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Role of Plate Length on Noise from Wall Jets

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Summary

The present study experimentally investigates the effect of the growth of inner layer on noise emission characteristics of wall jets. The plate length L considered for the current study vary in the range of $L/h = 2.5$ to 30, where h is the nozzle height. The jet is issued from a nozzle having the exit dimensions of 20 cm in width and 2 cm in height h . The jet Reynolds number, based on the nozzle height and jet exit velocity U_j , is varied up to $7.0 \cdot 10^4$. Acoustic measurements revealed the distinct variations in the noise levels with different plate lengths. The $L/h = 2.5$ wall jet has an increase in noise levels by around 10 dB compared to that of a free jet (background noise). Wall jets in the range of $L/h = 5$ to 20 radiate higher noise levels compared to other plates, while the least noise emissions are observed from fully developed wall jets ($L/h > 20$). The significant sources identified for noise emissions are the trailing edge and the secondary shear layer in the wall jets. The low frequency noise corresponding to the Strouhal number (based on h) below 0.2 is characterized as the trailing edge noise. The spectra of the wall jets collapse in the Strouhal number range (based on the inner layer thickness of wall jets) of ~ 0.2 to 1.0 indicating the secondary shear layer noise of wall jets.

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1. Introduction

A high momentum jet tangentially flowing over the surface of a rigid flat plate is termed as a wall jet. The wall jet has wide applications in engineering, such as in cooling of turbine blades, combustion chamber walls, electronic chips, and so on. The schematic of a wall jet is shown in Figure 1a. As observed from the figure, the wall jet has two regions, namely the inner shear layer and the outer layer. The former layer is due to the interaction between the jet and the solid surface of a plate, and the outer layer is due to the interaction between the jet and the ambient fluid. The inner layer initiates from the wall surface, and extends up to the location of maximum streamwise velocity, thus resembling a boundary layer (Figure 1a). The outer layer region is between the maximum streamwise velocity and the ambient flow velocity, thus representing a free shear layer [1]. Wall jet development is divided into three regions, namely, the potential core, transition, and fully developed regions [2]. The region where the maximum velocity is equal to the jet exit velocity is called the potential core [3], and typically, the potential core length is approximately four to eight times the nozzle height [4]. Downstream of the potential core, the wall jet undergoes a transition in the range of $10 \leq x/h \leq 20$, where h is the nozzle height, [5]. The outer layer has a larger entrainment rate, leading to the higher velocity decay. Following

is a fully developed region for $x/h > 20$, where the inner and outer layers grow along the downstream and merge to form a unified flow field [6, 7]. The velocity profile at the fully developed region is skewed, as shown in Figure 1a due to the faster growth in the outer layer compared to the inner layer. The dimensionless growth rate studies carried out by various researchers at different Reynolds number and nozzle exit dimensions are found to vary within the range of 0.073 ± 0.002 [8]. Numerous flow and acoustic studies have been carried out in the field of wall jets that are discussed in the following.

2. Background

In this section, the literature on research works carried out in the past with respect to the flow and acoustic characteristics in the wall jets, including the jet-surface interactions, are discussed.

Eriksson *et al.* [9] used LDV for studying the flow characteristics of wall jets using water as the working fluid. They found that mean velocity profiles are self-similar within $40 \leq x/h \leq 150$. They concluded that turbulent intensity is higher in the inner region of the wall jet compared to other wall-bounded flows like the flat plate boundary layer, channel, and pipe flows. Tachie *et al.* [10] carried out experiments on turbulent wall jets over the smooth and rough plates to measure the variation of velocity half-width, inner layer thickness, and velocity profiles. They estimated the spread rate to be around 0.085 at higher Reynolds number, and 0.09 at lower Reynolds

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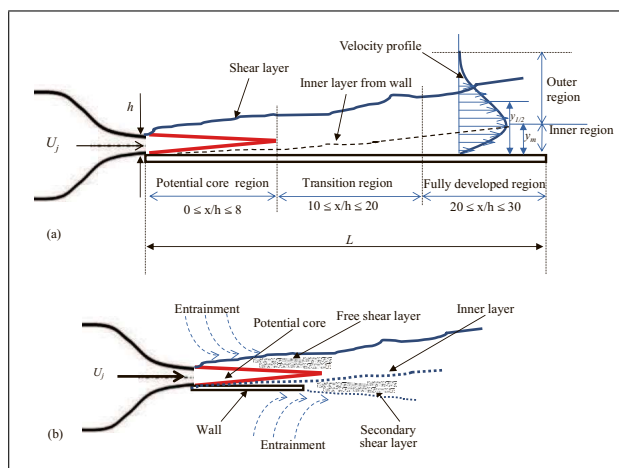


Figure 1. (a) Schematic of a (a) fully developed wall jet and (b) wall jet in a smaller plate.

number. Chab and Tachie [11] experimentally studied turbulent wall jets at different values of Reynolds number of 5000, 10000, and 20000 from a circular nozzle using PIV. They observed that the mean velocity profiles and turbulence statistics become self-similar and independent of the Reynolds number, respectively, beyond 20 to 40 times the jet exit diameter. Panidis *et al.* [12] presented the role of vorticity in the near-field region of a turbulent rectangular wall jet at the Reynolds number of 23000. The wall jet velocity distribution is seen as a distorted *dumbbell* shape with a saddleback profile due to the presence of the wall. The wall jets are observed to contract along the spanwise direction and expand in the lateral direction. Furthermore, due to the Coanda effect, the wall jet is attracted towards the surface. Tang *et al.* [13] experimentally studied the effect of surface roughness on the mean flow characteristics of a wall jet. The inner layer of the rough surface wall jet is found to be much thicker compared to the smooth surface wall jet. A fully rough surface increased the growth rate of the inner layer by approximately 4% compared to the smooth surface. Roy *et al.* [14] carried out experiments in a water channel to investigate the behaviour of eddies during the turbulent jet interaction with a horizontal rigid flat surface placed at a distance of 2.5 cm away from the nozzle. At an intermediate location, the interaction between the jet and the rigid surface increases the axial velocity fluctuations. A new mixing layer is observed in the transition region, and the region below this mixing layer is treated as the shear less mixing region.

The following literatures discuss the research works carried out on the noise emissions from the turbulent boundary layer of the flow over a rigid flat surface. Curle [15] proposed a theory on the influence of solid surface on noise emissions and corroborated that the noise from turbulent boundary layer behaves like a quadrupole, and unsteady pressure fluctuations due to the surface roughness behave like a dipole. Philips [16] reported that a uniform flow over a semi-infinite flat plate generates a dipole radiation. This radiation is found to decrease along the downstream of the plate and becomes insignificant. Hardin [17]

theoretically studied the noise emissions from the turbulent boundary layer flows at a low Mach number. He observed that the fluctuating Reynolds stresses are equivalent to a quadrupole noise source, which contributes to the boundary layer noise. In addition, the horse-shoe like vortices in the boundary layer are identified as the significant noise source. Interestingly, it is also noted that the turbulent boundary layer noise sources are less efficient than a free jet. Howe [18] reported the empirical models for wall-pressure spectrum and radiated sound in a turbulent boundary layer. In low Mach number flows, a similarity is observed between the wall-pressure spectrum and far-field frequency spectrum. He observed that the smooth wall behaves as a passive acoustic reflector of noise sources due to turbulent eddies compared to the rough wall.

Farabee and Casarella [19] experimentally studied the wall pressure fluctuations in a turbulent boundary layer. They established a scaling law for low, mid, and high frequency region of the pressure spectrum. Using velocity data and scaling law, they found that major turbulent contributions to low and high wave numbers are from the outer and inner layers, respectively. Lauchle [20] theoretically predicted the noise radiation from the boundary layer flow over an infinite rigid flat plate. Of all the noise sources generated, namely, the dipole, quadrupole, and octupole, the dipole is found to be efficient compared to the remaining sources at low Mach number flows. Further, it is noted that the shear stress fluctuations in the transition region leads to the generation of the dipole noise source. The noise level increases by 6 dB/octave at lower frequencies and drops at 6 dB/octave at high frequencies. Noise emissions due to the flow interaction with smooth and rough surfaces are theoretically studied by Smol'yakov [21]. He estimated the acoustic source to be a dipole in a rough plate and a quadrupole in a smooth plate. Smith and Morfey [22] numerically analysed the noise directivity in the boundary layer by placing an acoustically compact piston source near the wall. It is noted that the boundary layer thickness of 1/100th of the sound wavelength can significantly change the acoustic efficiency. The sound radiated from the turbulent boundary layer propagates upstream, and acoustic intensity is found to be lower for larger boundary layer thickness. Liu *et al.* [23] estimated the acoustic field from the turbulent boundary layer as a dipole using phased array microphones. The source strength of rough and smooth plates was compared using beamforming. Rough plates showed higher source strength than the smoother ones. Trailing edge noise of the rough plate was higher compared to a smooth plate due to increase in friction velocity and boundary layer thickness. Noise radiated from turbulent boundary layer was computed by Glerfelt and Berland [24]. Their main observation is that low frequency acoustic emissions are due to the hairpin-like vortices inside the turbulent boundary layer and radiation of these low frequency sources is in the direction opposite to the flow. Di Marco *et al.* [25] experimentally investigated velocity and pressure fluctuations in an incompressible jet flow over a tangential flat plate placed

at different radial positions from the nozzle axis. They identified three regions along the streamwise direction of the flow based on the root mean square pressure fluctuations $c_{p_{rms}}$ and mean pressure coefficient c_p . In the first region, $c_{p_{rms}}$ increases and c_p remain constant. In the second region, $c_{p_{rms}}$ is constant, and c_p reaches the maximum, and in the third region both decay. Further, the above authors extended their work to measure the velocity fluctuations and wall pressure fields simultaneously [26]. Cross statistical analysis between the two signals revealed the presence of the Kelvin-Helmholtz Instability in the flow field at small axial distances. Moreover, the wavelet analyses of the wall pressures indicated the breakdown of the large scale structures along with the plate. Blitterswyk and Rocha [27] conducted studies on wall pressure fluctuations in the turbulent boundary layer at low Reynolds number using a microphone array. They estimated that 42% of low-frequency noise originates from the buffer layer of the boundary layer, 17% is contributed by the structures above the logarithmic region. Data correlation within the buffer layer shows the low and high frequency peaks, which indicates the large and small scale structures, respectively. Mancinelli and Camussi [28] investigated the acceleration of the incompressible jet over the flat plate experimentally. They showed a significant correlation between the acceleration and wall-pressure signals within the potential core that is related to the Kelvin-Helmholtz instability mode.

