CHAPTER 6

The flow and thermal characteristics of turbulent jet on adiabatic wavy wall

6.1 Introduction

The impact of wavy wall amplitude on the fluid flow and thermophysical properties of a turbulent wall jet has been experimentally investigated, where the wavy wall is provided an adiabatic condition. For the current study, a heated jet with a Reynolds number of 15000 is deployed to flow over a sinusoidal wavy wall ($y = A * sin(\omega x)$). The amplitude of the wavy wall is varied between 0.2 and 0.6, and the frequency is kept ω_{10} for all the cases. The results are compared to those of the plane wall jet. The current problem is also numerically solved using the $k-\varepsilon$ RNG turbulent model and different thermal characteristics has been discussed for the adiabatic wall condition. The present study is also performed to provide the experimental results for the comparison purpose for those who are using numerical modeling. Thus, this work will also serve as the benchmark for validating numerical techniques working in the area of turbulent wall jet with a wavy wall.

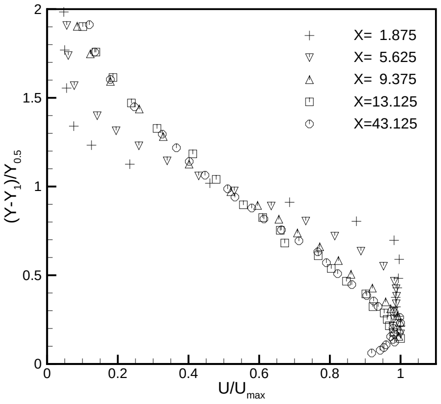


Figure 6.1: Self similar behaviour of velocity profile for the plane wall

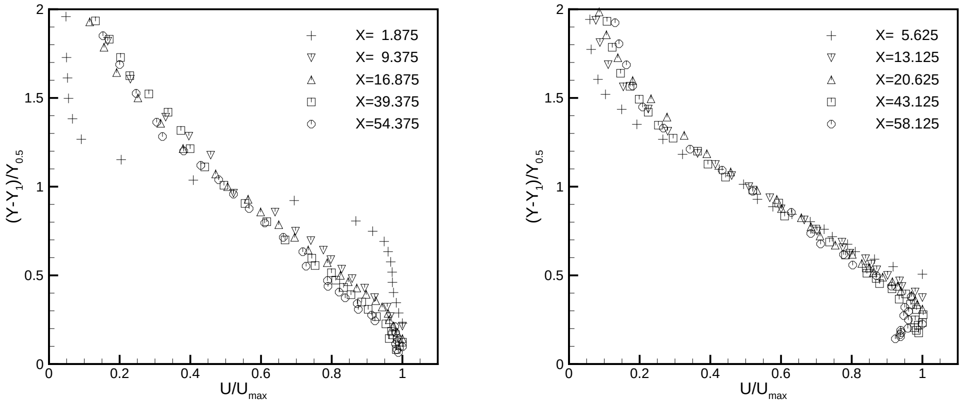
6.2 Result and discussion

6.2.1 Fluid flow behaviour

The influence of amplitude on the fluid flow behaviour like mean velocity profiles, turbulent intensity profiles, decay of jet, growth of jet spread and variation of power spectral density has been discussed in this section with the help of experimental data.

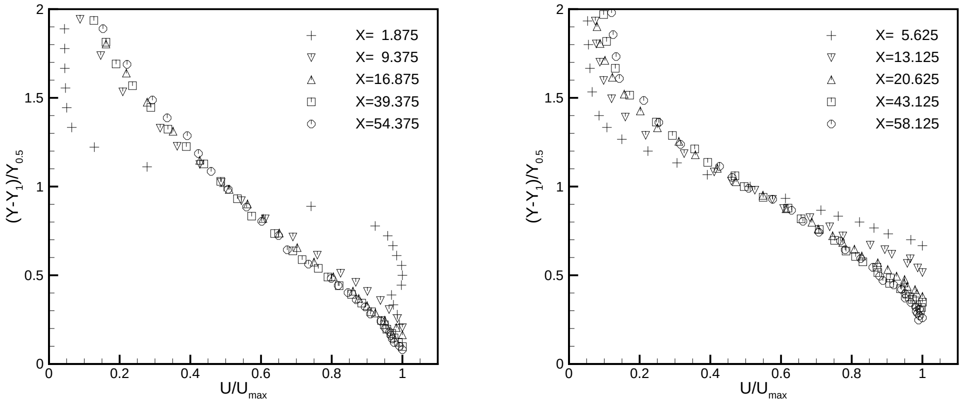
6.2.1.1 Self similar velocity profile

The velocity profile is non-dimensionalised using outer scaling method as elaborated by Wygnanski et al. [103], where streamwise velocity U is divided by streamwise maximum velocity U_{max} and cross stream location $Y - Y_1$ is divided by jet half width $Y_{0.5}$; Y_1 being the normal distance of the wavy surface from the x-axis at any specified location X and $Y_{0.5}$ is the distance normal from the wall, where the streamwise mean velocity becomes half of the maximum streamwise velocity U_{max}. The outer scaled velocity profile follows a self similar profile once the jet gets developed. The velocity profile for the plane wall jet is shown in fig. 6.1. In the case of plane wall jet, the self similar trend is evident from location $X = 9.375$ (2nd crest location), which means the flow gets developed beyond this location. The velocity profile for plane wall and wavy wall with different amplitudes at crest and trough are shown in fig. 6.2. The self similar behavior is observed in all the cases, but it gets delayed as the amplitude increases for both the crest and trough locations. For 0.2 amplitude, the self similar profile is visible from $X = 9.375$ (2nd crest) and $X = 13.125$ (2nd trough) for the velocity profiles at the crest and trough, respectively. Whereas for amplitude 0.4 and 0.6 the self similar behavior is followed from the $X = 16.875$ (3rd crest)



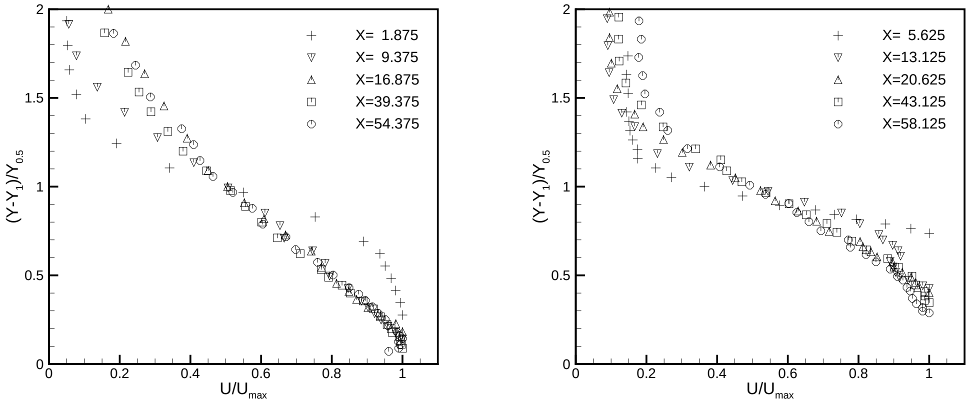
(a) 0.2 amplitude crest

(b) 0.2 amplitude trough



(c) 0.4 amplitude crest

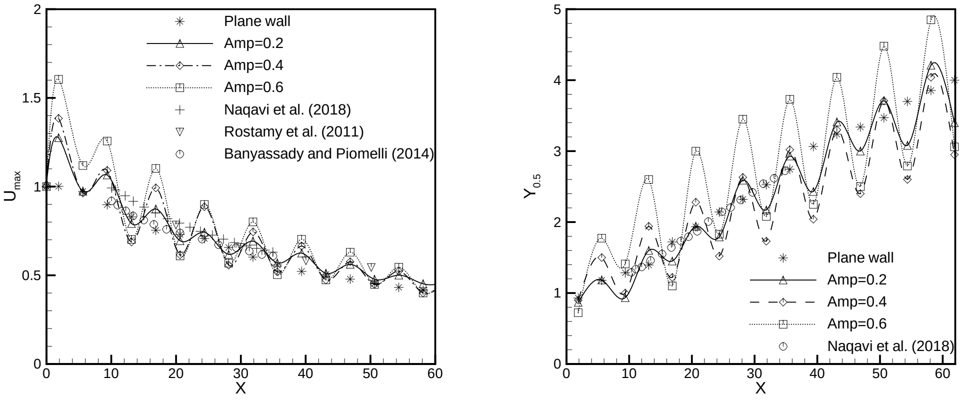
(d) 0.4 amplitude trough



(e) 0.6 amp crest

(f) 0.6 amplitude trough

Figure 6.2: Self similar behaviour of velocity profile for the wavy wall



(a) (b)

Figure 6.3: (a) The decay of maximum streamwise mean velocity and (b) the growth of the jet half width along the flow, for plane wall and wavy wall with different amplitudes.

and $X = 20.625$ (3rd trough) onwards. The delay in the self similar profile indicates the delay in the formation of developed zone. This happens due to increase in the turbulence in the case of 0.4 and 0.6 amplitudes, leading to higher intermixing of the jet fluid which stretches the transient zone. It is observed that in the case of wavy wall the peak of velocity profile shifted near the wall for the crest whereas, for the trough, it has been shifted away from the wall in comparison to the plane wall. In the case of plane wall jet, the peak of self similar profile is at $(Y - Y_1)/Y_{0.5} = 0.18$ which falls to 0.13, 0.1 and 0.1 at the crest and rises to 0.25, 0.31 and 0.36 at the trough for the amplitudes 0.2, 0.4 and 0.6 respectively. The shifting of peak near the wall with the increasing amplitude is the flow area gets restricted at the crest, which pushes the maximum velocity towards the wall. On the other hand, the fluid get larger area to flow near through which keep on increasing with increase in amplitude leads to shift peak away from the wall.

