

PIV and pressure measurements on two high-rise models in tandem arrangement

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ABSTRACT: Particle Image Velocimetry (PIV) and pressure measurements were performed on a high-rise model with a height (H) of 0.48 m and a width (B) of 0.12 m in a turbulent atmospheric boundary layer. Experiments were carried out for an isolated model and four tandem configurations with varying separation distance (S) between the models. Mean and standard deviation were determined for the PIV and the pressure dataset. Both velocity fields and pressure coefficient distributions show an increase in mean and fluctuating components near the entrance of the passage with decreasing separation distance. Proper Orthogonal Decomposition (POD) was performed on the PIV data to determine the most energetic modes. These modes were compared with observations from literature for tandem configurations in a laminar boundary layer. Similar modes were found (single, gap and coupled mode). In the current study it was found that the modes can occur simultaneously. Also the dominant mode differs from previous results described in literature for the investigated setup ranges.

KEYWORDS: High-rise buildings, wind interference, tandem arrangement, Particle Image Velocimetry

1 INTRODUCTION

Wind flow around a single isolated building has been studied extensively. Typical flow phenomena, such as the separation bubble and vortex shedding are quite well understood. There is less understanding on the changes of existing phenomena or the emergence of new phenomena when two or more high-rise buildings are in close proximity. A typical case is the tandem configuration, in which the wind approaches the buildings parallel to the intermediate passage. This configuration is known for particularly large mean velocities in the passage (e.g. Blocken et al, 2007) and large negative mean (Bronkhorst et al, 2011) and peak (Kim et al, 2010) pressures on the passage facades.

Yen and Liu (2010) performed pressure and visualization measurements using the smoke-streak technique on two square cylinders in side-by-side arrangement in quasi two-dimensional laminar flow. They found a change in flow patterns and vortex shedding frequency with increasing separation distance and classified three vortex shedding modes: the single mode ($S/B < 0.1$), the gap-flow mode ($0.1 < S/B < 5.5$) and the coupled vortex-shedding mode ($S/B > 5.5$). The gap-flow mode exhibits anti-phase vortex shedding; the vortex streets behind both models are symmetric with respect to the gap centre line. The coupled vortex-shedding mode has in-phase vortex shedding: the vortex streets behind both models are the same as the vortex street behind a single building, the interaction is observed in the in-phase rhythm of the vortex shedding. These flow characteristics of the tandem configuration defined by Yen and Liu (2010) for laminar flow were, to the author's knowledge, never investigated in an atmospheric turbulent boundary layer.

The goal of this paper is to obtain a better understanding of the flow phenomena and related pressure effects encountered in a tandem configuration of high-rise models in an atmospheric boundary layer. Particle Image Velocimetry (PIV) measurements were performed to obtain ve-

locity vector fields in the horizontal plane around the models. Separate pressure measurements in the same plane gave data on the local pressure distribution. This work describes the set up of the experiments and discusses results and findings.

2 MATERIALS AND METHODS

Wind tunnel experiments were carried out in the open circuit atmospheric boundary layer (ABL) wind tunnel of TNO in the Netherlands. It has a working section of approximately 13.5 m in length; the test section has a 3 m width and 2 m height. The boundary layer applied in this study had an aerodynamic roughness length $z_0 = 3.2$ mm. A detailed description of the flow field is given in Bronkhorst et al (2011).

2.1 Pressure measurements

The reference model is a wooden square cylinder with a height of $H = 0.48$ m and width $B = 0.12$ m. The pressure tap distribution on the faces is illustrated in Figure 1(a). The interfering model has the same dimensions as the reference model. Measurements were performed on the isolated configuration and four tandem configurations [as illustrated in Figure 1(b)]. The reference model was instrumented with pressure taps at 38 locations on each face. The current study only uses the data obtained at 0.32 m height (row $i = 4$), which is $2/3H$. The pressures were measured with a sampling rate of 400 Hz for a period of approximately 20.5 seconds. During pressure measurements the undisturbed static and dynamic pressure were measured with a pitot-static tube positioned at model roof height ($H = 0.48$ m). The mean velocity at this height, $U_H = 14.2$ m/s, corresponds with a width-based Reynolds number of $Re = U_H B / \nu \approx 1.1 \times 10^5$.