Finally, the following literature discussions on the noise emissions from wall jets are illustrated. Yu and Tam [29] reported an experimental work describing the noise generation from a turbulent wall jet over a flat plate of 12.75 cm in length with a sharp trailing edge. They observed that the convecting large-scale quasiorderly disturbance in the outer layer region of the wall jet over the trailing edge is the reason for the dominant trailing edge noise generation. Smith and Carpenter [30] proposed a method to theoretically model the noise generation from turbulent shear flows near a solid wall surface. They applied the method to model the noise in a plane wall jet and noticed a destructive interference at specific points along the wall surface. Because of this, the power emission is noted to be highest slightly away from the end of the potential core. Devenport *et al.* [31] experimentally investigated the roughness noise from a turbulent wall jet by varying the surface roughness from hydrodynamically smooth to fully rough surface having the grit size of 180 to 20. They found that the noise emitted from rough surfaces is broadband, and shifts towards the higher frequency with an increase in the flow speed. Chong and Vathylakis [32] experimentally investigated the radiated noise from the turbulent flow over a flat plate with straight trailing and serrated trailing edges. They reported that noise radiated from the serrated trailing edge is lesser by 0.5–1.0 dB compared to the straight edge trailing edge in the frequency range of $1 < f < 2.5$ kHz that is attributed to the boundary layer alteration for different edges.

The literature review reveals that ample research works have been carried out in the field of flow characteristics of

wall jets. Acoustic studies from such jets are emerging in large, and works have been carried out to understand the acoustic emissions due to surface roughness [31], pressure fluctuations in the boundary layer [25, 27]. It is noted that most of the works in literature are discussed on the fully developed wall jets with the plate lengths of $L/h > 20$. In such jets, the inner layer and the free shear layer merges to form a unified flow field [6, 7] as seen in Figure 1a. In the case of plates with smaller lengths ($L/h < 20$), the inner layer interactions at the trailing edge can significantly contribute to the noise emissions (Figure 1b). Further, an inner layer can generate a secondary free shear layer by entraining the air stream beneath the plate, thus resulting in additional noise emissions [33]. Therefore, the effect of inner layer growth over the plate and its interactions at the trailing edge, and the formation of the secondary shear layer resulting in the noise emissions are concentrated in this paper. This lacuna in the literature motivated the authors to investigate the role of plate lengths on noise emissions in wall jets. Further, this study enhances the researchers' insight into the variation of noise emission characteristics from a free jet to a fully developed wall jet. The spectral measurements and sound pressure levels analyses are carried out to investigate the noise from wall jets with the smaller plates.

3. Experimental methodology

3.1. Test facility

Experiments are performed in a semi-anechoic chamber having a cut-off frequency of 300 Hz. The schematic and photographic views of the experimental set-up are shown in Figure 2. The wedge tip-to-tip dimension of the anechoic chamber is 2.6 m $\times$ 2.6 m. The wedges attached to the chamber are 30 cm in depth. The setup consists of an open jet wind tunnel facility, and the air-flow is powered using a 10 HP centrifugal blower. The maximum flow velocity of 65 m/s is achieved at the nozzle exit, and the velocity is controlled by a variable frequency drive (VFD) unit using a computer. The jet is issued from a converging nozzle having a contraction area ratio of 10:1 with nozzle exit dimensions of 20 cm in width and 2 cm in height. A cubic contraction profile of the nozzle is considered to deliver a smooth flow out of the nozzle with a uniform velocity profile.

3.2. Plate models for wall jet study

The length L of the plates considered for the study are 5, 10, 20, 30, 40, 50, and 60 cm, corresponding to the non-dimensional lengths in the range $2.5 \leq L/h \leq 30$, where h is the nozzle height. For the different plate lengths considered, the corresponding trailing edge terminates in the different flow regimes of the wall jet, namely the (i) potential core ($\approx 7h$) (ii) transition, and (iii) fully developed ($> 20h$) regions, and the respective acoustic disturbance is captured and analysed. Photograph of plate models considered for the study is shown in Figure 3a. The plates

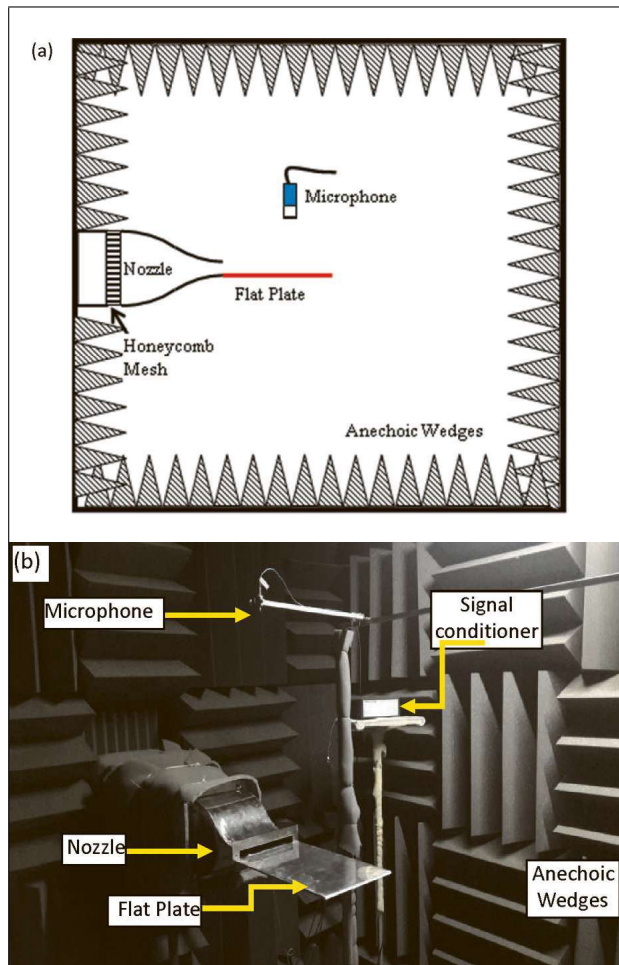


Figure 2. (a) Schematic and (b) photograph of the experimental setup.

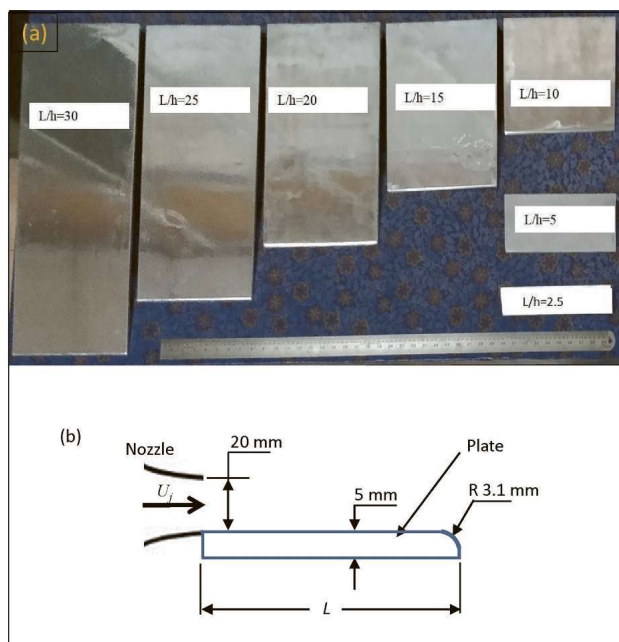


Figure 3. (a) Photograph of the wall jet plates. (b) Dimensions of the wall jet plate.

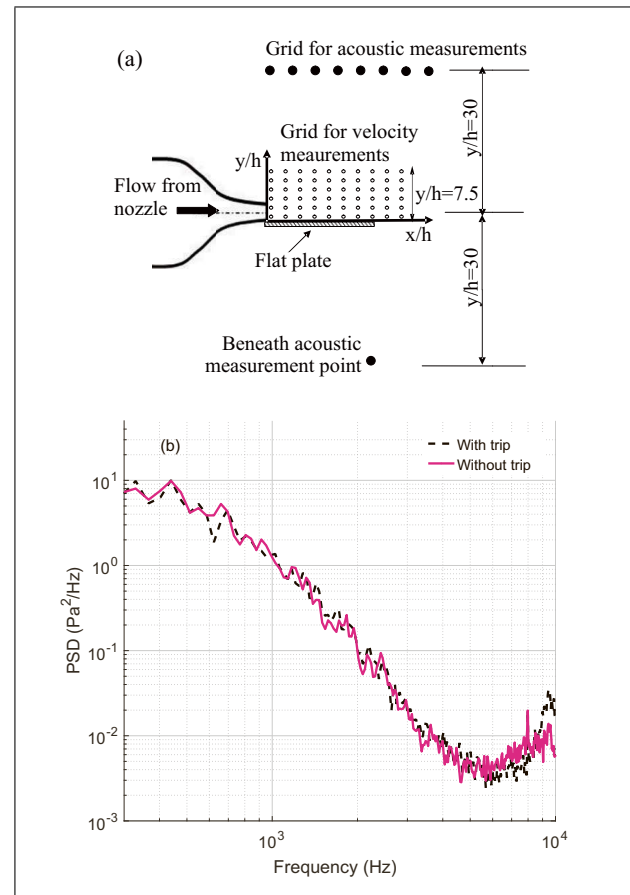


Figure 4. (a) Schematic of the measurement grid for flow and acoustic measurements (dimensions are not to scale). (b) Spectral comparison of $L/h = 10$ wall jet with and without tripping boundary layer at $Re = 7.0 \cdot 10^4$.

are fabricated using the CNC machine, and the surface is micro-finished to ensure a smooth flow over the plate. The surface roughness's values of the plates are tabulated in Table I, and are in the same order of magnitude, varying in the range of 0.21 to 0.356 μm . The span length and thickness of the plates are 250 and 5 mm, respectively. A curvature is provided at the trailing edge of the plates to prevent the vortex shedding (Figure 3b). These model plates are attached to the nozzle, as shown in the figure.