6.2.1.2 Flow Development

To track the flow development of jet, the streamwise maximum mean velocity U_{max} and $Y_{0.5}$ are plotted for each crest and trough location of the wavy wall. In fig. 6.3a, the graph of U_{max} for wavy wall of amplitudes 0.2, 0.4 and 0.6 has been compared with the results of plane wall case. The present plane wall results are also compared with the experimental result of Rostamy et al. [83] and numerical (LES) result of Banyassady and Piomelli [13]. The present plane wall result matches quite well with the results of Banyassady and Pilomelli [13], whereas the Rostamy et al. [83] and Naqavi et al. [68] results are a little higher than the present result. In the developed region, the decay of U_{max} follows the power law $U_{max}/U_0 = aX^{-n}$ where n is the decay rate of U_{max}. For the present plane wall case, $a = 4.9$ and $n = 0.6$ which is close to the observation made by Barenblatt et al. [14] with $a = 5.15$ and $n = 0.6$. The decay rate of Naqavi et al. [68] is 0.49. In the case of a plane wall, the potential core is maintained till $X = 5.625$. In contrast, in the wavy wall, the flow gets accelerated due to a favorable pressure gradient from the leading edge to the first crest, leading to the distortion of potential core in the beginning of flow. For the wavy wall case, flow starts with the transition zone where the mixing of fluid is high. At the first crest, the maximum value of U_{max} is obtained. The slope of the wall increases with the amplitude, so the favorable pressure gradient also increases, flow area gets more restricted resulting in an increase in the maximum value of U_{max}. For the amplitudes 0.2, 0.4 and 0.6, the maximum value of U_{max} rises by 26%, 37% and 60% respectively with respect to the plane wall case. This indicates there is increase in turbulence When fluid move forward the adverse pressure gradient is formed as the flow area is enlarged in the trough region, leading to reduce in U_{max}. This ups and down in the U_{max} value is persistent throughout the domain, but the intensity reduces due to the spreading of jet in downstream direction. In the developed region of wavy wall, the decay of U_{max} follows the power law for crest and trough separately. For the crest, the decay rate of U_{max} remains almost the same and equals to the decay rate of plane wall, but the value of "a" increases to 5.4, 6.04 and 6.5 for 0.2, 0.4 and 0.6 amplitude, respectively. The decay rate at the trough is around 0.4 for all the cases of wavy walls.

Fig. 6.3b shows the influence of wavy wall amplitude on jet spreading. The comparison with the plane wall jet is also shown. The result of Naqavi et al. [68] has also been plotted. It is to be noted that the present result is in good agreement with the result of Naqavi et al. [68]. The $Y_{0.5}$ is lesser at the crest and larger at the trough owing to the flow area which gets restricted in the crest region and becomes larger near the trough. From fig. 6.3b, it can be observed that the spreading in crest region is relatively less than the plane wall jet and in trough region, the spreading is higher in comparison to the plane wall jet. In the near field region $X \leq 15$, the spreading increases as the amplitude increases. The growth of $Y_{0.5}$ becomes linear ($Y_{0.5} = aX + b$) in the developed zone for the crest and trough separately; the slope "a" and y intercept "b"for the $Y_{0.5}$ at trough are relatively higher than that on the crest for all the amplitudes. In the case of 0.6 amplitude, the slope "a" is 0.38 and 0.5 and intercept "b" is 1.01 and 1.93, at crest and trough, respectively.

6.2.1.3 Turbulent intensity

The turbulent intensity variation along the cross stream direction is illustrated in fig. 6.4.

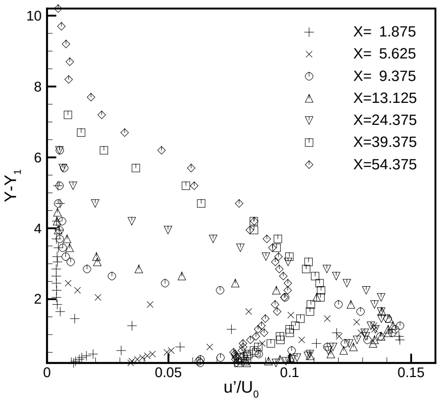
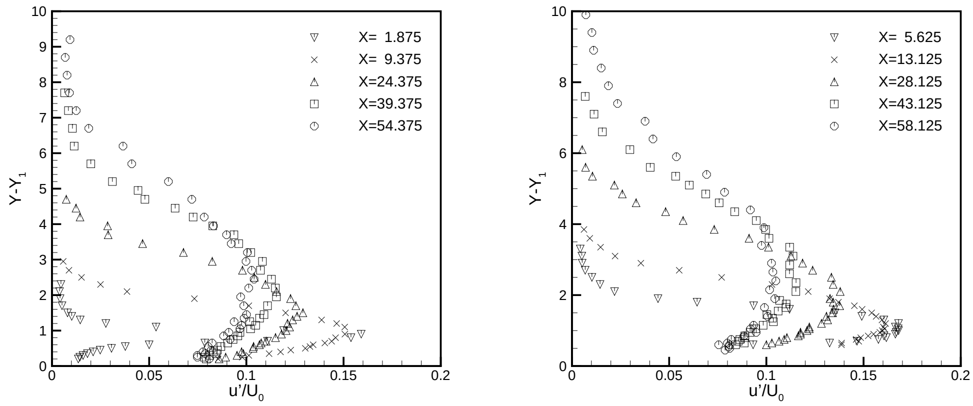


Figure 6.4: Variation of turbulent intensity in cross stream direction for plane wall jet

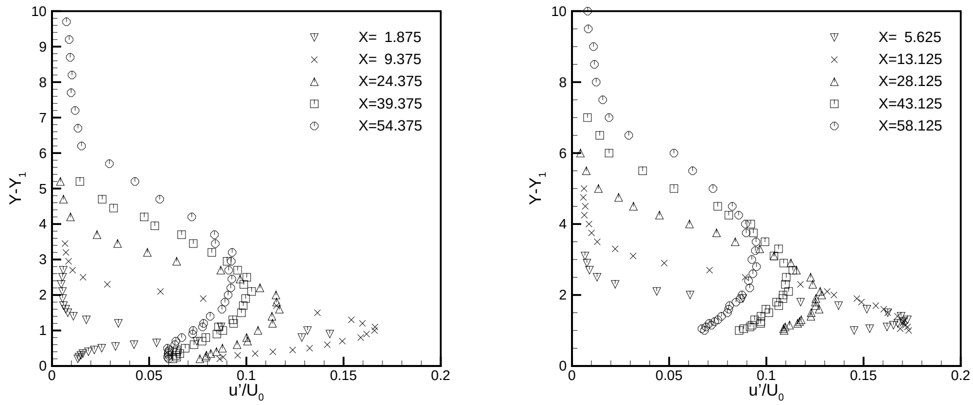
For the plane wall jet, the turbulent intensity spikes up to 14.5% of the inlet velocity in the near flow field at $X = 13.125$, i.e. second trough location. Beyond this, the turbulent intensity reduces.