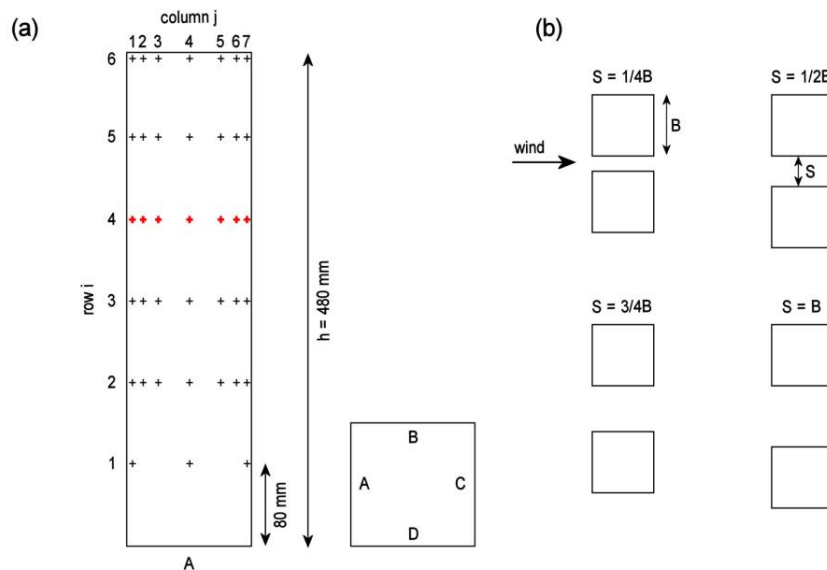


Figure 1. (a) pressure tap distribution on face A, the same distribution is found on face B, C and D, this study only uses the data obtained in row $i = 4$; (b) investigated tandem configurations.

2.2 PIV measurements

The tandem configuration consists of two wooden square cylinders with a height $H = 0.48$ m and width $B = 0.12$ m. Measurements were performed with a mean velocity at model height,

$U_H = 14.2$ m/s. The isolated configuration and four tandem configurations, illustrated in Figure 1(b), were investigated.

In order to evaluate the flow around the tandem square cylinders, two-component particle image velocimetry (PIV) is employed. The PIV measurements provide a velocity vector field with 2 velocity components in horizontal streamwise and spanwise x - and y -direction (u_x and u_y) at a height of $z = 0.32$ m from the ground. The PIV field of view (FOV) of approximately 600 by 460 mm is indicated in Figure 2(a), and is chosen to encompass the flow around both cylinders, the intermediate passage and a large portion of the cylinder wakes.

The illumination over the field of view is provided by a Quantel Evergreen 200 Nd:YAG double puls laser with 200 mJ maximum puls energy. The light sheet is generated downstream of the object of investigation. A LaVision Imager Intense CCD camera is placed above at a 90° angle with respect to the illumination sheet, and captures 1376×1040 pixel images, illustrated in Figure 2(b). The illumination and recording devices were synchronized and controlled by a LaVision Programmable timing unit controlled by Davis (Version 8, 64 bit) Software. Each test consisted of 200 image pairs at a recording frequency of 10 Hz. The double pulse interval was 250 microseconds. The chosen magnification yields a typical digital resolution of 2.3 pixels/mm. The images were analyzed with the Davis software; reflections in the raw images were corrected for through subtraction of the minimum pixel values over the 200 images, resulting in images as illustrated in Figure 2(c). Velocity vector fields were obtained through a multi-stereo cross-correlation with a final interrogation window of 16×16 pixels with 75% overlap.

The instantaneous velocity magnitudes are computed using $u(t) = [u_x(t)^2 + u_y(t)^2]^{1/2}$. The time-averaged mean and standard deviation velocity magnitudes, U and u_{std} respectively, were computed from the velocity magnitude time series. The results are presented non-dimensionally, referenced to the mean velocity at model height, U_H .