3.3. Experimental procedure

Experiments are carried out for jet exit velocities U_j ranging from 35 to 55 m/s. The corresponding Reynolds number, calculated based on the jet exit velocity and nozzle height, varies in the range of $4.5 \cdot 10^4$ to $7.0 \cdot 10^4$. The velocity measurements are carried out at different locations of wall jets, as shown in Figure 4a using a Pitot-static probe connected to a digital anemometer. The streamwise velocity measurements are taken along the plate length with an interval of $x/h = 1$. The lateral measurements are in the range of $0.25 \leq y/h \leq 7.5$, with an interval of $y/h = 0.05$. The acoustic measurements are carried out at mid-field distance of $30h$ from the jet axis using a quarter-inch free-field condenser microphone (PCB378C01) and

Table I. Surface roughness of different plates used for the study.

Plate length L/h	Surface roughness, μm
2.5	0.28
5	0.21
10	0.26
15	0.31
20	0.30
25	0.28
30	0.36

array microphone (GRAS 40PH). The microphone is traversed along the streamwise direction from the nozzle exit ($x/h = 0$) to the trailing edge of the plate and beyond for the given wall jet in the range $0 \leq x/h \leq 45$ (Figure 4a). The signal is acquired using a NI PCI-6143 sampling card at the rate of 150 kSa/s for the duration of 1 s. The acquired time signals are processed to obtain the frequency spectrum, sound pressure levels, and overall sound pressure levels variation along the streamwise direction. All the data acquisition and the post-processing are carried out using the LabView and MATLAB, respectively. The bin-size of 4096 points is considered for the Fourier transform that provides the spectra at a frequency resolution of 36.6 Hz. The experiments are repeated for 5–7 trials, and the sound pressure levels are found to be repeatable within ± 1 dB. The uncertainty estimate for the velocity measurements is accurate within $\pm 2.5\%$. The temperature variation inside the anechoic chamber is $\pm 1^\circ\text{C}$. The microphone is accurately positioned within ± 1 mm. In the current study, the background noise refers to the jets without the plates, therefore, corresponding to a free jet. The spectra of the acoustic data are represented in terms of power spectral density in Pa^2/Hz , and the frequency components are shown up to the value of 10 kHz. Experiments are also carried out by continuously varying the jet exit velocity/Reynolds number in small intervals by using the computer controlled VFD unit.

In the considered range of Reynolds numbers, the wall jets are found to be turbulent. This is ensured by carrying out the following experiments. The typical turbulent intensity levels measured at the nozzle exit on the centre- and lip-lines using the hot-wire anemometer (DANTEC Make, MiniCTA System) for the jet Reynolds number of $6.4 \cdot 10^4$ are found to be around 1.5% and 10.2%, respectively demonstrating the fact that the flow at the nozzle exit is turbulent. This is further ensured by acquiring the acoustic data for $L/h = 10$ wall jet by attaching a tripping wire at the leading edge of the plate, and comparing the same without the tripping wire. Their corresponding spectra shown in Figure 4b are almost similar, thus proving that the wall jet is turbulent.

4. Results and discussion

In this section, the flow and acoustic characteristics of wall jets are presented. Flow results are discussed first. Second,

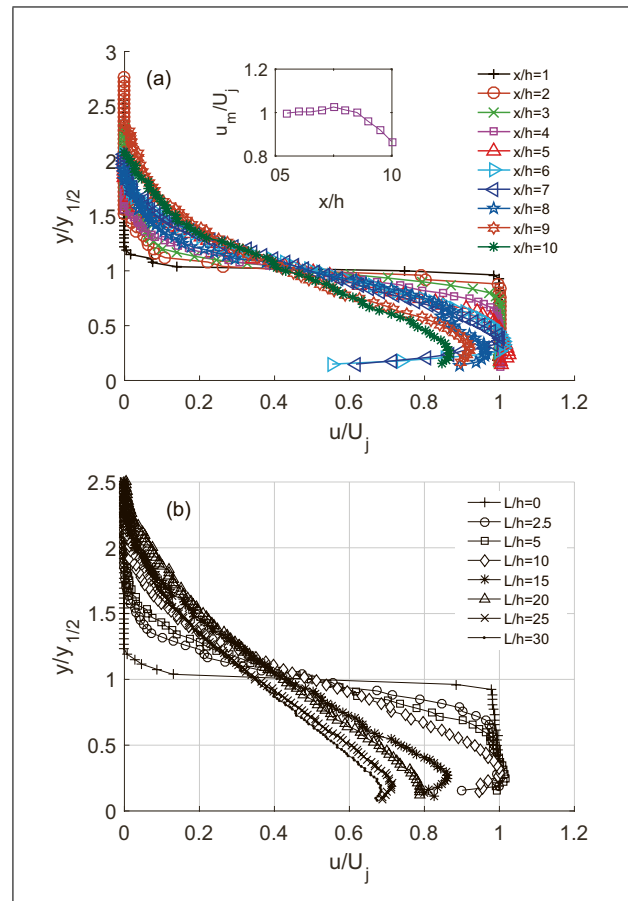


Figure 5. (a) Velocity profiles at different streamwise locations for $L/h = 5$ at jet exit velocity of 45 m/s. (b) Velocity profiles at the trailing edge for different plate lengths at jet exit velocity of 50 m/s.

the evolution of mid-field noise spectra and Overall Sound Pressure Levels (OASPL) with the Reynolds number are considered.

4.1. Flow characteristics of wall jets

Figure 5a shows the velocity variation across the wall jet for different streamwise locations x/h for the plate length of $L/h = 5$ at the Reynolds number of $5.8 \cdot 10^4$. The velocity is normalised with the exit jet velocity ($U_j = 45$ m/s) and the distance across the wall jet is normalised with the velocity half-width $y_{1/2}$. The velocity half-width represents the distance from the wall to the position in the wall jet, where the streamwise velocity has reduced to half of the maximum streamwise velocity u_m . From the figure, the initial reading can be observed starting from a distance of $y/y_{1/2} = 0.15$ since it accounts for the dimensions of the Pitot-tube that is used for the velocity measurement. It is evident from the figure that near the nozzle exit, at $x/h = 1$, the velocity profile is top-hat. The free shear layer is seen to increase gradually along the streamwise direction of the wall jet. Interestingly, the maximum jet velocity $u/U_j = 1$ is observed up to the axial distance of $x/h = 7$ from the nozzle exit. This corroborates the fact that the potential core of the wall jet extends beyond

the plate length of $L/h = 5$. Beyond the axial distance of $x/h = 7$, the maximum velocity of the wall jet flow tends to decrease as the flow experience the free shear layer from either of its sides. This is also illustrated in the inset figure (Figure 5a) that indicates the maximum velocity (u_m) variation along the axial distance of the wall jet [3]. The free shear layer growth is at a higher rate compared to the boundary layer growth at the plate. For instance, at $x/h = 7$, the $y/y_{1/2}$ in the free shear layer varies from ~ 0.4 to 2.0 , while on the boundary layer side, the $y/y_{1/2}$ variation is found from the wall surface to 0.4 . Figure 5b shows the velocity profiles plotted with different plate lengths for the jet Reynolds number of $6.4 \cdot 10^4$. In this case, the velocity profiles are measured at the trailing edge of all the plates considered for wall jets. The velocity profiles within $L/h \leq 10$ depicts the region of the potential core, transition in the range of $10 \leq L/h \leq 20$, and beyond, a fully developed region which is in congruence with the flow literature [4, 5, 6, 7]. The transition in the range of $10 \leq L/h \leq 20$ is confirmed from the following facts. (i) The velocity profile at $L/h = 15$ shows a larger decrease in the maximum velocity u_m . (ii) At $L/h = 20$, the velocity profile near the wall surface is noted to be flatter compared to those at other L/h . This illustrates that the inner layer thickness y_m is smaller at $L/h = 20$ compared to the other cases, albeit this could not be proved with measurements in the present study. These observations are in congruence with the literature data of Hsiao and Sheu [5], which confirms that the region in the range of $10 \leq L/h \leq 20$ is in the transition. The variation of velocity half-width $y_{1/2}/h$ in the range of plate lengths L/h considered is plotted in Figure 6a for $Re = 6.4 \cdot 10^4$. The obtained values are in congruence with those of Eriksson *et al.* [9] and Tachie *et al.* [10] which are plotted along the streamwise direction of larger length wall jets. The gradient of the velocity half-width of the wall jet in the current study is estimated to be around 0.063 , which is comparable to those of the literature [8, 9], where it is estimated to be around 0.073 . The difference in the estimates between the present study and the literature data is due to the facts that (i) the plate lengths considered are smaller for the present study, and (ii) the variation in the nozzle lip thickness that affects the growth of wall jets [8]. The variation of inner layer thickness y_m/h in the range of plate lengths L/h considered is plotted in Figure 6b for $Re = 6.4 \cdot 10^4$, and is compared with the data of Tachie *et al.* [10], which is obtained along the streamwise direction of the wall jet at different Reynolds numbers. The maximum plate length used in the study is $L/h = 30$ and the inner layer thickness in the considered range of plate lengths are seen to match well with the literature. The inner layer thickness varies linearly with the plate length. The present and literature data results indicate that the inner layer thickness does not depend on the considered range of Reynolds number.