The turbulent intensity profile is plotted for the amplitudes 0.2, 0.4 and 0.6 at different crest and trough locations separately in fig. 6.5. The maximum turbulent intensity is noticed at $X = 5.625$ (1st trough), $X = 13.125$ (2nd trough) and $X = 13.125$ (2nd trough) for the amplitude 0.2, 0.4 and 0.6, respectively. The maximum rise in turbulent intensity for amplitude 0.2, 0.4 and 0.6 is 16.8%, 17.4% and 18.8%, respectively. This also shows that turbulence is enhanced by using a wavy wall. Once the maximum turbulent intensity is achieved, it starts reducing as fluid moves forward in all the cases for crest as well as trough. For the same cycle, the turbulent intensity at the trough is a little higher than the turbulent intensity at the crest. This is because of the expansion of fluid near the trough region, which increases the randomness in near wall region. The influence of amplitude on the turbulent intensity at the 2nd crest and 2nd trough and at 8th crest and 8th trough, is shown in figs. 6.6a-6.6d. In figs. 6.6a and 6.6b, the turbulent intensity at 2nd crest and 2nd trough increases as the amplitude increases. However, at the 8th crest and 5th trough locations, the turbulent intensity is almost same for all the cases. It can be concluded that as the amplitude increases the turbulent intensity also increases in near flow field, but as the fluid moves forward, the influence of amplitude becomes insignificant. The increase in the turbulent intensity in the near field signifies a higher intermixing of jet fluid with the surrounding stagnant fluid resulting in a higher heat transfer rate.



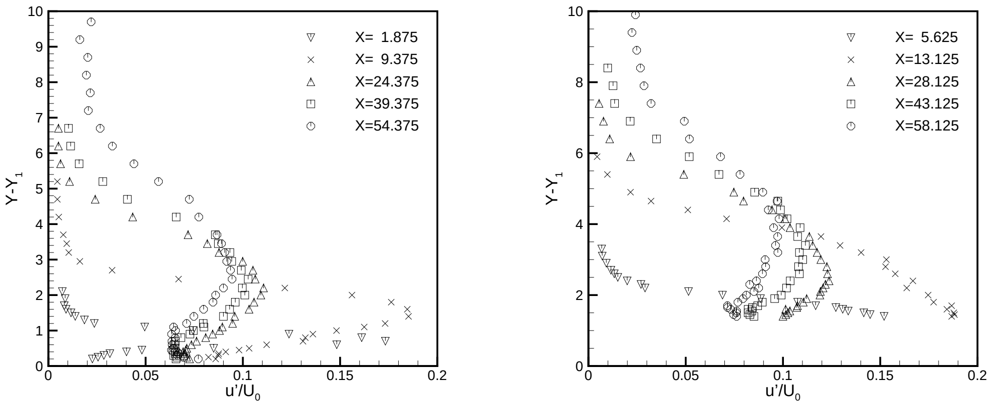
(a) 0.2 amplitude crest

(b) 0.2 amplitude trough



(c) 0.4 amplitude crest

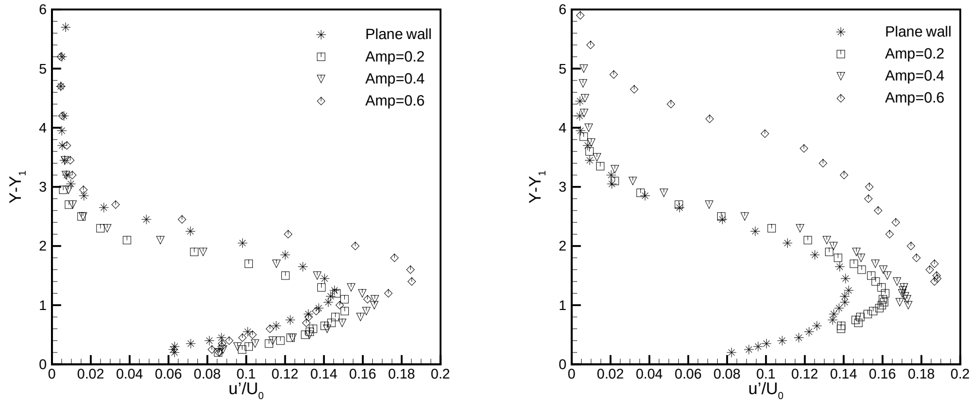
(d) 0.4 amplitude trough



(e) 0.6 amplitude crest

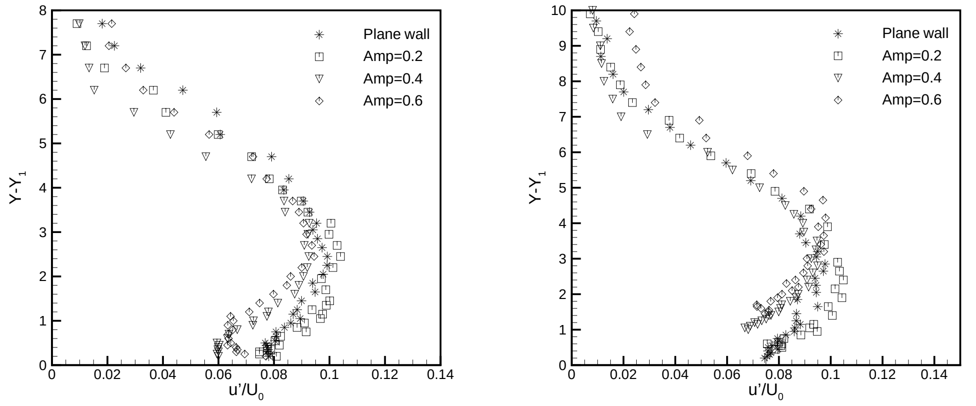
(f) 0.6 amplitude trough

Figure 6.5: Variation of turbulent intensity for different amplitudes at crest and trough



(a) X=9.375 (2^{nd}crest)

(b) X=13.125 (2^{nd} trough)



(c) X=54.375 (8^{th} crest)

(d) X=58.125 (8^{th} Trough)

Figure 6.6: Comparison of turbulent intensity for wavy walls and plane wall at different streamwise locations

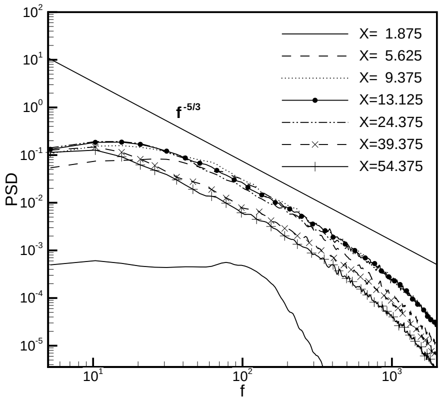
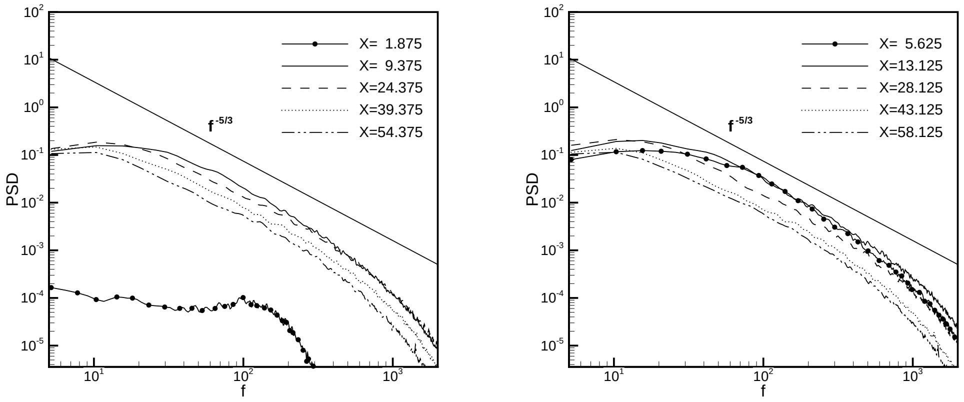


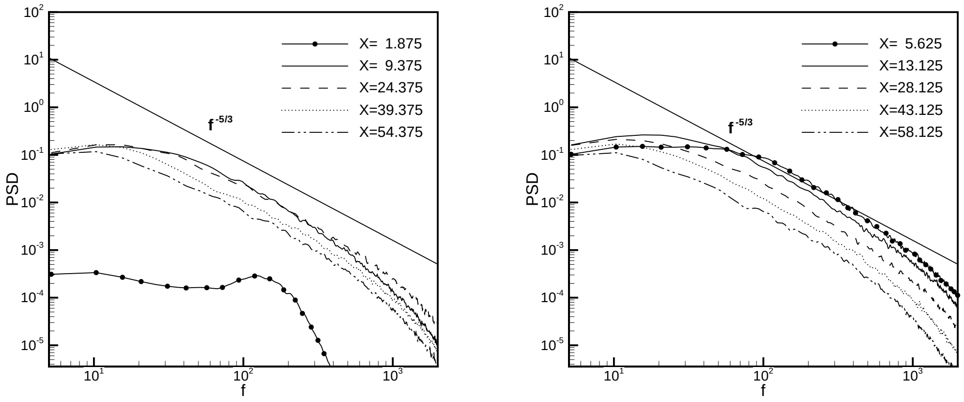
Figure 6.7: The power spectral density for plane wall jet at $Y - Y_1 = 1.5$

