem flat plates and a square cylinder. The available literature on flow past flat plates in tandem arrangement, together with the values of the gap ratio, the measurement techniques, the measured parameetrs, and the Strouhal numbers are summarized in Table 3.

It was obtained that the flow structure between bluff bodies in tandem arrangement considerably depends on the gap ratio; certain flow parameters, such as the Strouhal number, also depend on this parameter. For different bluff bodies in tandem arrangement this phenomenon was investigated by Igarashi [37], Igarashi [38], Auteri et al. [31], Auteri et al. [32], and Sumner et al. [39] and a strong dependence of the Strouhal number on the gap ratio was found to exist.

**Table 3.** Selected studies of flow past flat plates in tandem arrangement

| Researchers | Reynolds number | Gap ratio | Turbulence intensity | Blockage ratio | Aspect ratio | Technique | Measurements |
|---|---|---|---|---|---|---|---|
| Auteri, Belan [32] | $8.7 \times 10^3 < \mathrm{Re} < 7.5 \times 10^4$ | 0.9, 1.2 | 0.20% | 10% | 7.1 | FV, LDA, CTA | St, U |
| Auteri, Belan [31] | 8340 | 0.25–7.5 | 0.3% | 10% | 7.1 | FV, CTA | St |
| Nakamura [29] | $1.5 \times 10^4$ | 0.3–2.0 | – | 1.70% | 13.2 | FV, CTA | St, $C_P$ |
| Hacışevki [30] | $3.2 \times 10^4$ | 0.2, 0.5, 1.0, 2.0 | 0.5–0.8% | 6% | 14 | CTA | St, U |
| Dianat [33] | $3.2 \times 10^4$ | 0.3, 0.5, 1.0, 1.8, 2.0 | 0.80% | 6% | 14 | Numerical | St, U, CP |
| Hacışevki and Teimourian [36] | $3.2 \times 10^4$ | 1.0 | 0.5% | 6% | 14 | CTA | St, U |

CTA, constant temperature anemometry; FV, flow visualization; LDA, laser Doppler anemometry; St, strouhal number; $C_P$, pressure coefficient.

A variation of the Strouhal number as a function of the gap ratio between two flat plates was investigated by Auteri et al. [31]. For the gap ratio $g/D = 0.9$ (critical gap ratio) it was found that the Strouhal number first increases and then rapidly decreases. This observation demonstrates the existence of two distinct flow regimes. The FFT spectral analysis for this interval also exhibits a double peak corresponding to two different Strouhal numbers. Thus, due to the observed bistability, the flow structures alternate from the configuration corresponding to a value lower than the critical gap ratio to another configuration corresponding to a value greater than the critical gap ratio. Although for the gap ratios smaller than the critical value the Strouhal number remains close to that for a single plate, it starts to decrease suddenly and at the gap ratio 3.5 reaches a minimum value. Moreover, it was observed that for large gap ratios the flow regime is independent of the Reynolds number. However, the critical gap ratio increases with the Reynolds number and the flow regimes corresponding to the low gap ratios are also to some extent Reynolds-number-dependent.

It was also reported that the shedding frequency is considerably influenced by the size of vortices rolled up within the gap region of the "dual body." Auteri et al. [31] conducted an experimental study to investigate this dependence. Their smoke visualization demonstrated a decrease in shedding frequency, as a result of the greater vortex dimensions inside the gap.

Another interesting feature of flow past two normal flat plates in tandem is the formation of two recirculation regions inside the gap between the plates and in the wake behind the back plate. The study conducted by Auteri et al. [32] revealed that at low gap ratios between the plates the two recirculation regions inside the gap rotate in the direction opposite to that in two recirculation regions in the wake. However, at larger gap ratios all these recirculation regions rotate in the same direction, as shown in Fig. 2.