4.2. Acoustic spectra of wall jets

Figure 7 shows the spectra at different Reynolds numbers of $2.7 \cdot 10^4$, $4.5 \cdot 10^4$, and $7.0 \cdot 10^4$ for $L/h = 5$ and 15

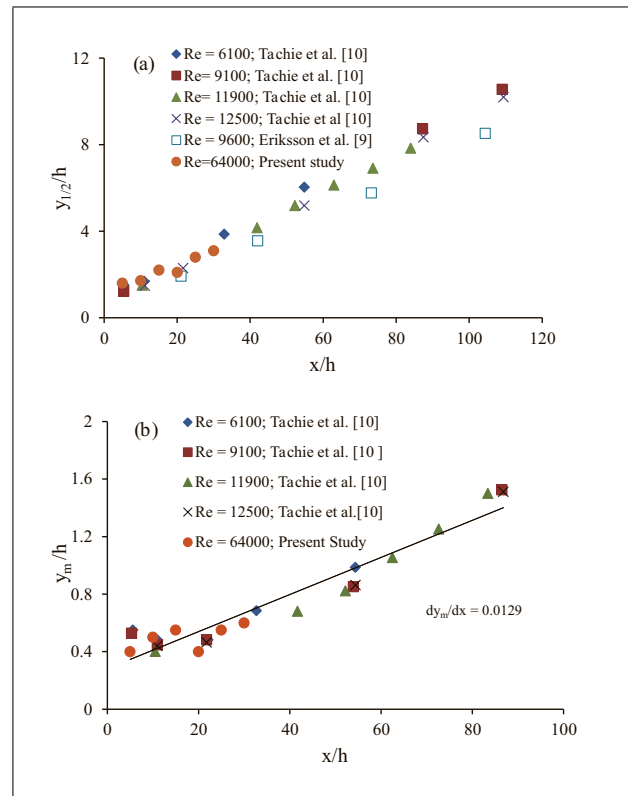


Figure 6. The variation of (a) velocity half-width ($y_{1/2}$) and (b) inner layer thickness (y_m) with the axial length of wall jet.

wall jets, and compared with the free jet noise/background noise. The spectra are captured at the trailing edge of the plate at a vertical distance of $y/h = 30$. At lower Reynolds number of $2.7 \cdot 10^4$, the wall jet noise is dominant up to ~ 1 kHz compared to the free jet noise; at moderate Reynolds number of $4.5 \cdot 10^4$, the wall jet noise is dominant up to ~ 2 kHz; and at higher Reynolds number of $7.0 \cdot 10^4$, the wall jet noise is dominant up to ~ 3 kHz compared to the free jet. This illustrates that the wall jet induces higher frequency noise components with an increase in the flow velocity. The noise could be attributed to the sources such as the flow-surface interaction, scattering at the trailing edge, free shear layer, and inner layer thickness that will be discussed in the subsequent sections. Further, the lower frequency noise of a wall jet is larger by almost two orders of magnitude than the higher frequency noise at higher Reynolds number (Figure 7b,c,e,f). The low frequency noise of wall jet increases almost by three orders of magnitude with an increase in the Reynolds number while the high frequency noise increases at most by two orders. In the Figures 7a,b,d,e, a few low amplitude tones are noted at higher frequencies in the lower and moderate Reynolds numbers for both the background and wall jet spectra. This assures that these tones are not specific to the wall jet, and therefore, it is presumed that they are facility induced, and consecutively neglected in the future discussions.

Figure 8 shows the waterfall spectra with plate lengths at different Reynolds numbers. The noise of a free jet

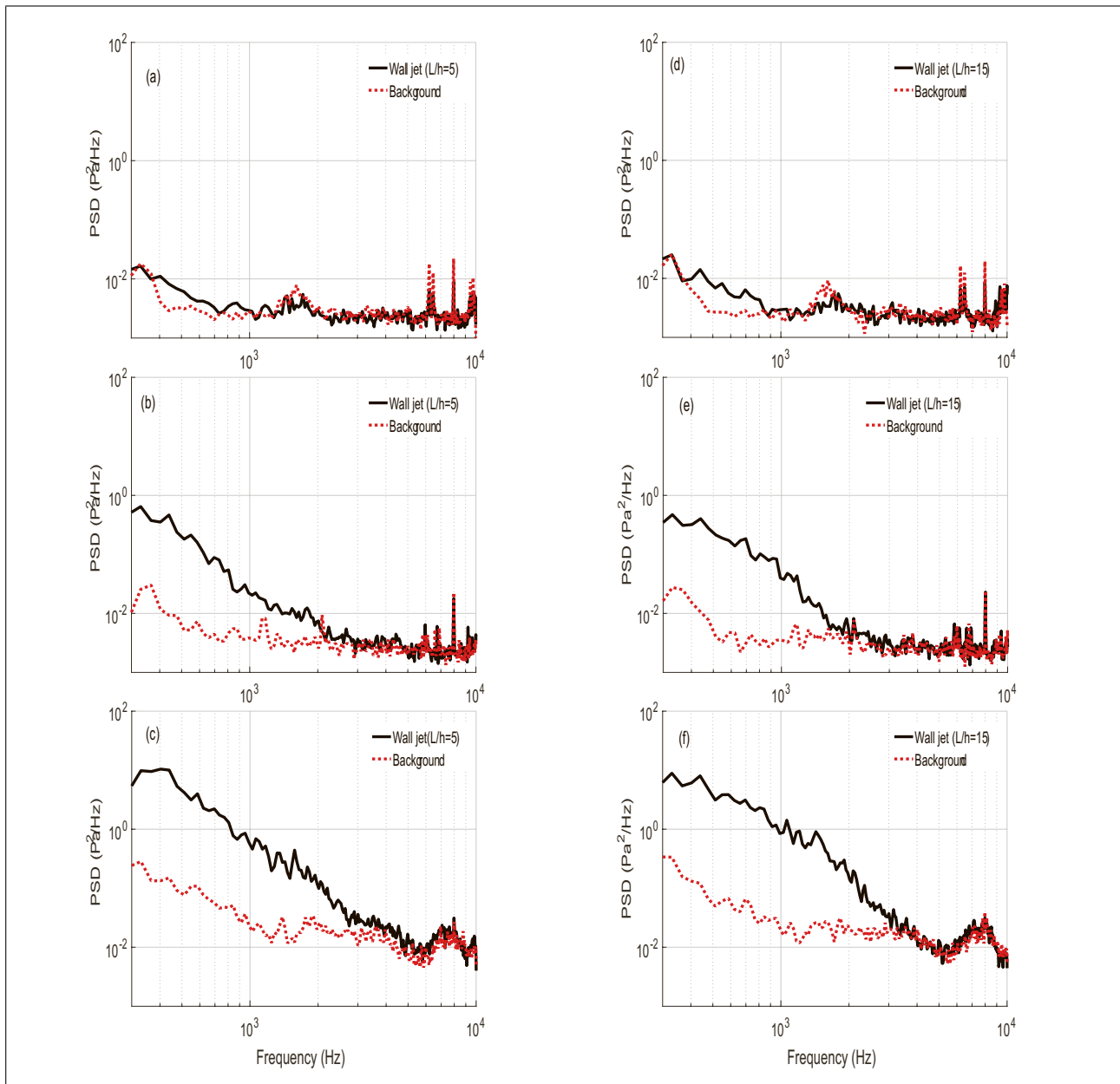


Figure 7. Comparison of the spectra obtained for wall jets of $L/h = 5$ and 15 with the background noise ($L/h = 0$) for $Re = 2.7 \cdot 10^4$ (a,d) $Re = 4.5 \cdot 10^4$ (b,e) and $Re = 7.0 \cdot 10^4$ (c,f).

($L/h \approx 0$) is found to be lowest compared to those of the wall jets considered. It is observed from the figure that with an increase in the plate length, the low frequency noise ($0.3 \text{ Hz} \dots 1 \text{ kHz}$) increases up to $L/h = 5$, and thereafter decreases over the range of $10 \leq L/h \leq 30$, however, with a larger gradient in the range of $20 \leq L/h \leq 30$ (Figure 8). This variation in the noise is attributed to the termination of plates at different flow regimes of the wall jet. For instance, plates with $L/h \leq 5$ terminate within the potential core (Figure 5b) while plates in the range of $10 \leq L/h \leq 20$ terminate in the transition region, and plates with $L/h > 20$ belong to a fully developed wall jets category. It is conjectured that the smaller plate shields the potential core from the entrainment from one side of the wall jet [33] and thus increasing the noise levels at lower

plate lengths, as noted in Figure 8. The physical reason for the variation in the noise levels in a lower frequency range is attributed to different noise sources in the wall jets. From the literature, the noise sources identified during the flow interactions with a rigid surface are dipole and quadrupole [15, 16, 17, 18, 19, 20, 21]. The former noise source is primarily noticed at the trailing edge and the transition region [35, 20]. The latter source is noticed near the wall surface region [17]. Therefore, with an increase in the plate length $L/h > 10$, the momentum of the wall jet inner layer decreases, thereby reducing the dipole strength at the trailing edge compared to the shorter plate wall jet. However, with an increase in plate length, the turbulent intensity of the inner layer is observed to increase [5], and the corresponding noise source is seen to increase. This is elaborated in