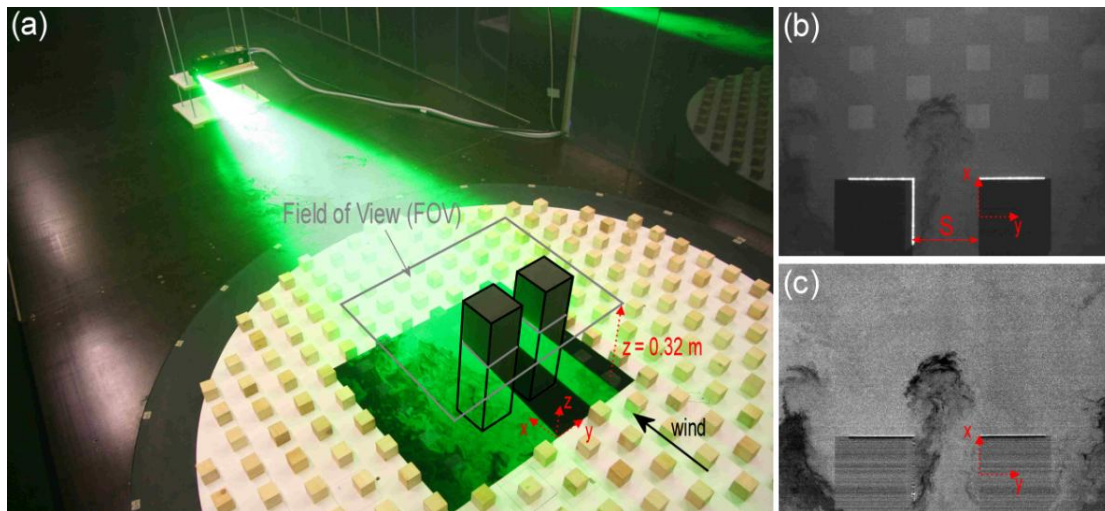


Figure 2. PIV measurements: (a) experimental set up, (b) raw image, (c) image after manipulation to correct for reflections.

3 RESULTS AND DISCUSSION

3.1 Mean and standard deviation velocity field and pressure coefficient distribution

The mean velocity field around the single isolated building at $z = 2/3H$ is illustrated in Figure 3(a). Flow phenomena such as the separation on the side face and the counter rotating mean wake structure behind the model are visible in the vector field. These flow features change significantly when two models are placed in tandem arrangement. First of all, for the studied configurations, the vector fields indicate that mean separation and recirculation are not present in the passage. Instead an increase is observed in the passage and low forward velocity around the side walls. Secondly, the strength of the jet at the exit of the passage has a large influence on the mean wake structure behind the models.

Blocken et al (2007) performed a tandem configuration study on building models with full scale dimensions $B \times D \times H = 40 \text{ m} \times 20 \text{ m} \times 20 \text{ m}$. They determined an increase in mean velocity at pedestrian level (2 m). However, at larger heights (approximately $1/2H$) they found a decrease in mean longitudinal velocity of 10-25%. Blocken et al related this effect to an upward flux through the top of the passage caused by the overpressure region in front of the buildings near the ground. This effect reduced the longitudinal velocity through the passage at larger heights. The current study shows that the height of the buildings has a large influence on the flux through the passage, as there is a large velocity increase in the passage. In case of high-rise buildings, the high pressure region is not near the ground, resulting in a downward flux below approximately $2/3H$ (i.e. the stagnation point of buildings is in the region of $2/3H$) and an upward flux above $2/3H$.

Figure 3(b) shows the mean pressure coefficient distribution. On face A, the mean pressure coefficient increases with decreasing separation distance. This increase is particularly large near the passage entrance, where an increase is observed from $C_{p,mean} = 0.3$ (isolated case) to $C_{p,mean} = 0.6$ ($S/B = 1/4$). This increase indicates the merging of the overpressure regions in front of the two buildings. The mean pressure distribution on face B is severely influenced by the neighbouring model. Near the entrance, the mean pressure coefficient increases with decreasing separation distance, from $C_{p,mean} = -0.7$ in the isolated case to $C_{p,mean} = -1.6$ for $S/B = 1/4$. Near the passage exit, the mean pressure coefficients decrease towards the coefficients observed on face C. The influence of the adjacent model on the mean pressure coefficient distribution on face C and D is small.