Figure 3 presents the Strouhal number ($S_t = f_s D/U_\infty$) in the wake region of two normal flat plates in tandem arrangement as a function of the gap ratio between the plates obtained in different studies. Clearly that the Strouhal number increases with increase in the gap ratio up to a certain critical value. However, the further increase in the gap ratio results in a reduction in the Strouhal number. This phenomenon can be the result of transition from the "single body" to the "dual body" vortex shedding mode. The critical gap ratio, at which the behavior of the Strouhal number changes abruptly, was reported to be 0.9 by Auteri et al. [31] and 1.2 by Nakamura [29]. Moreover, Auteri et al. [31] also observed that at low gap ratios between flat plates in tandem the measured Strouhal number is higher than in the case of a single plate. However, as the gap ratio exceeds the critical value, the Strouhal number abruptly diminishes to values lower than that for the single plate.

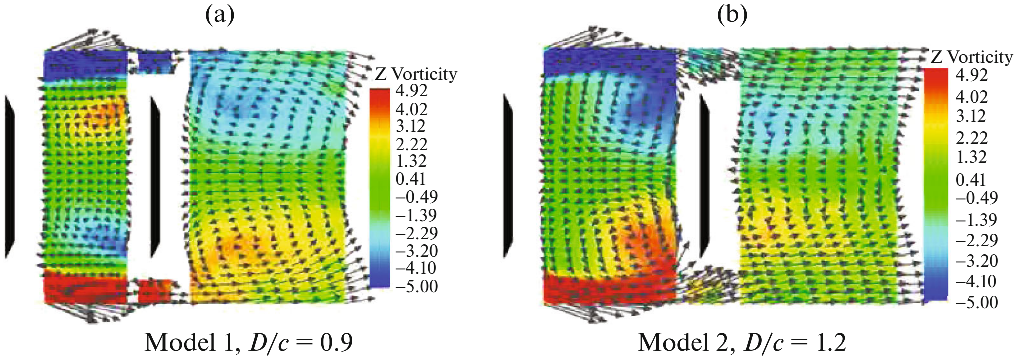


**Fig. 2.** Mean velocity vector fields and $Z$ component of the mean vorticity fields [s-1], Re = 46800 (figure taken from Auteri et al. [32]).

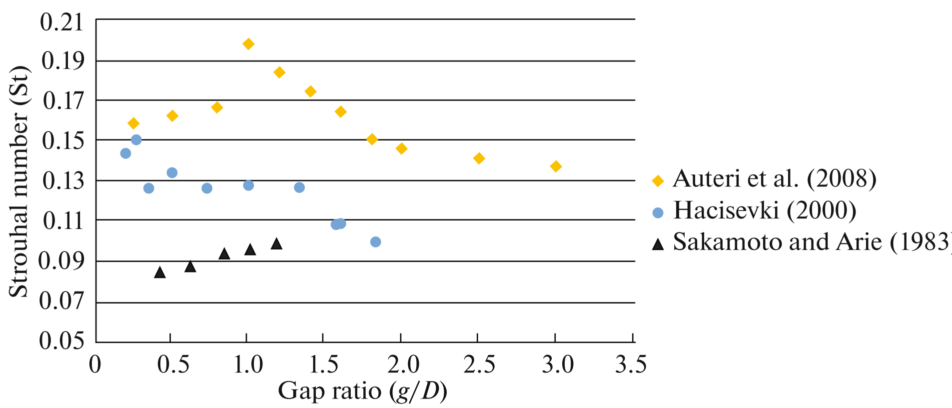


**Fig. 3.** Variation of the Strouhal number with the gap ratio between the plates.

## 4. SIDE BY SIDE ARRANGEMENT

The side by side arrangement is another interesting configuration of bluff bodies with many applications in the day-to-day life. In the previous section we considered the wake interference of two bluff bodies, when the downstream body is located in the near wake of the upstream body. The wake interference can also occur in the case of two closely spaced bluff bodies. Zdravkovich [40] suggested that three flow regimes for two side by side cylinders can exist depending on the spacing between the bodies, namely, separate vortex streets behind each body, a biased gap flow, and a common vortex street.