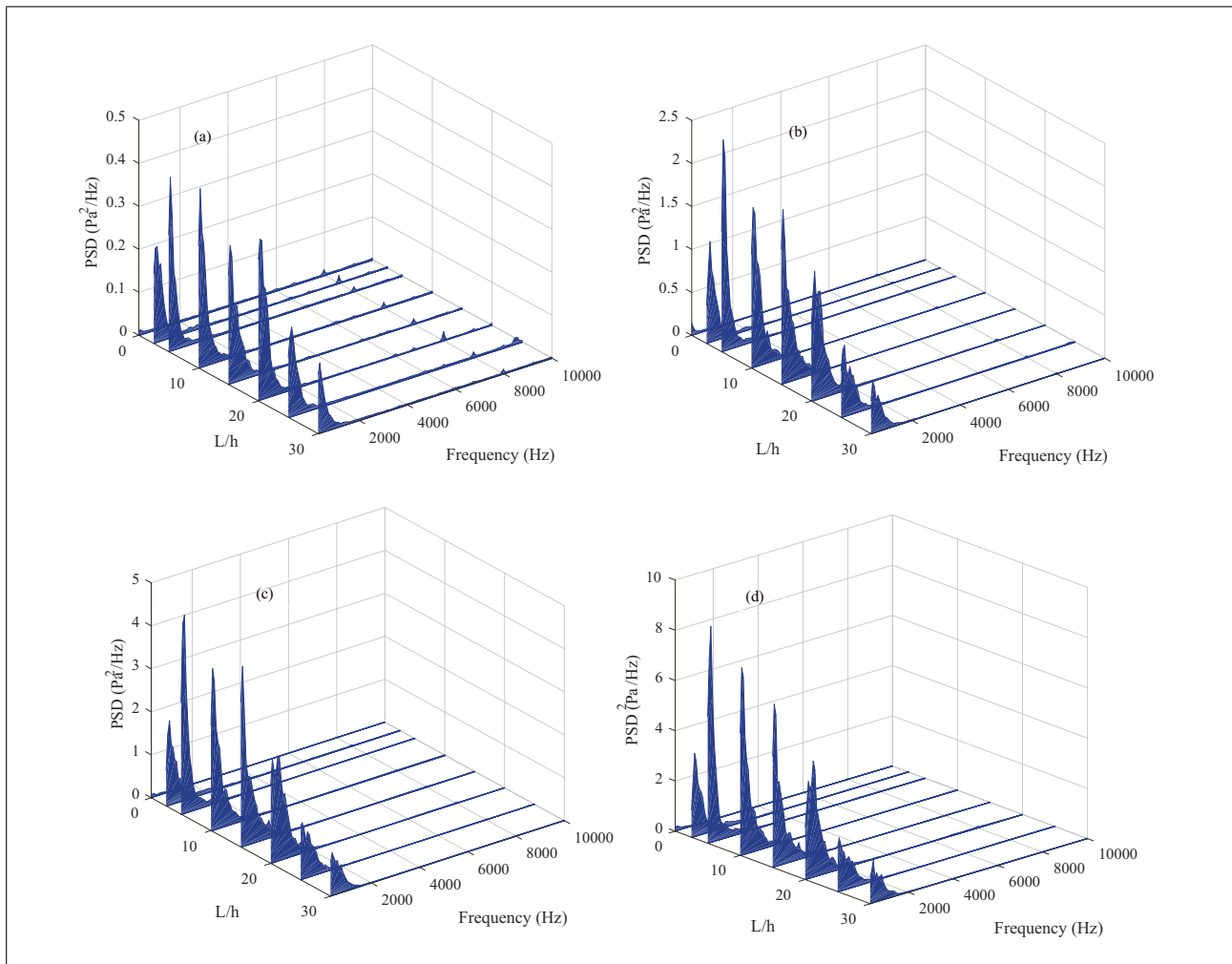


Figure 8. Waterfall spectra variation with plate lengths of wall jets at (a) $Re = 4.5 \cdot 10^4$ (b) $Re = 5.8 \cdot 10^4$ (c) $Re = 6.4 \cdot 10^4$ (d) $Re = 7.0 \cdot 10^4$.

detail in Section 4.4. To ensure the correctness of the acquired data, a typical acoustic spectrum for $L/h = 5$ wall jet at a jet exit velocity of 35 m/s is compared with that of Chong and Vathylakis [32] at similar conditions, and is shown in Figure 9. The spectral variation in both the studies is almost similar up to the frequency of ~ 3 kHz, where the noise is broadband. However, higher frequency noise components (> 3 kHz) are observed in the present study, which is due to the facility induced noise, as discussed earlier. The noise levels in both the spectra are different, as they were procured at different positions from the source (60 cm in the present study and 105 cm in the compared study).

The overall sound pressure levels (OASPL) are plotted with plate lengths for different Reynolds numbers in Figure 10 at nozzle exit $x/h = 0$ and the trailing edge of the plate. The OASPL trend is observed to be similar at all the Reynolds number. The maximum OASPL is around 80 dB in the range of $L/h = 5$ to 20, and decreases to 75 dB for $L/h = 30$ at the Reynolds number of $7.0 \cdot 10^4$, while the background noise is around 68 dB at the same Reynolds number. Figure 11 shows the variation of OASPL with the Reynolds number for different wall jets of $L/h = 5$,

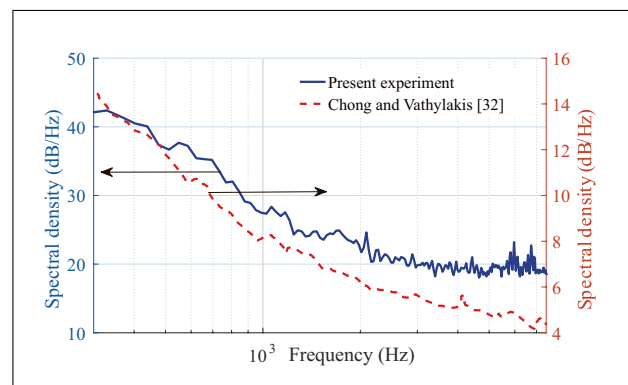


Figure 9. Comparison of acoustic spectrum for $L/h = 5$ wall jet at jet exit velocity of 35 m/s.

15, and 25. The OASPL variations at the lower Reynolds numbers are insignificant. However, beyond the Reynolds number of $\sim 3.0 \cdot 10^4$, the OASPL is observed to increase with an increase in the Reynolds number for all the wall jets. The OASPL is highest for $L/h = 5$, followed by a slightly lower value for $L/h = 15$ and a large reduction for $L/h = 25$ wall jet. Importantly, the presence of a plate can

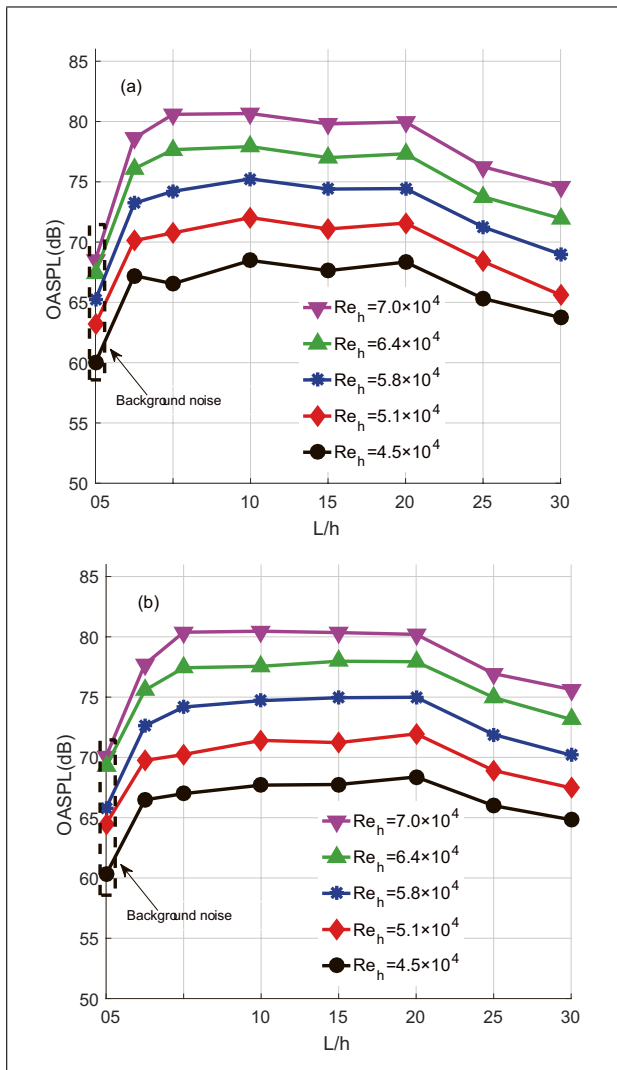


Figure 10. OASPL comparison for wall jet with L/h for microphone placed at (a) $x/h = 0$ and (b) trailing edge of different wall jets.

increase the noise emission by almost 12 dB (compared to free jet noise) if the plate length considered is within the potential core to transition region.

4.3. Noise variation along the wall jet

Figure 12 shows an interesting plot at the Reynolds number of $7.0 \cdot 10^4$ illustrating the OASPL variation along with the streamwise locations x/h for different L/h wall jets. The filled markers in the figure represent the acoustic data acquired within the plate length of the wall jet, and the unfilled markers represent the one acquired beyond the plate. The highest x/h with a filled marker corresponds to the trailing edge for the given L/h . The OASPL variation with L/h at the trailing edge is shown as the dashed line in the figure which is consistent with that of Figure 10b. The OASPL of fully developed wall jets ($L/h = 25$ and 30) are observed to increase along the plate length by almost 3 dB (Figure 12). However, for developing wall jets ($L/h \leq 20$), the OASPL along the plate length is found to be almost constant. The reason for an increase in the

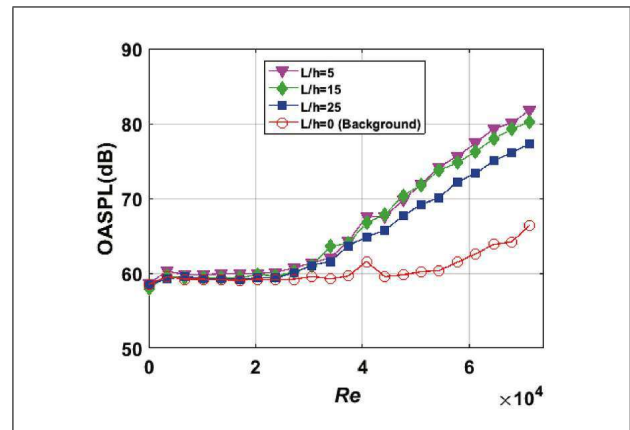


Figure 11. Variation of OASPL with Reynolds number for different plate length wall jets.

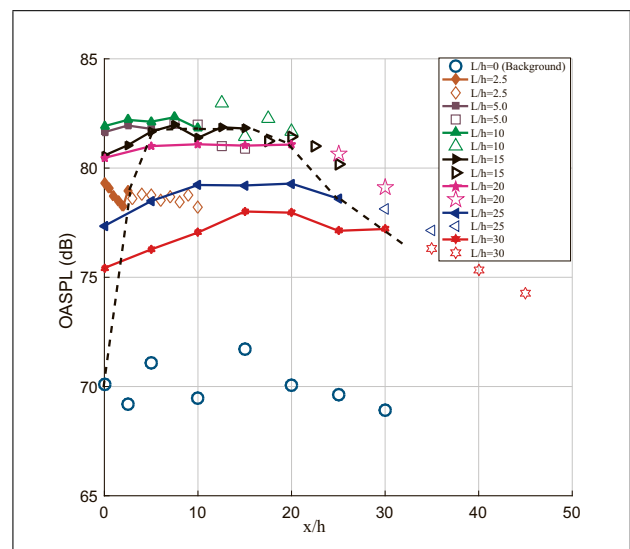


Figure 12. OASPL variations along different streamwise at $Re = 7.0 \cdot 10^4$. Filled markers indicate the noise data within the plate while the unfilled markers correspond to the data beyond the wall jet.