6.2.1.4 Power spectral density

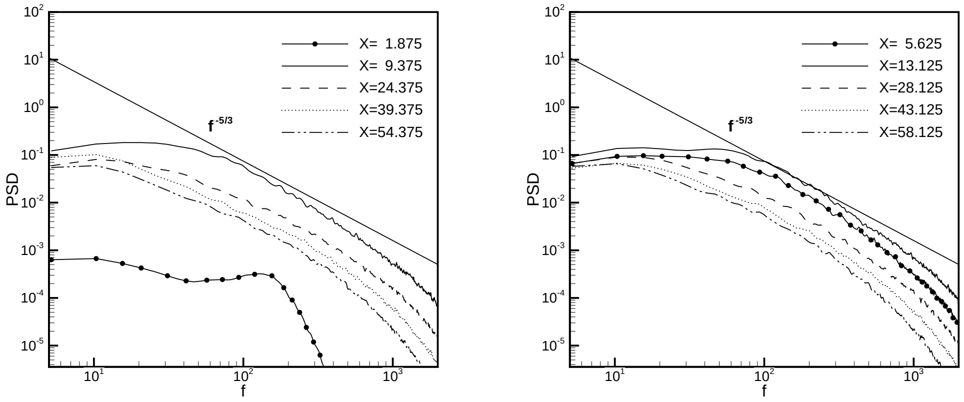
Power spectral density (PSD) shows the energy related with the turbulent fluctuation and it is a continuous function of frequency. The variation of power spectral density of fluctuating velocity at various streamwise locations is plotted with respect to the frequency (Hz) on a log-log scale. Fig. 6.7 shows the variation of power spectral density for different locations in X direction at $Y - Y_1 = 1.5$ for the plane wall jet. It can be seen from fig. 6.7 that PSD increases till $X = 9.375$ and after that the PSD remains almost same up to $X = 39.375$ followed by a reduction in its value. The PSD follows the Kolmogorov power law (–5/3 scaling-law) during the frequency range $60 \leq f \leq 500$ after the flow is developed (from location $X = 9.375$ onwards). Bisoi et al. [16] have also mentioned that the PSD follows Kolmogorov power law in the developed region of turbulent jet. For the larger frequency, the PSD is more fluctuating, implying that the larger frequency signals carry large-scale eddies. The PSD for the wavy wall with amplitudes 0.2, 0.4 and 0.6 is illustrated for different crest and trough in fig. 6.8 at the location $Y - Y_1 = 1.5$. From figs. 6.8a, 6.8c and 6.8e, it can be observed that at $Y - Y_1 = 1.5$, PSD is maximum at 2nd crest and as fluid moves downwards, the PSD reduces for all the amplitudes. The PSD is directly connected to the turbulent intensity, i.e. in the higher intensity region, vortices have a higher impact, which leads to a higher value of PSD. Figs. 6.8b, 6.8d and 6.8f show the PSD for the trough location. In the trough location of amplitudes 0.2 amd 0.6, the maximum PSD is observed for the 2nd trough ($X = 13.125$) and it reduces as fluid moves forward. The same trend is followed by 0.6 amplitude, but for the smaller frequency only $f \leq 60$; beyond this frequency, the PSD for 1st trough becomes maximum. In the trough region, the PSD is slightly higher than the valua at the crest for the same cycle, as in the trough region the randomness is high due to sudden increase in the area of flow. The influence of amplitude on the PSD



(a) 0.2 amplitude crest (b) 0.2 amplitude trough

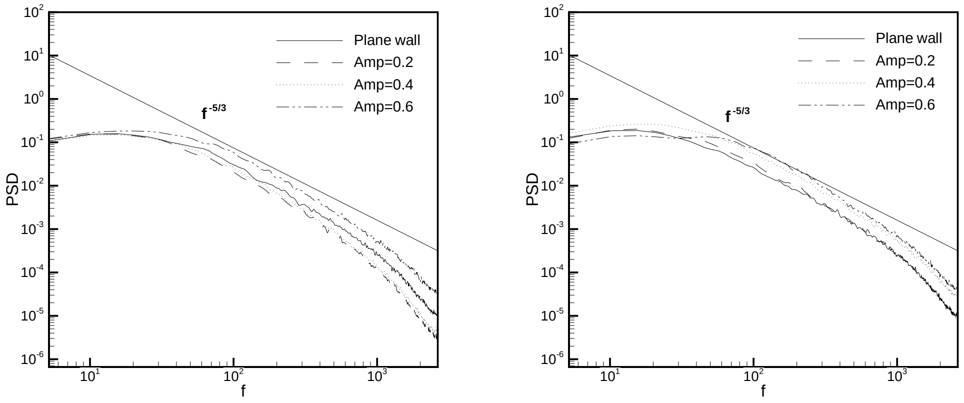


(c) 0.4 amplitude crest (d) 0.4 amplitude trough

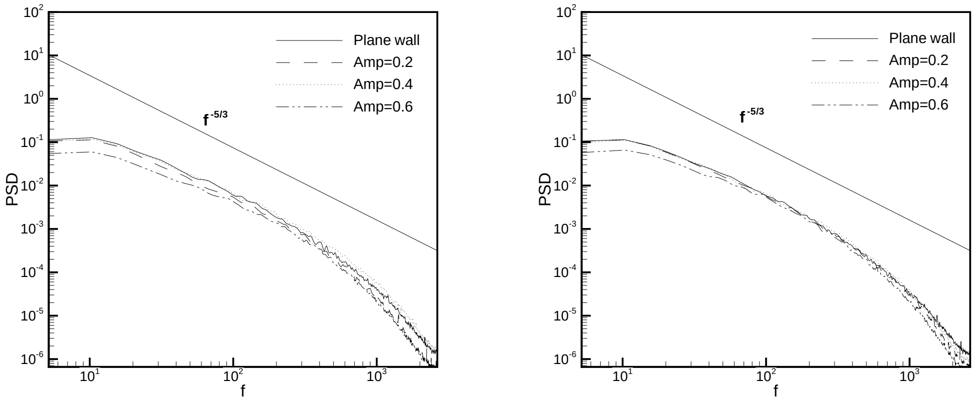


(e) 0.6 amplitude crest (f) 0.6 amplitude trough

Figure 6.8: The power spectral density for crest and trough locations of different amplitudes at $Y - Y_1 = 1.5$



(a) X=9.375 (2^{nd}crest) (b) X=13.125 (2^{nd} trough)



(c) X=54.375 (8^{th} crest) (d) X=58.125 (8^{th} Trough)

Figure 6.9: Comparison of power spectral density for wavy walls and plane wall at a cross stream position $Y - Y_1 = 1.5$, for different streamwise locations

in the near field (2nd crest and trough) as well as in the far field (8th crest and trough) is showcased in fig. 6.9 at a cross stream location of $Y = 1.5$. It can be observed that in the near flow field, as the amplitude is increasing the PSD is also increasing for both the crest and trough regions. Whereas, in far field, the influence of amplitude fades away and the PSD remains almost same for all the amplitudes.

6.2.2 Thermal behaviour

The influence of amplitude on the thermal behaviour like mean temperature profiles, fluctuating temperature profiles, decay of wall temperature and growth of thermal jet half width has been discussed in this section with the help of experimental data.