In the case of two flat plates in side by side arrangement, the vortex shedding phenomenon on the outer edge of initiated shear layer on the narrow wake side, i.e., biased flow was observed. Contrariwise, in the case of a wide wake the flow was unbiased, the vortex shedding phenomenon was not observed, and in the near wake region the development of turbulent fluctuations was clearly visible.

Hayashi et al. [41], Behr et al. [42], Miau et al. [43], and Gad [44] investigated the wake region behind two normal side-by-side flat plates. It was found that for small spacings lower than $s/D = 2.0$, the gap flow demonstrates a biased pattern to either side in a stable mode and the direction of such flow remains unchanged unless being disturbed.

For very closely spaced plates ($s/D = 0.2$) the individual vortices shed from each plate are indistinguishable and the gap flow is fairly weak. The shear layers on the outer edges of the plates interact with each other and consequently form a large-scale vortex in the wake region behind the plates. This flow pattern is similar with the vortex shedding from a single flat plate. As the separation ratio increases beyond $s/D = 0.5$, the onset of the individual vortex shedding phenomenon is clearly evident. Thus, the shedding phenomenon is observed behind the plate in the biased side of flow, whereas in the wake region behind the other plate any vortices do not roll up. However, further downstream in the wake this small-scale vortex street becomes barely discernible and is submerged in a larger vortex which rolls up behind the two plates. Increasing the separation ratio between the plates beyond the value 1.25 leads

(a) (b)

(c) (d)

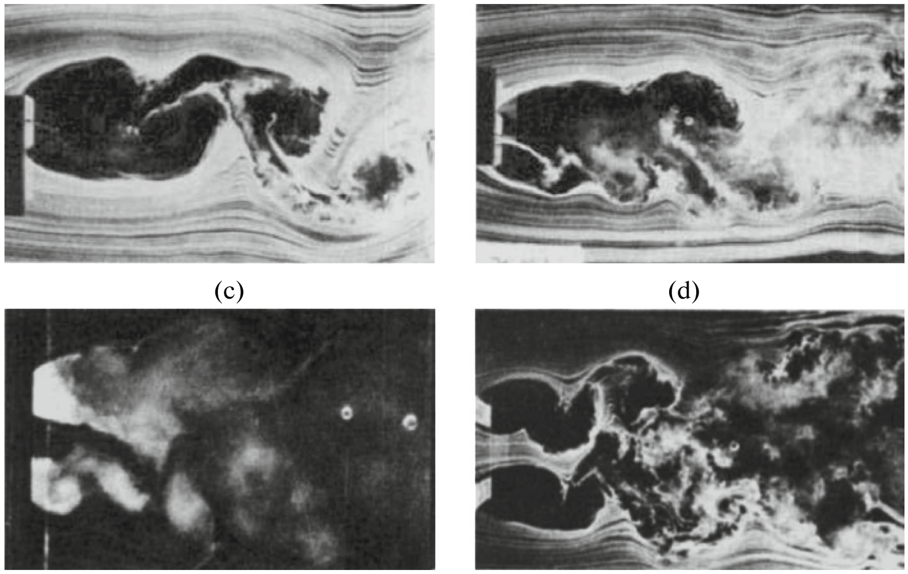

**Fig. 4.** Flow visualization behind two side by side flat plate rows for (a) $s/D = 0.2$, (b) 0.75, (c) 1.5, and (d) 2.5 (figures taken from Hayashi et al., 1986).

to the vanishing of the biased flow pattern and independent and individual flow structures are formed in the wake region behind the plates. The flow visualization makes it possible to trace the development of the vortex structures both in the gap flow and in the shear layers formed on the outer edges of the plates. However, further downstream these two vortex streets decay, due to the lack of space for their independent development, and merge into a single, clearly visible wake. The smoke visualization of such a structure is shown in Fig. 4 [41].