OASPL along x/h for the fully developed wall jets can be understood from the following explanation. From the literature, it is noted that the transition in the wall jets occurs at an axial distance of $x/h \approx 20$, and the shear stresses in the region are found to be higher compared to the other regions [5]. Thus, the OASPL is seen to increase up to $x/h \approx 20$, and a decrease in the further downstream (Figure 12). These characteristics is also observed in Figure 13 that compares the spectrum between the locations, $x/h = 0$ and the mid-plate location of different plates at the Reynolds number of $7.0 \cdot 10^4$. At $L/h = 25$ and 30 (Figure 13e&f), the noise levels in the frequency range of 0.3–1.5 kHz are found to be higher in the latter location compared to the former one. Further, Figure 12 also illustrates that the OASPL beyond the plate is comparatively lower than that within the plate for most of the L/h wall jets. To analyse this behaviour, the acoustic spectra are compared at the mid-plate location and beyond the plate

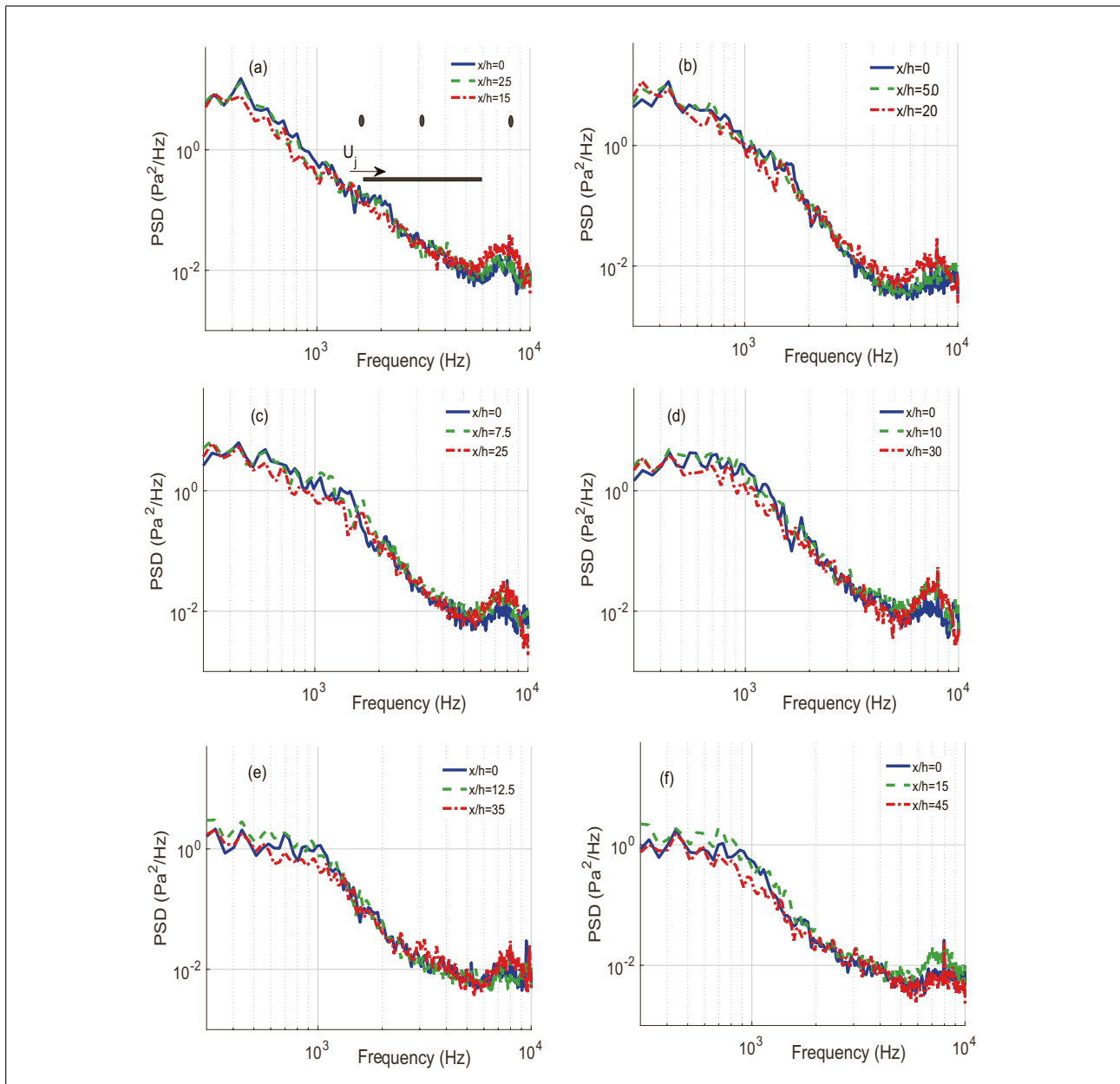


Figure 13. Spectral comparison at $x/h = 0$, mid-plate and beyond the wall jet (locations are shown in the inset) for (a) $L/h = 5$; (b) $L/h = 10$; (c) $L/h = 15$; (d) $L/h = 20$; (e) $L/h = 25$; (f) $L/h = 30$ at $Re = 7.0 \cdot 10^4$.

in Figure 13 for all the wall jets. In the lower frequency range of around 300–3000 Hz, the noise emissions within the plate length of wall jets are found to be higher compared to that beyond the plate, while the spectral difference is insignificant at a higher frequency range of above 3 kHz. This is attributed to the noise due to the flow-surface interaction within the plate compared to that beyond the plate. Interestingly, the difference in the low frequency range is higher for wall jets of $L/h = 15$ to 30 compared to those at smaller L/h , as the surface area is larger for the former plates (Figure 13).

4.4. Noise source identification

To analyse the contribution of flow-surface interaction in noise emissions, the noise measurements are carried out at

the locations, $y/h = 30$ (above the plate) and $y/h = -30$ (beneath the plate), as shown in Figure 4a. The above-plate microphone and the beneath-plate microphone are placed at the trailing edge (same x/h). A similar technique is handled by Brown [34] and Bastos *et al.* [35] to identify the noise sources. Figure 14 shows the spectral comparison of wall jets having the plate lengths of $L/h = 5$ to 30 at $Re = 7.0 \cdot 10^4$. In most of the spectra, noise beneath the wall jet is slightly higher than that of the above plate in the low frequency range of around 300–1500 Hz (Figure 14). It is conjectured that the noise sources in this frequency range are the trailing edge interactions and the secondary shear layer. The arrival to this conclusion is from the fact that the beneath microphone captures the noise from the direct vicinity noise sources, which in the present case

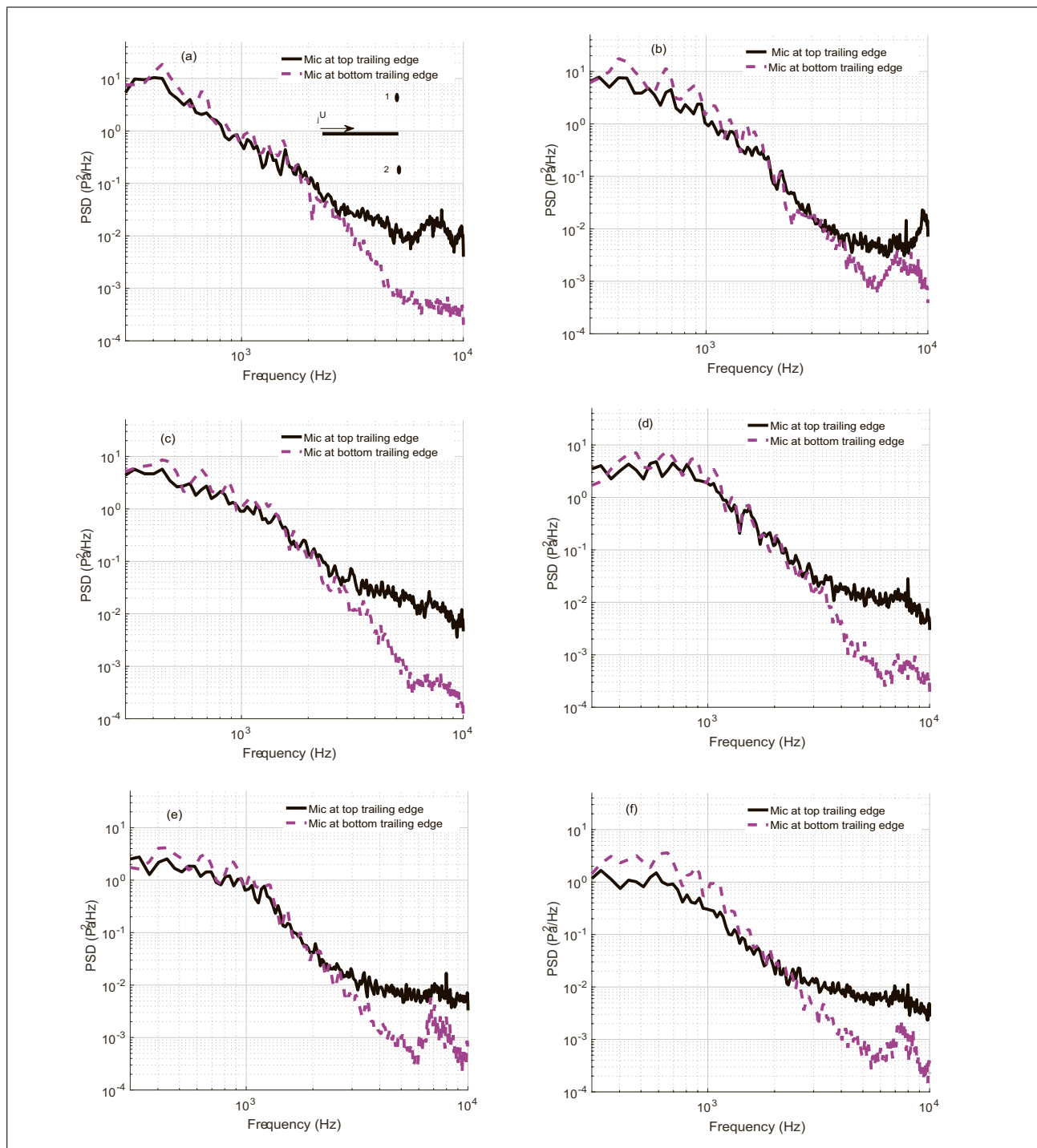


Figure 14. Spectral comparison at the trailing edge between the above and below-placed microphones (as shown in the inset) for plate lengths of (a) $L/h = 5$; (b) $L/h = 10$; (c) $L/h = 15$; (d) $L/h = 20$; (e) $L/h = 25$; (f) $L/h = 30$ at $Re = 7.0 \cdot 10^4$.