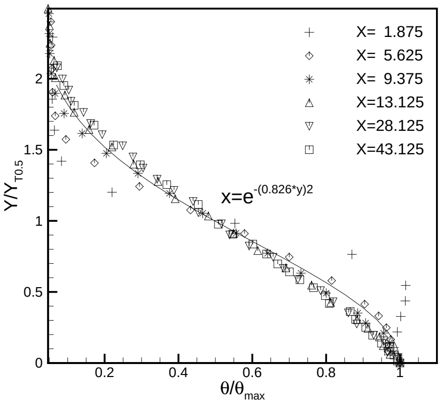
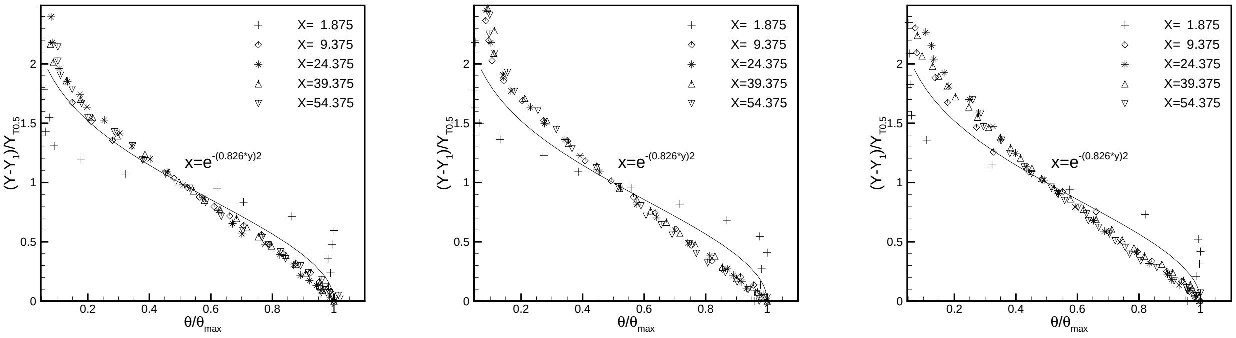


Figure 6.10: Temperature profile for plane wall jet

6.2.2.1 Self similar temperature profile

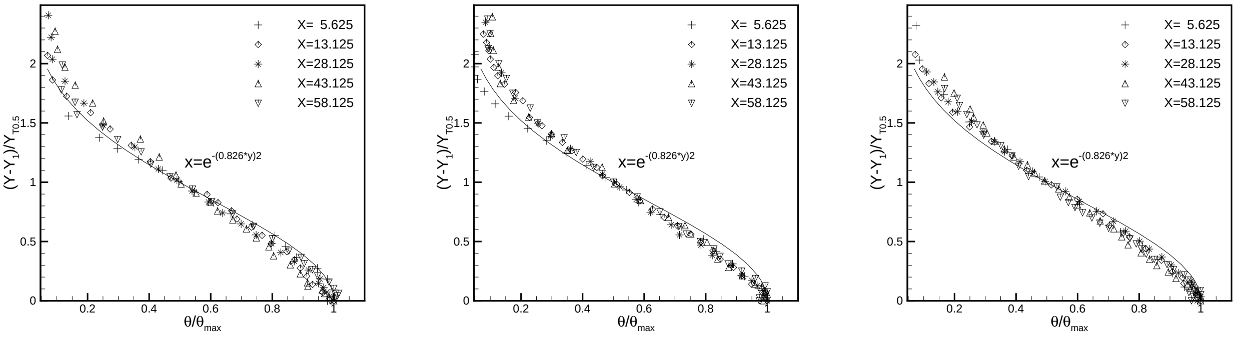
To show the self similar behaviour of temperature profile, it is normalized by using outer scaling method as explained by Wygnanski et al. [103]. In fig. 6.10, the temperature profile for the plane wall jet has been shown. It can be seen that the temperature profile starts following the self similar behavior from $X = 9.375$ onwards. In the case of plane wall jet, the temperature profile follows the Gaussian curve, $\theta/\theta_{max} = e^{-(c*(Y-Y_1)/Y_{T0.5})^2}$, with the coefficient $c = 0.826$. Hoch and Jiji [40] have similar observation in the case of temperature profile for plane wall jet with $c = 0.833$, which is near to the present value. In fig. 6.11, the temperature profile for the wavy wall with amplitude 0.2, 0.4 and 0.6 has been plotted for crest and trough separately. In the case of wavy wall, the temperature profile attains the self similar trend from X = 9.375 (2nd crest) and X = 13.125 (2nd trough) at the crest and trough, respectively. Moreover, it remains the same for all the amplitudes. Due to the adiabatic condition, no heat is transferred through the bottom wall and the temperature is maximum near the wall and it reduces continuously to reach the ambient temperature at the end of free shear layer. In the case of wavy wall, for all the amplitudes, the temperature profile shows self similar behaviour from $X = 9.375$ and $X = 13.125$ onwards for crest and trough locations respectively. The self similar temperature profile deviates from the Gaussian curve as the amplitude increases from 0.2 to 0.6 in the crest location. However, for trough, the temperature profile follows the Gaussian curve in the developed region. Near the crest location, as the amplitude increases the jet gets less area to spread leading to a sharp decay in temperature near the wall as we move upward. So, for higher amplitude, the temperature profile does not follow Gaussian curve.



(a) 0.2 amplitude crest

(b) 0.4 amplitude crest

(c) 0.6 amplitude crest

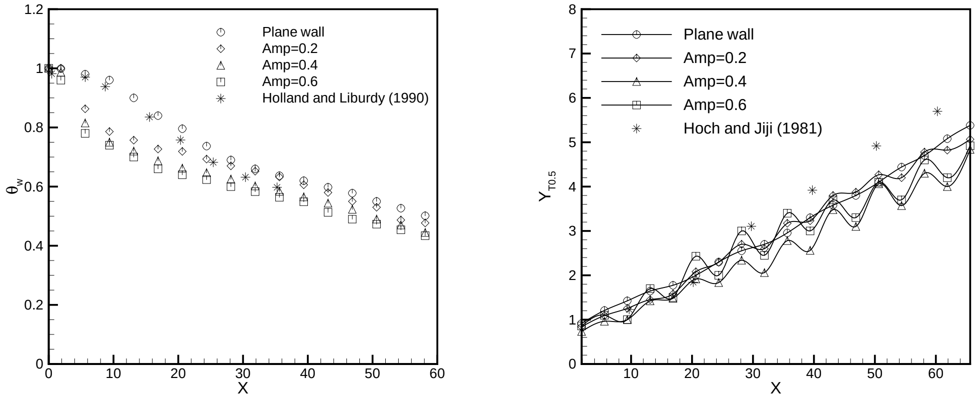


(d) 0.2 amplitude trough

(e) 0.4 amplitude trough

(f) 0.6 amplitude trough

Figure 6.11: Temperature profile for wavy walls



(a) (b)

Figure 6.12: (a) The variation in bottom wall temperature and (b) the growth of the thermal jet half width along the flow, for plane wall and wavy wall with different amplitudes

6.2.2.2 Wall temperature and the thermal jet half width

In fig. 6.12a , the variation of normalized wall temperature $\theta_W = (T_w - T_\infty)/(T_0 - T_\infty)$ in the streamwise direction (X) is plotted for plane wall and wavy wall with different amplitudes.The results of plane wall case have been compared with the Holland and Liburdy's [41] results, and the present result matches very well with the literature result. The decay of wall temperature can be divided into three parts; The first one is where the temperature of wall remains almost constant. In the second region, the wall temperature decays with a very fast rate due to the intermixing of fluid, and further in third region, the wall temperature decays with a slower and constant rate. In the case of plane wall jet, the wall is maintained at the jet exit temperature till $X = 5.625$ whereas in the case of wavy wall it reduces to $X = 1.875$. In the intermixing zone, the wall temperature decays with a higher rate in plane wall ($5.625 \leq X \leq 28.125$) as well as wavy wall ($1.875 \leq X \leq 24.375$), however the decay in the case of wavy wall is relatively high in the case of wavy wall. This indicates higher intermixing of fluid within the jet and the cold ambient fluid. Further in the downstream direction, stream wall temperature decay follows the power law $\theta_W = AX^{-n}$, where A and n (decay rate) are the constants. For the plane wall case, $A = 3.25$ and $n = 0.456$. Similar observation has been done by Kumar and Kumar [54], where $A = 9.4$ and $n = 1.04$, the variation in the constant A and the decay rate n is due to the nature of jet. As they have used 3D jet, the decay of wall temperature is higher as jet spreads in z direction also. For the wavy wall, the decay rate n increases to 0.466, 0.483, and 0.494 for the amplitudes 0.2,

Table 6.1: Value of constants of linear equation followed by the trend of $Y_{T0.5}$ at crest and trough in Thermally developed zone

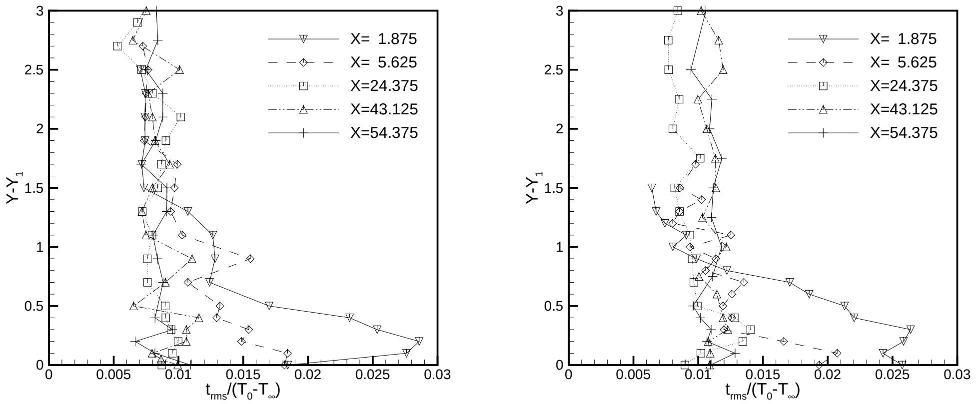
amp	crest		trough	
	b	c	b	c
0.2	0.07	0.45	0.068	0.78
0.4	0.057	0.39	0.066	0.52
0.6	0.059	0.56	0.054	1.4

0.4 and 0.6, respectively. For the higher amplitude, along with the intermixing of cold ambient fluid, the increase in total arc length of the wavy wall also contributes in increasing the decay rate of wall temperature.