Figure 4(a) shows the standard deviation velocity fields with decreasing separation distance. The high velocities near the sides are characteristic for the shear layer. In the tandem configuration, an increase is observed in the shear layers near the faces on the outside. In the passage, large values are found closer to the building face than on the outside faces. With decreasing separation distance, the large standard deviation velocities are concentrated near the entrance of the passage.

Figure 4(b) illustrates the standard deviation pressure coefficient distribution. On face A, a small increase is found which is largest at a separation distance of $S/B = 1/2$. Large effects are observed on the distribution of face B in the passage. In the isolated case, the largest coefficients are observed near the trailing edge. This increase is a well-known effect caused by reattachment (e.g. Surry and Djakovich, 1995). The movement of the zone of reattachment results in a change in inclination with which the fluid approaches the surface which is responsible for an increased variation in pressure. Because the velocity magnitude varies little, no large standard deviation values are observed in this region.

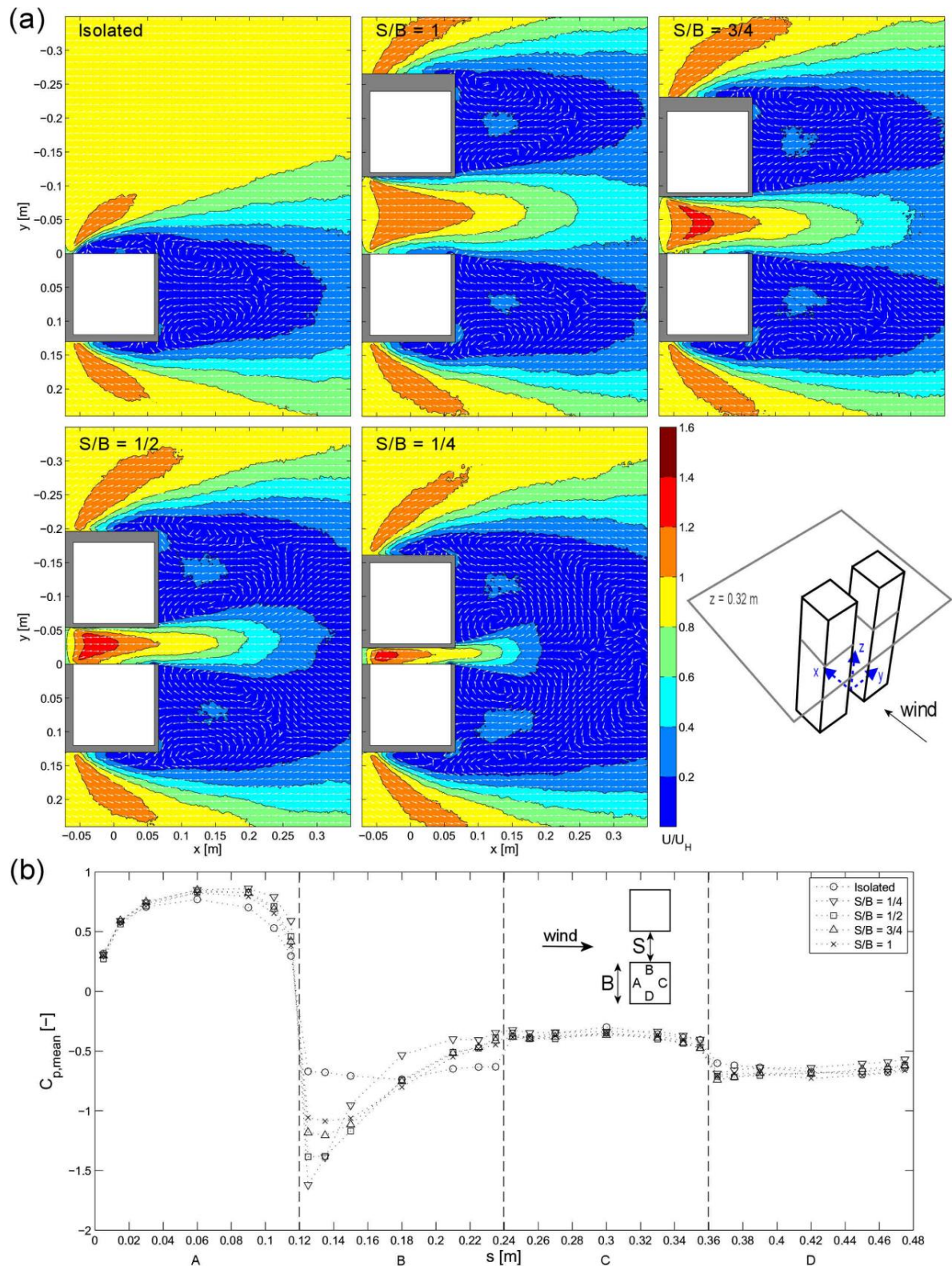


Figure 3. (a) Variation of the mean velocity field with increasing separation distance between the buildings at $2/3H$: isolated building; $S/B = 1$; $S/B = 3/4$; $S/B = 1/2$; $S/B = 1/4$. (b) Influence of the separation distance on the mean pressure coefficient distribution at $2/3H$.