An investigation of the shedding frequency revealed that for the separation ratio beyond 2.0, as the biased flow pattern disappears, the Strouhal number is independent of the $s/D$ ratio. It was also found that in this case two equal and identical Strouhal numbers correspond to the two individual vortex streets and they are in agreement with the Strouhal number in the wake region behind a single plate. However, in the case of close proximity of the plates ($s/D < 2.0$) two sets of the Strouhal number are observable. One of these corresponds to small-scale vortices formed in the biased flow region, while the other is associated with the large-scale vortex street, which rolls up further downstream in the wake region. Thus, the vortices are shed from the biased side of wake at higher frequency than from the unbiased side [41, 43].

Moreover, it was noticed that the Strouhal number is in inverse relation with the separation ratio between the plates. As the separation ratio increases up to the value $s/D = 2.0$, the Strouhal number decreases approximately by 45%. In addition, for the separation ratio smaller than $s/D = 1.3$, different vortex shedding frequencies corresponding to asymmetric bistable wake regime were found [43, 44].

Another important observation is that the plate on the biased side of the flow exhibits a regular shedding phenomenon with a higher drag force. Contrariwise, the unbiased side behaves in a fully opposite way [41].

## 5. SUMMARY

The wake flow behind a flat plate has always attracted the attention of researchers. In this study an attempt is made to review the selected literature on the flow past different arrangements of flat plates. Single, inclined, tandem, and side-by-side arrangements are the basic configurations that are reviewed for both experimental and numerical studies. These arrangements are investigated in terms of the Strouhal number, the aerodynamic forces, and the flow field patterns, as stated in detail in Tables 1–4. Moreover, the effects of the Reynolds number, the gap and separation ratios, the inclination angle, and the freestream turbulentce intensity on the wake structure characteristics are studied. It is concluded

**Table 4.** Selected studies of flow past flat plates in side by side arrangement

| Researchers | Reynolds number | Separation ratio ($s/D$) | Aspect ratio | Technique | Measurements |
|---|---|---|---|---|---|
| Hayashi, Sakurai [41] | $0.6 \times 10^4 <$ Re $< 1.9 \times 10^4$ | 0.2–2.5 | 8.8–74 | FV, CTA, numerical | $C_P$, $C_D$, $C_L$, St, U |
| Miau, Wang [43] | $1.3 \times 10^3 <$ Re $< 1.2 \times 10^4$ | 0.4–2.0 | 4 | FV, CTA | St, U |
| Gad [44] | 20 000 | 0.25–1.25 | 10 | FV, numerical | $C_P$, $C_D$, $C_L$ |
| Behr, Tezduyar [42] | 80, 160 | 0.5–2.0 | – | numerical | $C_L$, $C_D$ |
| Higuchi, Lewalle [63] | 1500 | 1.0–2.0 | 24 | FV, LDA | U |

CTA, Constant temperature anemometry; FV, Flow visualization; LDA, Laser Doppler anemometry; St, Strouhal number; $C_D$, Drag coefficient; $C_P$, Pressure coefficient; $C_L$, Lift coefficient.

that the single flat plate normal to flow is the most studied configuration in the available literature. Despite the simplicity of the single flat plate configuration, the corresponding flowfield behaves in a complex manner. The tandem and side-by-side configurations were studied using flow visualization and quantitative measurements. New measurement techniques, such as Particle Image Velocimetry or Laser Doppler Velocimetry, have provided the capability to explore the physics of flow behavior. These attempts led the identification of the vortex shedding mechanism from these complicated configurations.

Obviously that numerical simulation provides a better insight of the flowfield behavior but the complexity of the flow field requires further investigation of this subject. The results of numerical simulations considerably depend on the choice of an appropriate numerical model. Hence, different turbulence models are employed with their advantages and disadvantages.

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