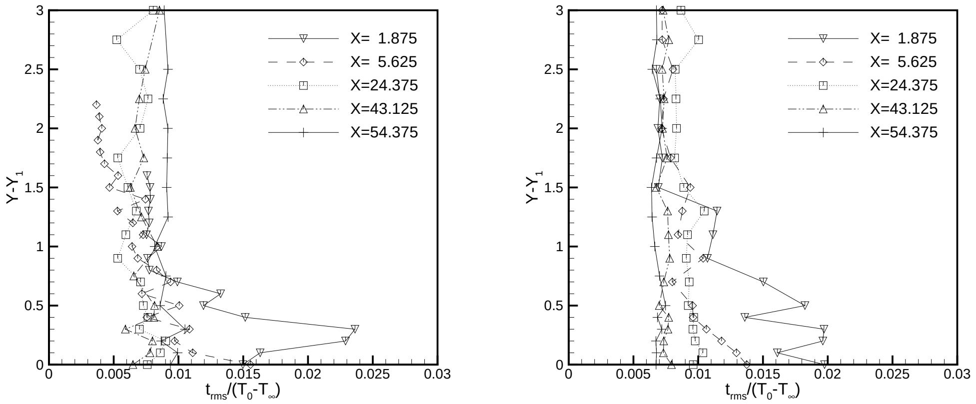
The diffusion of thermal energy of jet in the enclosed domain is dictated by the growth of thermal half width $Y_{T0.5}$. Fig. 6.12b shows the variation of thermal half width of turbulent jet of plane wall and wavy wall with different amplitudes. The result in the plane wall case has been compared with the result of Hoch and Jiji [40]. The difference in the present and literature results might be due to the difference in the Reynolds number at the exit of nozzle. For the plane wall jet, in the thermally developed zone, the growth of thermal half width becomes linear as $Y_{T0.5} = bX + c$, where $b = 0.0735$ is the slope and $c = 0.445$ is the intercept on $Y_{T0.5}$. For the wavy wall, the trend of thermal half width also becomes wavy as the $Y_{T0.5}$ is relatively higher at the trough than crest for any given cycle. Because in the crest region, the jet gets accelerated and to satisfy the continuity, the area of spread is lesser in comparison to the area of spread in the trough region. In comparison to the plane wall jet, the growth of thermal half width is relatively less in case of wavy wall. The growth of $Y_{T0.5}$ reduces as the amplitude increases from 0.2 to 0.4 and in the case of 0.6 amplitude, the growth of $Y_{T0.5}$ is little higher than the 0.4 amplitude wavy wall. This might be due to the formation of re-circulation zone in 0.6 amplitude [58] which does not allow the jet air to come in contact with the wall, leading to an increase in $Y_{T0.5}$ in the case of 0.6 amplitude. In the wavy wall cases, the growth of thermal half width at crest and trough locations follows linear equation separately, in the thermally developed zone. The constants b and c for crest and trough of wavy wall with different amplitudes are listed in table 6.1.

6.2.2.3 Temperature fluctuation

In order to get a detailed information of thermal behaviour of the turbulent wall jet, discussion on fluctuating temperature is an important part. As it gives an idea of thermal diffusion and the entertainment of ambient fluid in jet. The fluctuating temperature of turbulent heated jet has been studied by very few researchers [7, 54, 63, 72]. The develop-



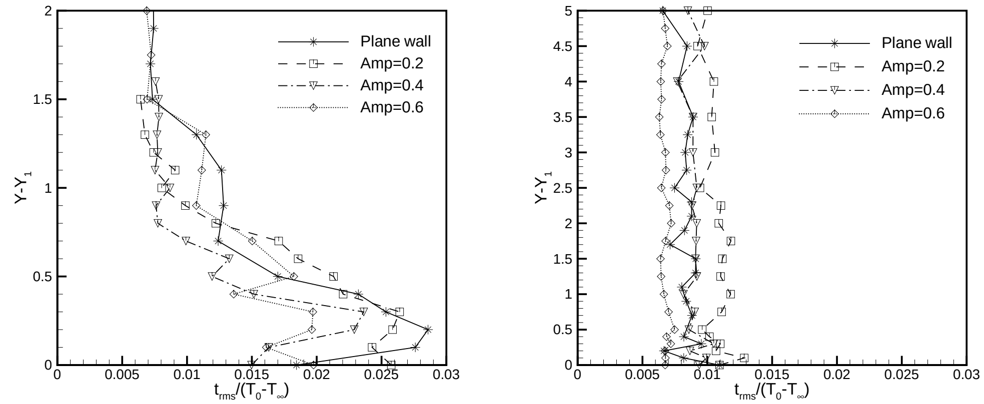
(a) Plane wall (b) 0.2 amplitude



(c) 0.4 amplitude (d) 0.6 amplitude

Figure 6.13: The variation of temperature fluctuation in wall normal direction

ment in the fluctuating temperature profile at different downstream locations X for plane wall and wavy wall and the influence of amplitude on the fluctuating temperature are discussed in this section. Fig. 6.13 shows the variation of fluctuating temperature t_{rms} in wall normal direction for plane wall and wavy walls, where $trms = (<(T-T_{mean})^2>)^{1/2}$ is normalized by $T_0 - T_\infty$, which is the temperature difference with respect to ambient at the inlet. In the case of fluctuating temperature, the influence of amplitude is felt up to $X = 24.375$; beyond this location, the profile becomes almost flat for all the amplitudes. It can be observed that for all the cases, t_{rms} is higher near the exit of nozzle due to the high intermixing of fluid and high thermal energy of fluid within the jet and it reduces as the jet moves forward and t_{rms} becomes almost flat in the thermally developed region. This happens because in the thermally developed region, the thermal energy gets distributed



(a) (b)

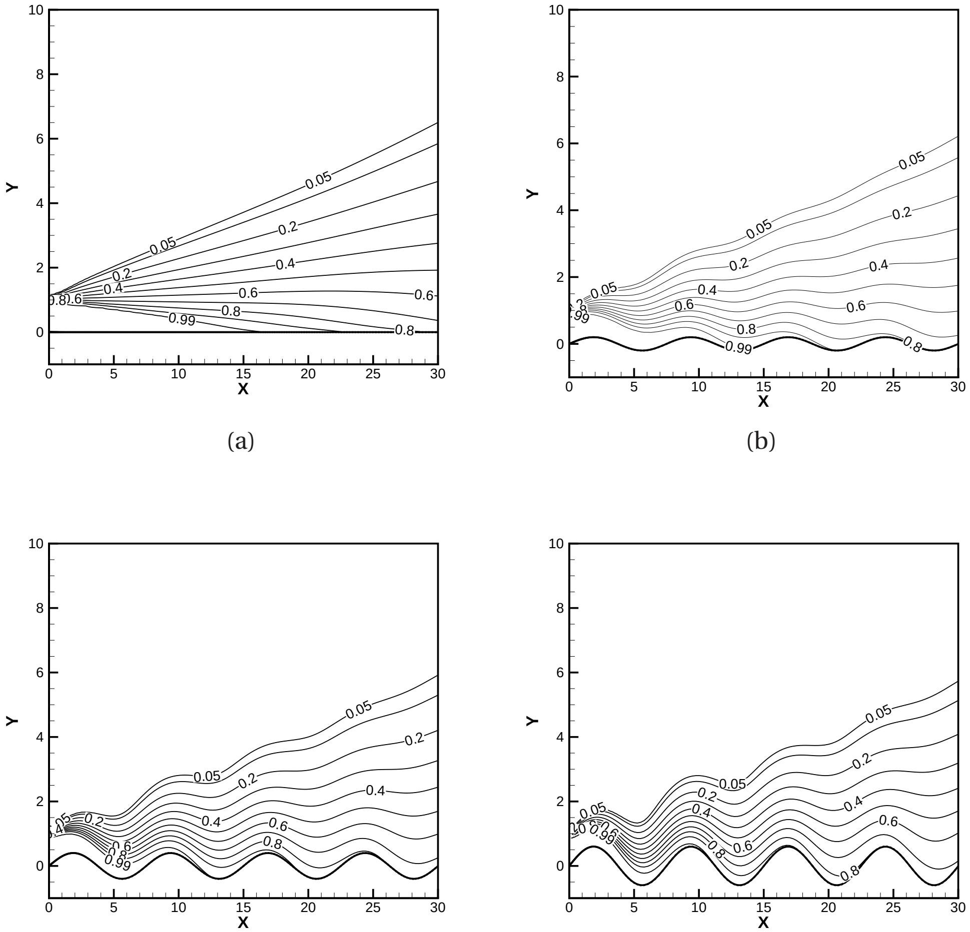
Figure 6.14: The comparison of the variation of temperature fluctuation in wall normal direction for different cases at (a) $X = 1.875$ and (b) $X = 54.375$