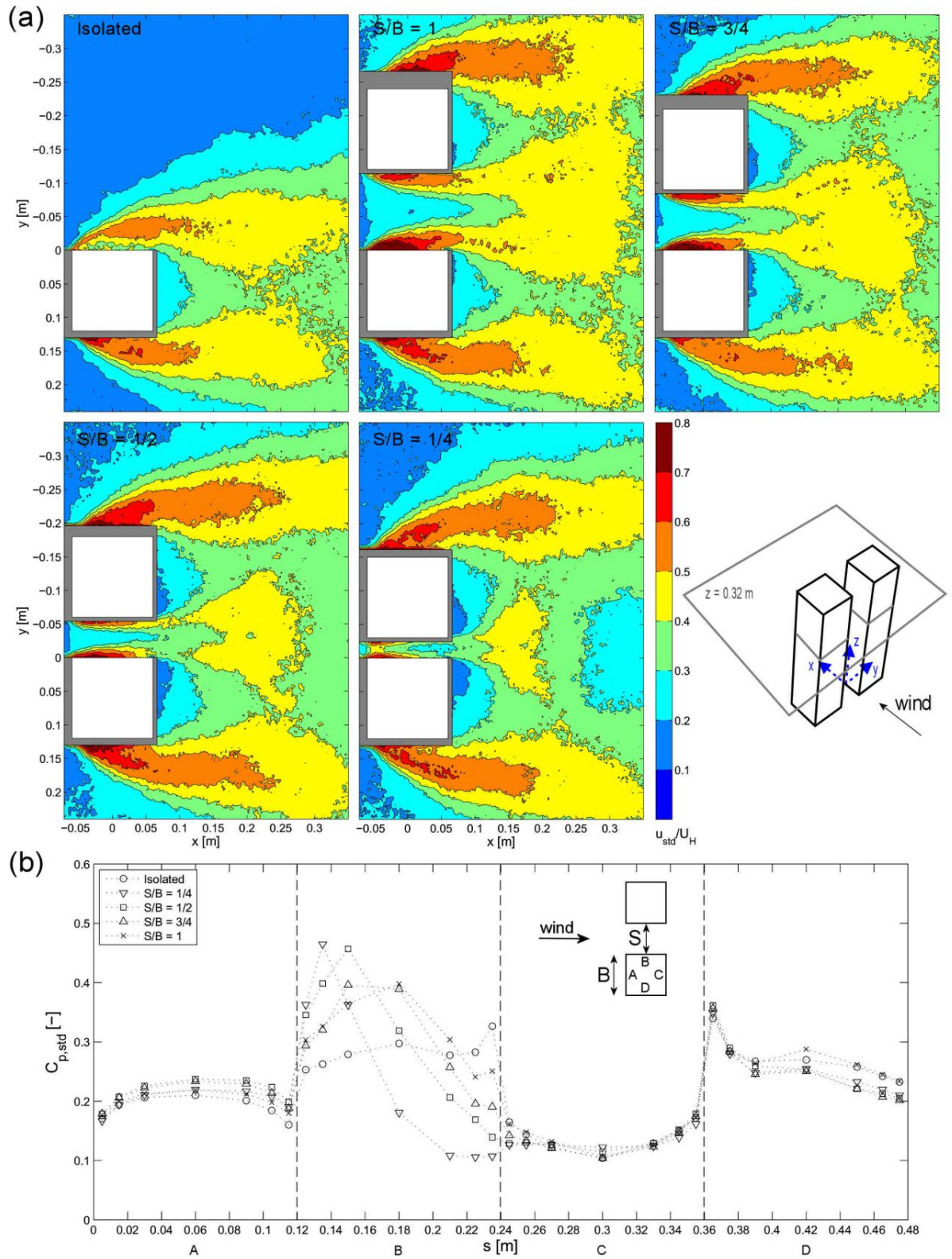


Figure 4. Variation of the standard deviation velocity field with increasing separation distance between the buildings at $2/3H$: isolated building; $S/B = 1$; $S/B = 3/4$; $S/B = 1/2$; $S/B = 1/4$. (b) Influence of the separation distance on the standard deviation pressure coefficient distribution at $2/3H$.

The standard deviation pressure coefficients near the entrance of the passage increase with decreasing separation distance. This is in agreement with the increase in velocity fluctuations in this region. Near the exit of the passage, there is a reduction in standard deviation pressure coefficient. The standard deviation velocities also show a decrease in this region. Small effects are observed on face C and D.

3.2 Instantaneous and POD analysis of the velocity field

Figure 4 shows three sequential snapshots of the $S/B = 3/4$ configuration. Large differences compared to the mean flow results of figure 2 can be observed. Where the mean velocity field of figure 2 indicated no separated flow in the inner passage, the instantaneous velocity fields show separation does occur, either on left or right side or simultaneously on both sides. These observations are in agreement with the standard deviation visualizations observed in Figure 4.