are the above-mentioned, compared to the above-placed microphone [35]. A further illustration is depicted in the form of a cartoon in Figure 15. The inner layer is expected to grow along the plate length, and interacts at the trailing edge to generate noise. Further, the secondary shear layer region is formed due to this inner layer and entrainment that radiates noise, as shown in Figure 15. An additional interesting fact observed in Figure 14 is that above ≈ 3 kHz, a decrease in the noise levels is observed with the

beneath-plate microphone compared to its counterpart. It is speculated that this noise is the contribution from the upper free shear layer of the wall jet. The reason to arrive this conclusion is that the above-plate microphone is in the direct vicinity of the upper shear layer while its counterpart is shielded by the plate thus preventing the acoustic waves from travelling beneath the plate (Figure 15). This fact can also be encountered from the spectrum of a free jet that essentially should capture this high frequency noise from the

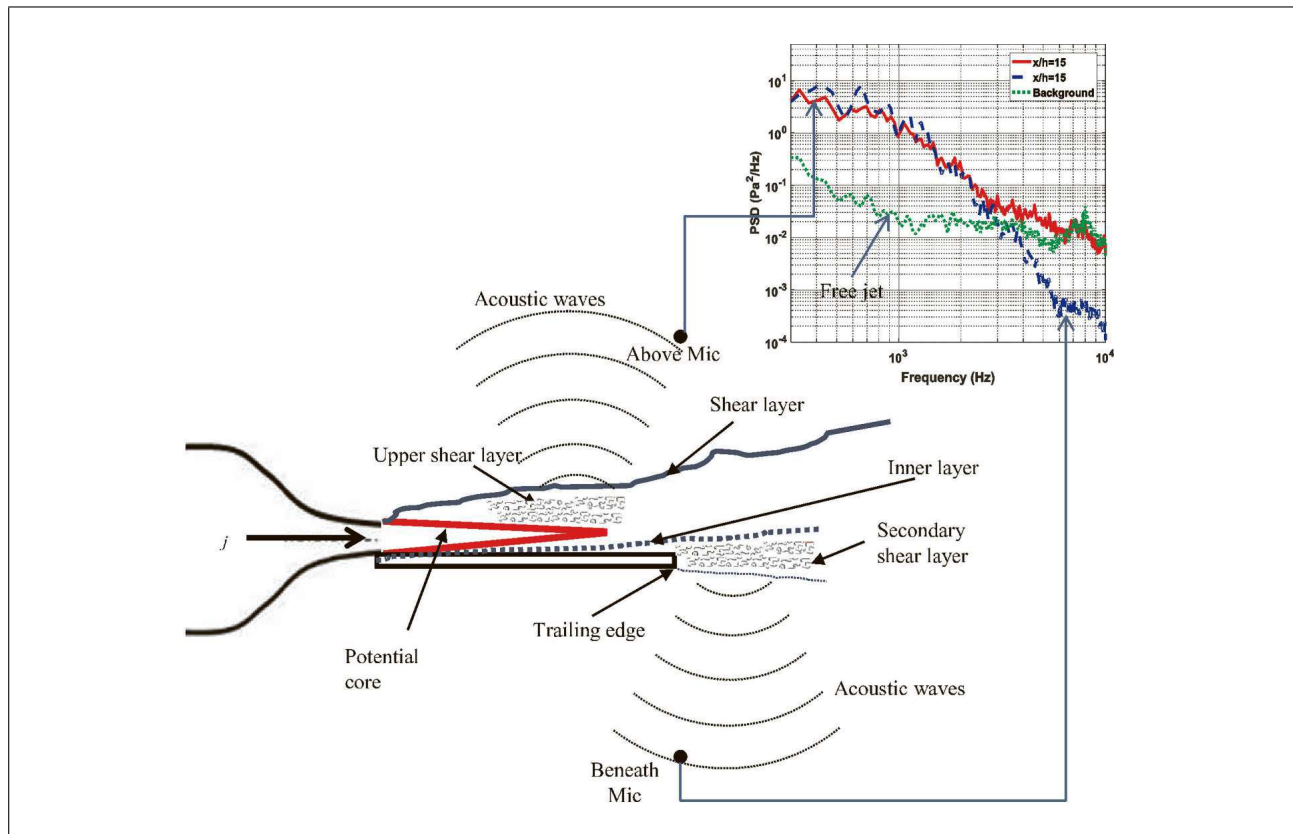


Figure 15. Cartoon representing the flow and acoustic regions, and corresponding spectra of a typical wall jet.

shear layer. The inset in Figure 15 proves the above point where the high frequency noise of free jet above 3 kHz almost matches with that of a wall jet. In addition, the noise above 3 kHz is also attributed to the surface roughness of the plate. Therefore, this analysis results in a conclusion that the low frequency noise (< 3 kHz) augmentation is due to the trailing edge and secondary shear layer, and the high frequency noise (> 3 kHz) contribution is from the upper free shear layer.

Albeit the noise dominates in the frequency range of 300–3000 Hz for all wall jets, the effects of trailing edge interaction on noise emission remain unclear. This section investigates the above perspective by carrying out a simple tripping wire experiment at the trailing edge. A very thin wire (~ 0.2 mm) is adhered along the span at the trailing edge of the $L/h = 5$ plate, and the noise of wall jet is captured at $Re = 7.0 \cdot 10^4$. The spectra variation with Strouhal number (based on the nozzle height) comparing the noise emissions without and with tripping is shown in Figure 16. Tripping the flow near the trailing edge increases the noise levels in the Strouhal number range of 0.1–0.18. This ensures that the noise up to the frequency range of ~ 600 Hz is due to the flow interactions at the trailing edge. Brown [34] and Brooks and Hodgson [36] noticed the trailing edge noise in the lower frequency range corresponding to the Strouhal number less than 0.2, while in the present study, the corresponding Strouhal number is found to be around 0.18 that is in congruence with the former. The dominance of the trailing edge noise can also

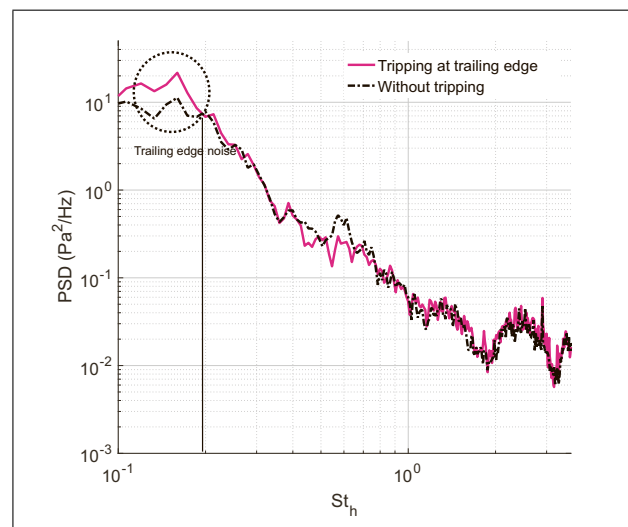


Figure 16. Spectral comparison of $L/h = 5$ wall jet with and without tripping at the trailing edge at $Re = 7.0 \cdot 10^4$.

be observed in the spectral comparison of all wall jets in Figure 17 at $Re = 7.0 \cdot 10^4$. The low frequency acoustic amplitude for $L/h = 5$ wall jet is found to be higher compared to all other wall jets. With an increase in the plate lengths, this noise amplitude is observed to decrease. The spectra in the range of ~ 750 – 1250 Hz reveal that the noise increases with an increase in L/h . This noise can be understood as the contribution from the secondary shear