throughout the jet. Figs. 6.14a and 6.14b show the influence of amplitude on the temperature fluctuation in the near field $X = 1.875$ and in the far field $X = 54.375$, respectively. In the near field, at $X = 1.875$, the temperature fluctuation is higher in the wall region $Y - Y_1 \leq 0.5$; it reduces in upward direction. In the adiabatic wall condition, the thermal energy of jet remains high in the wall region as no heat dissipates through the wall, whereas in the outer region, the jet is in contact with the cold surrounding where the thermal energy of jet fluid can dissipate easily. In fig. 6.14a, it can also be observed that T_{rms} reduces as the amplitude of wavy wall increases. This might be due to increase in the arc length of wavy wall as the fluid travels a little longer distance as amplitude increases. This leads to decrease in the thermal energy which is accumulated near the wall. In the far field location, $X = 54.375$, the waviness of wall has no effect on the temperature fluctuation as the t_{rms} becomes almost flat and value is near to zero for all the cases. Because in far field, the thermal energy is depleted and dissipated throughout the jet.

6.2.3 Numerical results

6.2.3.1 Temperature distribution

Fig. 6.15 shows the temperature distribution in the near field ($X \leq 30$) for plane wall and wavy wall. In wavy wall cases, the thermal potential core gets thinner and shorter with the increasing amplitude. In the case of plane wall jet, the thermal potential core is maintained till $X = 15$, which decreases to $X = 13.5$, $X = 12.4$ and $X = 11$ for the amplitudes 0.2, 0.4 and 0.6 respectively. Because of the restriction caused by the slope of wavy wall, the



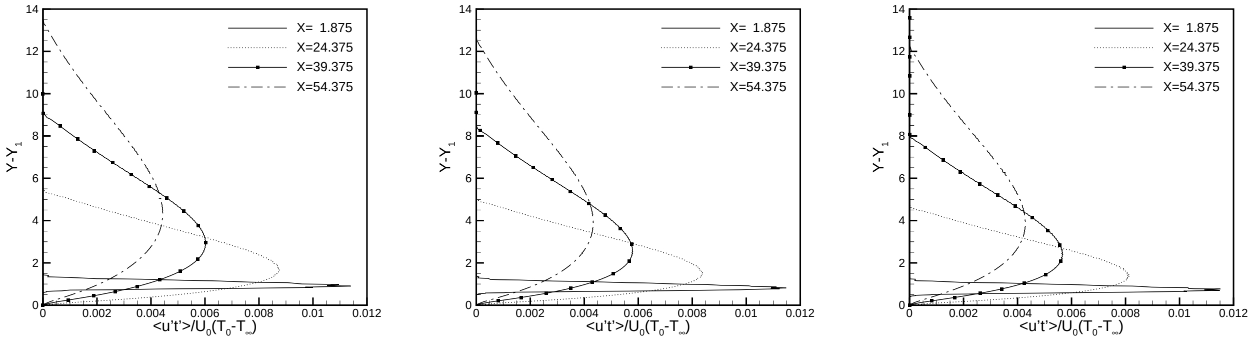
(a)

(b)

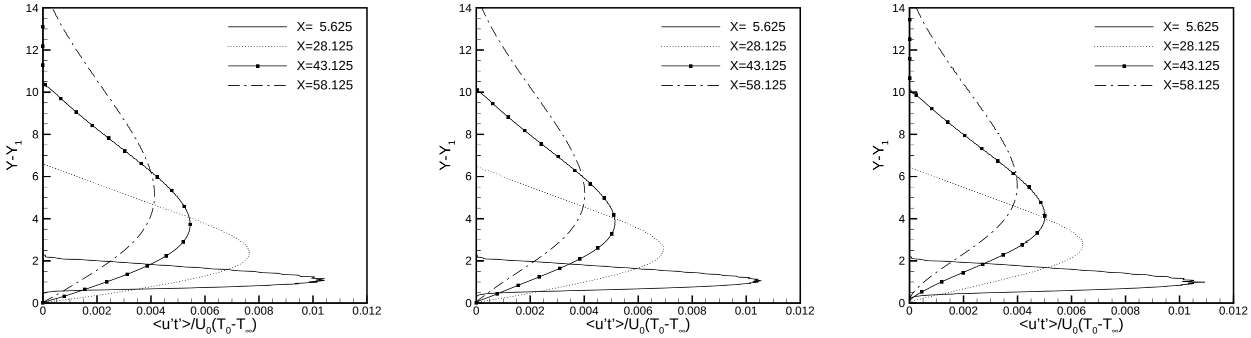
(c)

(d)

Figure 6.15: Temperature contour for (a) plane wall jet, (b) wavy wall of 0.2 amplitude, (c) wavy wall of 0.4 amplitude and (d) wavy wall of 0.6 amplitude



(a) 0.2 amplitude (crest) (b) 0.4 amplitude (crest) (c) 0.6 amplitude (crest)



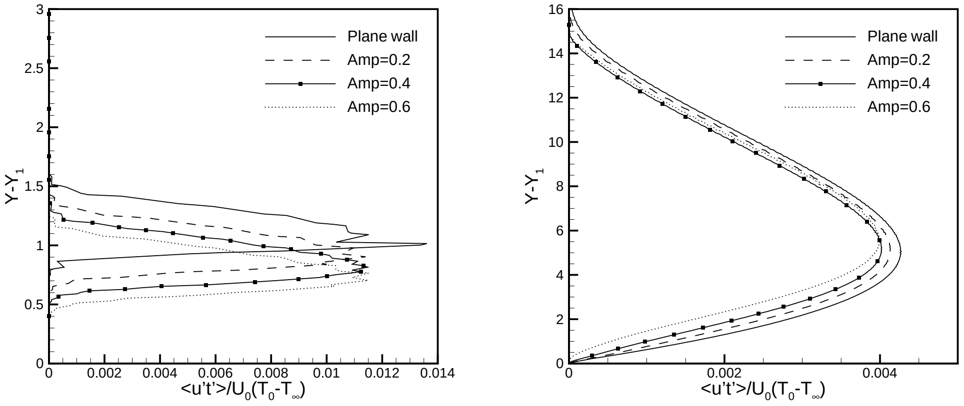
(d) 0.2 amplitude (trough) (e) 0.4 amplitude (trough) (f) 0.6 amplitude (trough)

Figure 6.16: Variation of the cross-stream turbulent heat flux <v't'> for wavy wall with different amplitudes

mean velocity starts increasing as the fluid moves from the leading edge to the first crest, which distorts the velocity potential core. And the transition zone starts from the leading edge, which increases the intermixing of fluid within the jet and the ambient fluid [56]. Due to higher intermixing, the thermal energy dissipates with a higher rate; this makes the thermal potential core thinner and shorter. Also, the effective surface area of contact also increases with increase in the amplitude of the wall. This makes jet to travel more.