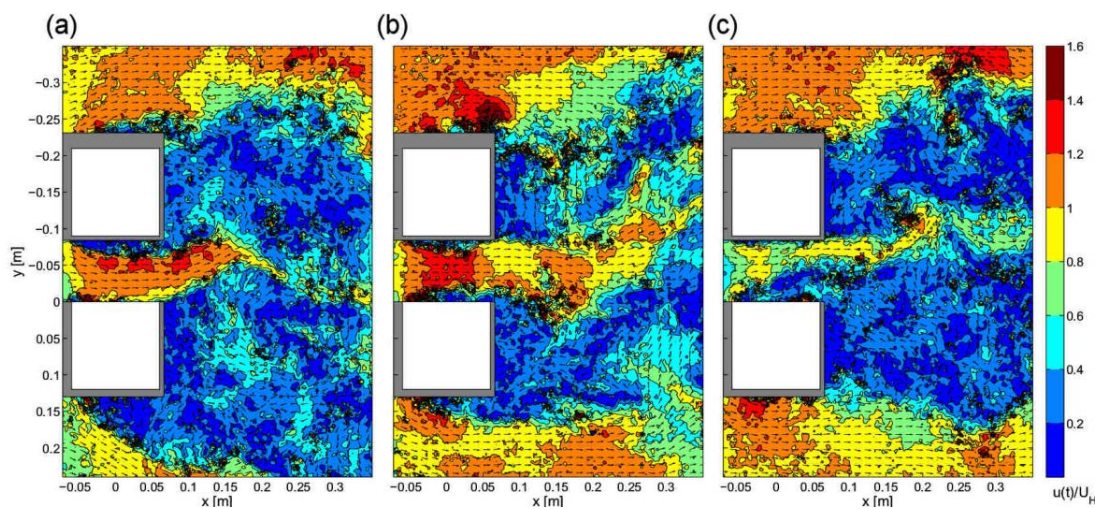


Figure 5. Instantaneous velocity fields illustrating the alternating behavior of the separation zones in the passage: (a) separated zone on right side, (b) separated zone on both sides, (c) separated zone on left side.

In order to obtain a better understanding of the underlying patterns in the turbulent flow, proper orthogonal decomposition (POD) was employed on each dataset of 200 vector fields. POD is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables. The transformation is defined in such a way that the first principal component has the largest possible variance and each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to (i.e., uncorrelated with) the preceding components. For velocity fields, the largest variance corresponds to the highest fluctuation kinetic energy. The two most energetic modes for $S/B = 3/4$ and the most energetic mode for $S/B = 1/4$ are depicted in Figure 6. On the left of the figure, the modified fluctuation velocity magnitude $\text{sgn}(u_y) \cdot U_i$ for the 1st and 2nd mode is depicted. The $\text{sgn}(u_y)$ term is added to indicate the relative direction in the mode shape. On the right of the figure, the mode velocity field is added to and subtracted from the mean velocity field to show the influence of the mode on the velocity field.