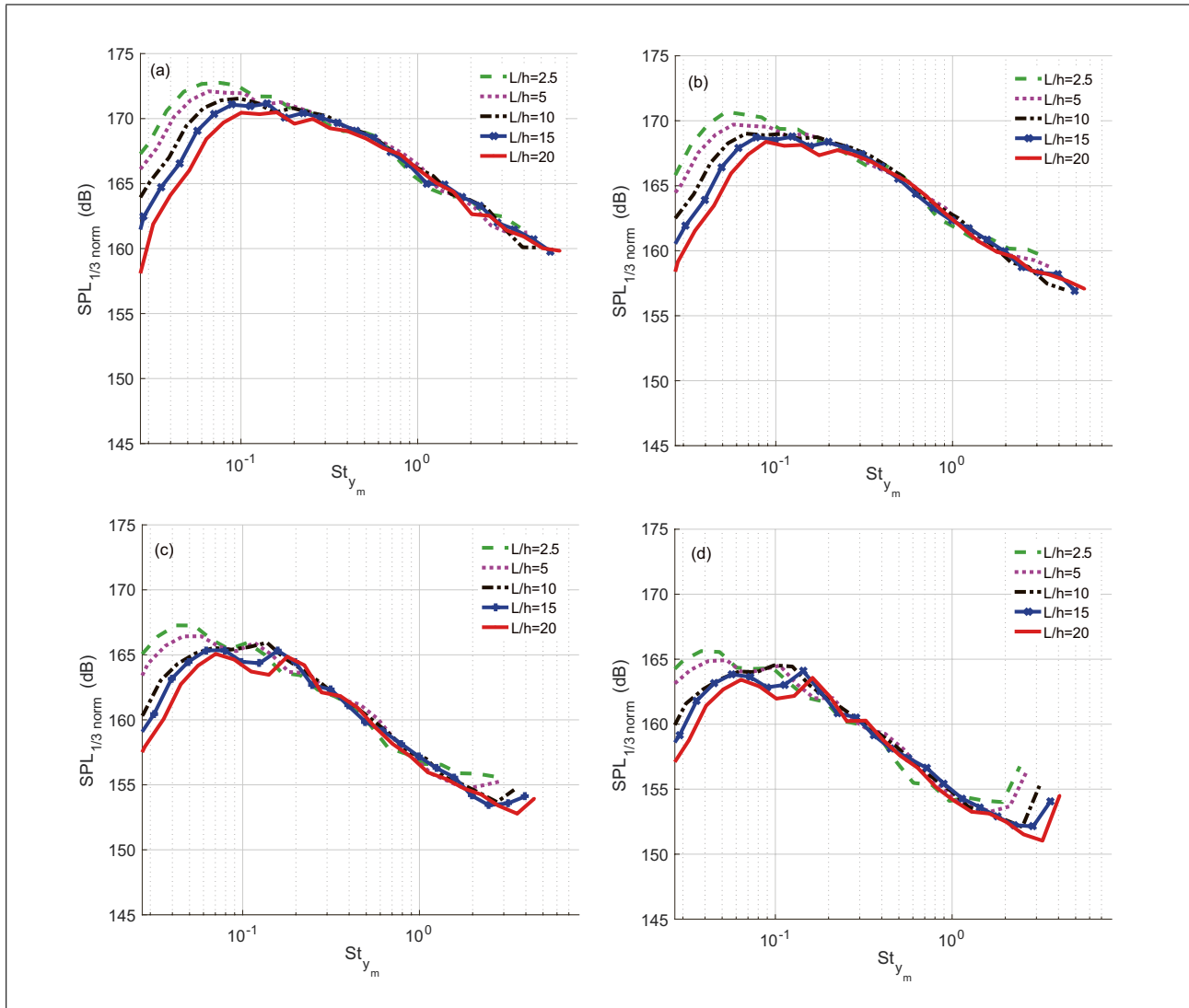


Figure 18. Normalized spectra in one-third octave bands for (a) $Re = 4.5 \cdot 10^4$, (b) $Re = 5.1 \cdot 10^4$ (c) $Re = 6.4 \cdot 10^4$ and (d) $Re = 7.0 \cdot 10^4$.

layer (Figure 15). Since the secondary shear layer growth depends upon the inner layer thickness at the exit of the plate, the former increases with the plate length, thus emitting higher noise. Further, the scaling analysis of the obtained acoustic spectrum is carried out to study the secondary shear layer noise. Therefore, the acoustic spectrum obtained for the different plate lengths is normalised using the Equation (1) which is used by Brooks and Marcolini [37], and Moreau and Doolan [38] for scaling of the noise. In this equation, the scaling is done with the inner layer thickness y_m by considering the one-third octave band of the spectrum.

$$\text{SPL}_{1/3\text{norm}} = \text{SPL}_{1/3} - 50 \log_{10}(M) - 10 \log_{10}(y_m b / r^2), \quad (1)$$

where $\text{SPL}_{1/3}$ is the acoustic spectrum in one-third-octave bands, M is the Mach number based on jet velocity U_j , b is the span length of the plate, and r is the distance of the microphone from the trailing edge. The normalized spectra are plotted against the Strouhal number, Equation (2),

defined based on the inner layer thickness.

$$\text{St}_{y_m} = \frac{f \cdot y_m}{U_j}. \quad (2)$$

The inner layer thickness values of different plate lengths are obtained from the curve fit shown in Figure 6b. The normalised spectra are shown in Figure 18 for different Reynolds numbers which collapses in the Strouhal number range 0.2...1.0 that corresponds to the frequency range of a secondary shear layer noise.

From the findings in the preceding section, the noise in the frequency range of 300–750 Hz is categorised as the trailing edge interaction noise; 750–3000 Hz due to the secondary shear layer; and 3 to 10 kHz due to upper free shear layer. The present discussion illustrates their sound pressure levels (SPL) at different plate lengths. These noise components are shown in the spectrum in Figure 19 at $Re = 7.0 \cdot 10^4$ of $L/h = 5$. Figure 20a shows the sound pressure levels in the frequency range of 300–750 Hz with L/h for different Reynolds numbers. The maximum SPL is observed to be for $L/h = 5$ (~80 dB) compared to

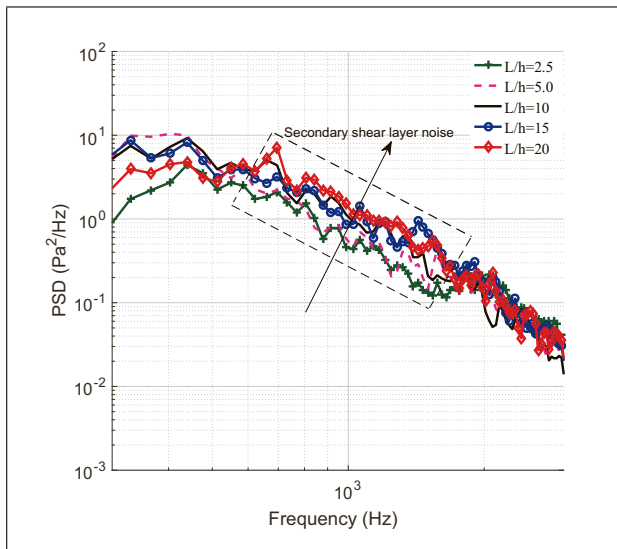


Figure 17. Spectra showing the secondary shear noise at $Re = 7.0 \cdot 10^4$ with L/h .

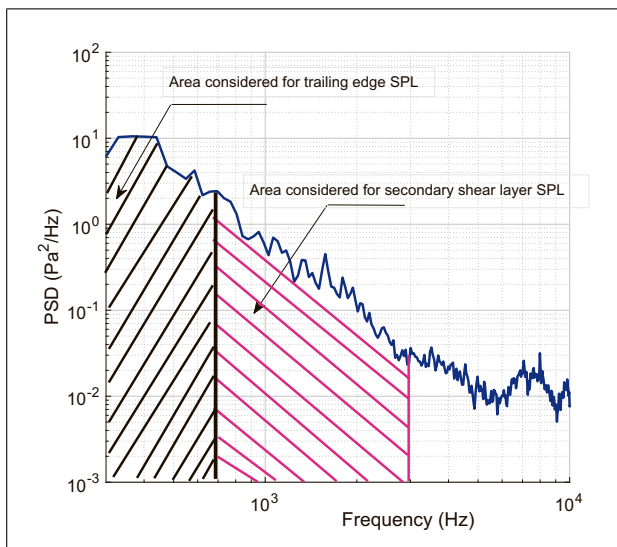


Figure 19. Area considered under power spectrum of $L/h = 5$ wall jet at trailing edge of the plate at $Re = 7.0 \cdot 10^4$ for calculation of various noise levels.

other wall jets at higher Reynolds numbers. With further increase in L/h , the trailing edge scattering noise is observed to decrease up to 73 dB for $L/h = 30$. Figure 20b shows the sound pressure levels in the frequency range of 750–3000 Hz with L/h for different Reynolds number that is designated to the secondary shear layer. The figure clearly illustrates that the maximum noise level increases gradually from 74 to 77 dB up to $L/h = 20$ and decreases to around 71 dB at $L/h = 30$.

5. Conclusions

The present paper elaborates on the importance of the plate length on noise emissions from wall jets. The lengths of the plates considered for the study are in the range of

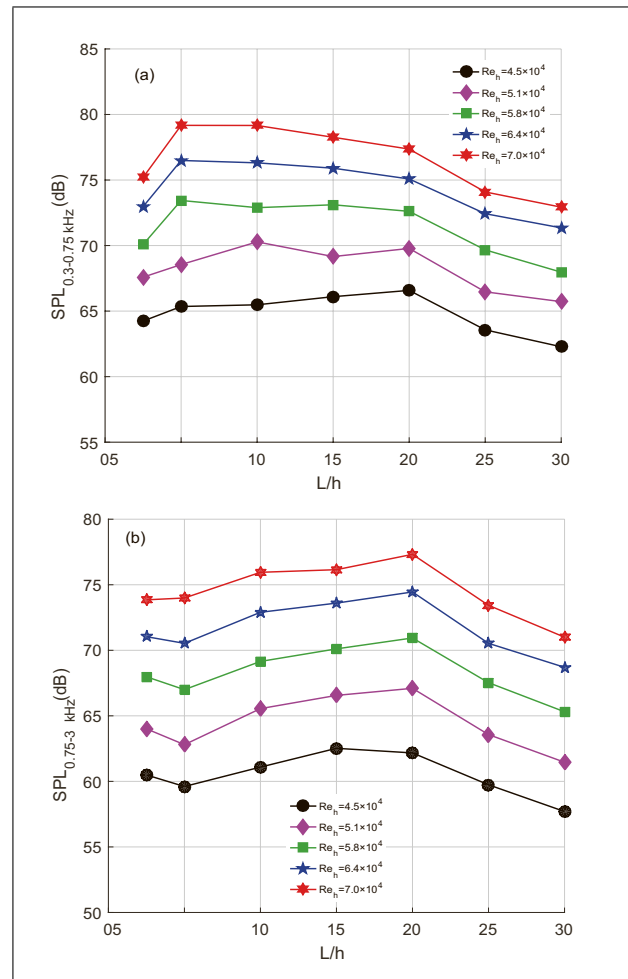


Figure 20. (a) Trailing edge noise and (b) secondary shear layer SPL variations with L/h for different Reynolds number.

$2.5 \leq L/h \leq 30$. The trailing edge of these different plates terminates in the different flow regimes of the wall jet, namely the potential core, transition, and fully developed regions, and their respective acoustic disturbance are captured and analysed. Mid-field acoustic measurements led to the following important conclusions. The wall jet with the smallest plate length of $L/h = 2.5$ increases the noise levels by around 7–12 dB compared to the free jet noise, which is due to the flow-surface interaction. The OASPL is observed to increase along a fully developed wall jet due to the higher shear stress in the transition region of the wall jet [5].

The noise emissions are further categorized into low and high frequency noise. The significant noise contribution is from the lower frequency range (< 3 kHz) that is mainly due to the (i) trailing edge interactions, and (ii) secondary shear layer. Results from various experiments revealed that the noise emissions up to 750 Hz are attributed to the trailing edge. This noise level is found to be higher for lower plate length wall jets and found to decrease with an increase in the plate length. The corresponding Strouhal number (based on nozzle height) is found to be around 0.18. Scaling studies showed that the noise emissions in

the Strouhal number (based on the inner layer thickness) range of 0.2 to 1.0 are attributed to the secondary shear layer. As the plate length increases up to $L/h = 20$, the turbulent shear stress in the inner layer increases, and thus, the noise from the secondary shear layer is seen to increase. The high frequency noise emissions above 3 kHz are identified as the contributions from the upper shear layer noise of the wall jet.

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