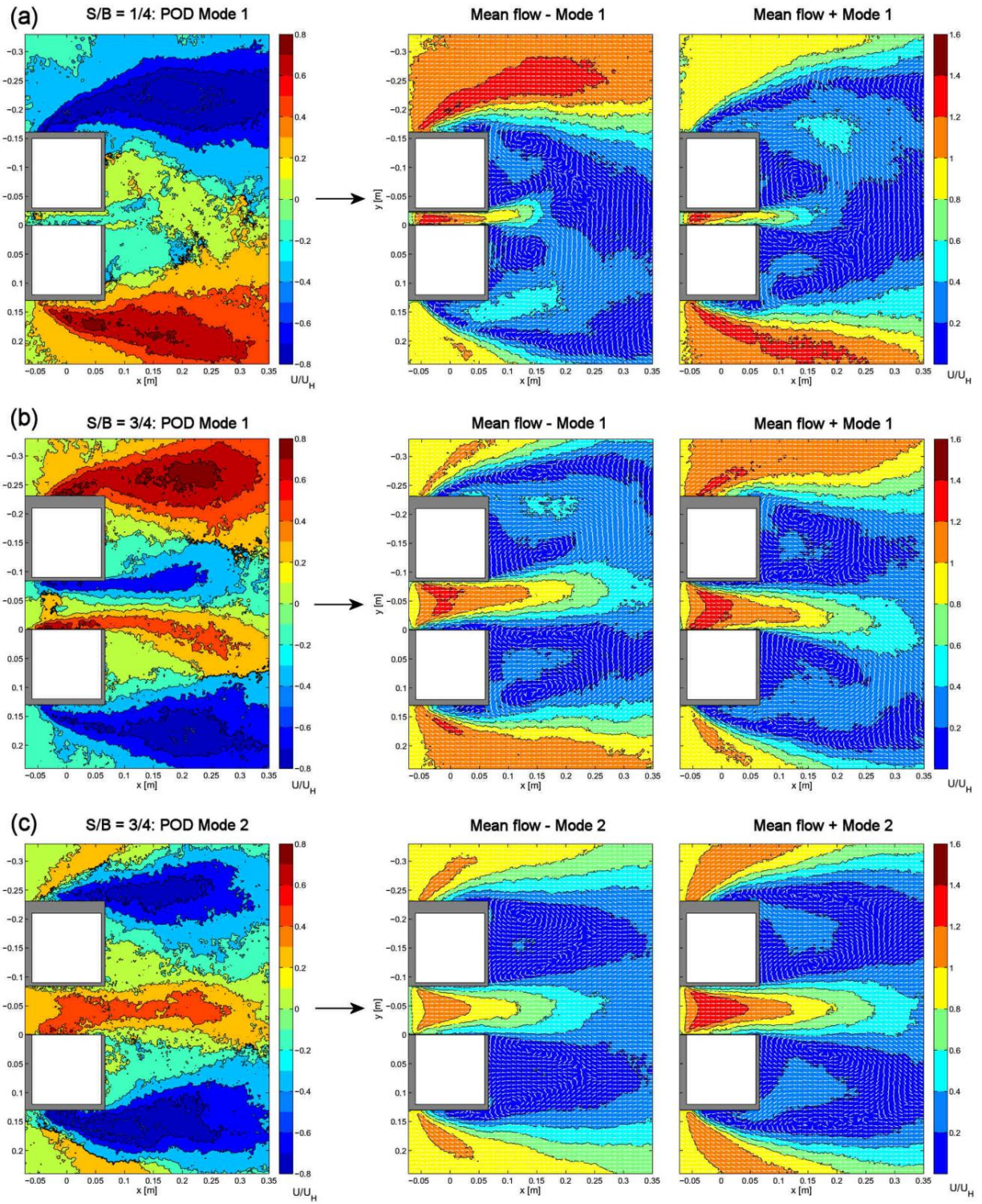


Figure 6. POD modes and effect in the flow field for: (a) Mode 2 ($S/B = 1/4$), (b) Mode 1 ($S/B = 3/4$) and (c) Mode 2 ($S/B = 3/4$).

The 1st POD mode obtained for $S/B = 1/4$ is illustrated in Figure 6(a). Most of the energy of this mode is observed in the flow outside of the tandem configuration, little energy is observed in the passage. This energy distribution is similar to the single model case, which is why this mode is defined as a single mode in Table 1. The 1st POD mode determined for $S/B = 3/4$ is shown in Figure 6(b). For this separation distance, an increase in energy is observed both on the outside as well as in the passage. This mode is responsible for in-phase vortex shedding behavior of the vortex streets behind both models, in Table 1 this mode is specified as the coupled mode. This mode also is characterized by alternating separation from either sidewall in the passage, something observed in the snapshots of figure 5 as well. Figure 6(c) shows the 2nd POD mode determined for $S/B = 3/4$, this mode is responsible for large velocity fluctuations in the gap between the models. In Table 1 this mode is defined as the gap flow mode. For some S/B values, the mode is characterized by combined separation from both sidewalls simultaneously in the passage, something observed in the snapshots of figure 5 as well. .

The modes illustrated in Figure 6 and provided in Table 1 are similar with the flow patterns described by Yen and Liu (2010). They performed smoke visualizations on similar models in a laminar boundary layer ($2262 < Re < 12560$) for opening ratios of $S/B = 0$ to 12, and observed a number of distinct flow patterns:

1. the single mode ($S/B < 0.1$);
2. the gap-flow mode ($0.1 < S/B < 6$);
3. the coupled vortex shedding mode ($S/B > 6$).

The specific ranges defined by Yen and Liu for the three observed modes, suggests that these modes do not exist simultaneously in laminar boundary layer flow. The energy fractions specified in Table 1 shows that these modes can coexist and that the gap-flow mode, for the studied cases, is an energy-wise secondary flow mode with respect to the single and coupled mode. The gap-flow mode coexists with the coupled mode. The difference in oncoming turbulence levels between both studies could be responsible for the different observations between the current work and the study performed by Yen and Liu (2010). Although the spectral characteristics of the pressure measurements performed by Yen and Liu (2010) suggest less stringent ranges for the different flow modes in a laminar flow as well.

Table 1. Energy fractions of flow modes obtained with POD and comparison with Yen and Liu (2010).

Separation Distance	Energy fractions per flow mode			Flow mode Yen and Liu (2010)
	Single	Coupled	Gap-flow	
Isolated	20%	-	-	Single
$S/B = 1/4$	16%	-	-	Gap-flow
$S/B = 1/2$	-	16%	6%	Gap-flow
$S/B = 3/4$	-	16%	6%	Gap-flow
$S/B = 1$	-	15%	7%	Gap-flow

4 CONCLUSIONS

Particle Image Velocimetry (PIV) and pressure measurements were performed to obtain a better understanding of the flow phenomena and related pressure effects encountered in a tandem

configuration of high-rise models in an atmospheric boundary layer. The mean and standard deviation values of the velocity field and the model pressure coefficient distribution were determined. Increases in mean and standard deviation velocity were observed in the passage with decreasing normalized separation distance (S/B). The regions of high standard deviation velocity fluctuations can be related to wall pressures in the passage region. Although the mean flow shows no backflow in the passage, intermittent separation from the sides of the passage occurs. POD is implemented to determine the most energetic modes. Three modes can be observed, single, coupled and gap-flow. For the isolated building and $S/B=1/4$ case, the single mode is dominant. For the other separation distances, both gap-flow and coupled mode coexist, with the coupled mode being dominant energy-wise. This is in contrast with literature on laminar boundary layer flows, where only isolated modes are observed, and only the gap-flow mode is present in the currently investigated S/B ranges. The differences should be caused by the turbulence in the oncoming boundary layer. The currently observed coupled and gap-flow mode can be linked to separation of one or both inner walls in the passage respectively. An investigation into a more direct link between observed flow modes, velocity fluctuations and peak façade pressures is intended in future research.

5 REFERENCES

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