6.2.3.2 Turbulent heat flux

The cross stream turbulent heat flux <v't'> is calculated by using formula <v't'> $= -(\nu_t/pr_t)(dt/dy)$, where ν_t is turbulent viscosity and Pr_t is the turbulent Prandtl number. The turbulent heat flux is normalised by the quantity based on inlet parameter ($U_0(T_0 - T_\infty)$. Fig. 6.16 shows the variation of cross-stream turbulent heat flux <v't'> for different crest and trough locations of the wavy wall. The <v't'> remains positive throughout, as for any location X,

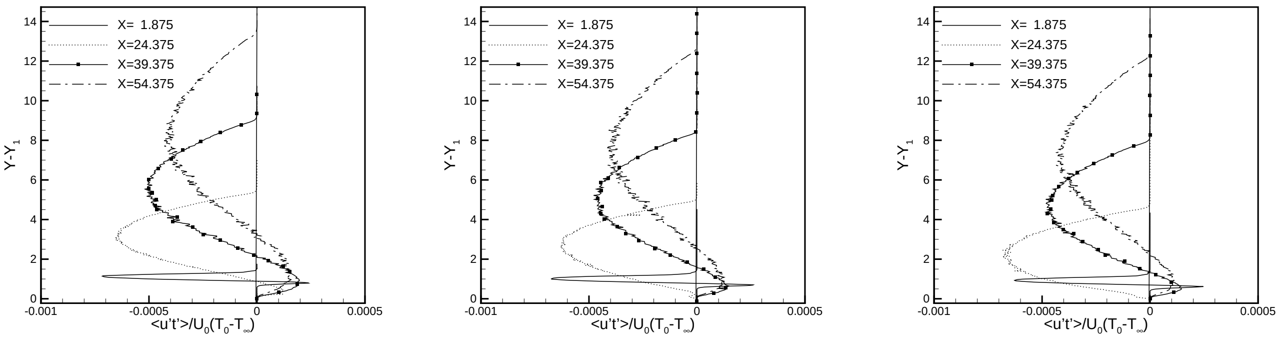


(a) (b)

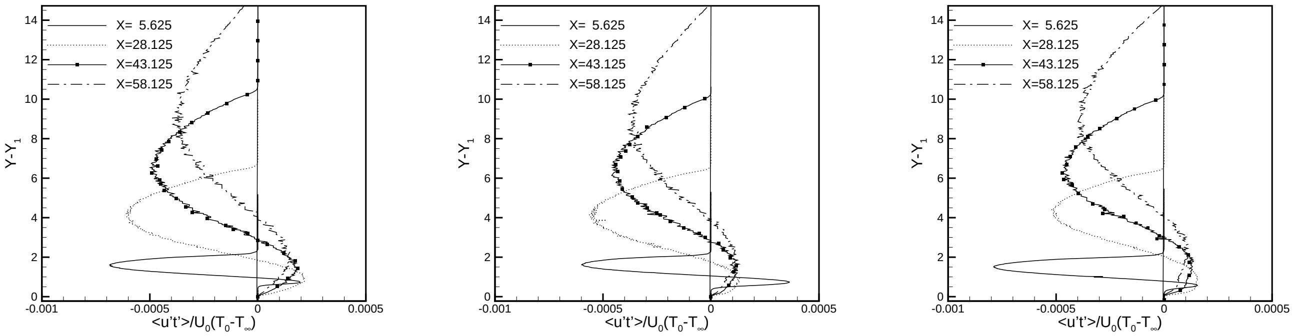
Figure 6.17: The comparison of streamwise heat flux for different amplitude wavy walls and plane wall at (a) $X = 1.875$ (b) $X = 58.125$

the gradient dt/dy remains negative in the wall normal direction. Because for heated jet (with adiabatic wall) the temperature is maximum near the wall and it keeps on decreasing to become equal to the surrounding fluid temperature in the wall normal direction. The value of cross-stream turbulent heat flux is much higher than the value of streamwise turbulent heat flux, which indicates that the thermal energy diffuses with a higher rate in wall normal direction in comparison to the streamwise direction. For any wavy wall, the <v't'> decreases as the fluid moves in downward direction. Also, the peak of <v't'> is found to shift a little closer to the wall for the crest location in comparison to the peak at the trough location for same cycle. This might be due to the area of flow near the crest is lesser than the area of flow near the trough. The influence of amplitude of wavy wall on the cross-stream turbulent heat flux at X = 1.875 and X = 56.125 is shown in fig. 6.17. For X = 1.875, the <v't'> remains zero till the thermal potential core. Similar to the <u't'> profile, the <v't'> profile also shifted closer to the wall with the increasing amplitude. For the wavy wall cases, the maximum value of <v't'> remains almost same, which is less than the maximum value of <v't'> for the plane wall jet. Because in the case of plane wall jet, the thermal potential core is thickest among all the cases. Whereas in the far field, the value of <v't'> reduces with the increasing amplitude (till 0.4 amplitude) and for 0.6 amplitude, it remains close to the value obtained for the case of 0.4 amplitude.

The variation of streamwise turbulent heat flux (<u't'>) and cross-stream turbulent heat flux (<v't'>) at different downstream locations for plane and wavy walls are illustrated in figs. 6.18 and 6.16, respectively. The streamwise turbulent heat flux <u't'> is calculated by using formula <u't'> = $-(\nu_t/pr_t)(dt/dx)$. The turbulent heat flux <u't'> gives the turbu-



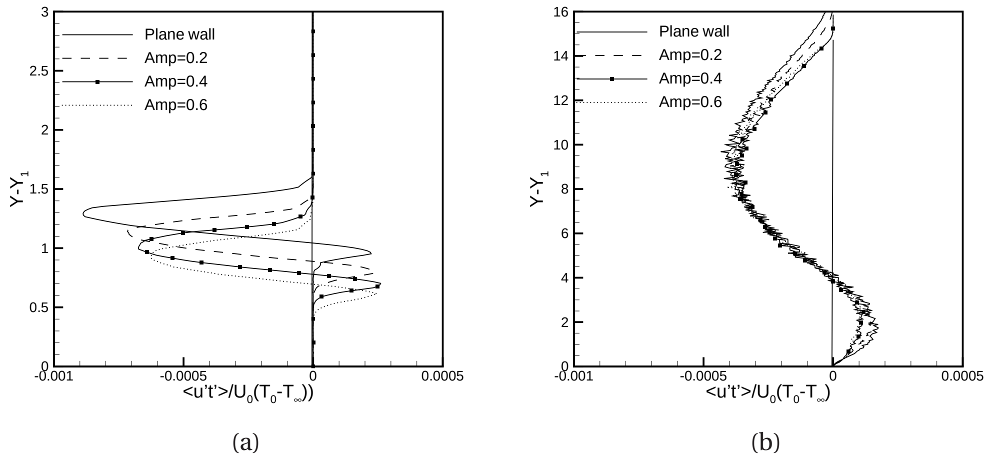
(a) 0.2 amplitude (crest)
(b) 0.4 amplitude (crest)
(c) 0.6 amplitude (crest)



(d) 0.2 amplitude (trough)
(e) 0.4 amplitude (trough)
(f) 0.6 amplitude (trough)

Figure 6.18: Variation of the streamwise turbulent heat flux <u't'> for wavy wall with different amplitudes

lent heat transport in the x-direction which is generated due to the fluctuating streamwise velocity and fluctuating temperature. Whereas the cross-stream turbulent heat flux <v't'> gives the turbulent heat transport in the y-direction which is generated due to the fluctuating cross-stream velocity and fluctuating temperature. In fig. 6.18, the change in the streamwise turbulent heat flux (<u't'>) is shown for crest and trough locations separately for wavy wall. The streamwise turbulent heat flux is positive near the wall as the temperature gradient dt/dx is negative close to the wall. In the outer region of the jet, due to the continuous spreading of jet, the temperature of jet attains the surrounding temperature at relatively longer distance from the wall, that is why the temperature gradient dt/dx becomes positive and the streamwise turbulent heat flux becomes negative in the outer region. In all the cases, both the negative and positive values are highest at the location $X = 1.875$ and $X = 5.625$ for crest and trough respectively. The value of <u't'> reduces as the fluid moves forward in the downward direction, in the outer region of jet. The influence of amplitude of wavy wall on the streamwise turbulent heat flux in near field ($X = 1.875$)



(a) (b)

Figure 6.19: The comparison of streamwise heat flux for different amplitude wavy walls and plane wall at (a) $X = 1.875$ (b) $X = 58.125$

and in far field (X = 56.125) are shown in fig. 6.19. For the near field, the <u't'> remains almost zero till the height of the potential core. In the positive flux region, the <u't'> remains almost same for all the cases, although the profile is shifted closer to the wall with the increasing amplitude. This happens because the thickness of thermal potential core reduces with the increasing amplitude. In the outer flow region, where <u't'> is negative, the value of <u't'> reduces as the amplitude increases. In the far field location, the value of streamwise turbulent heat flux <u't'> reduces as the amplitude increases in both the upper and lower shear layers.

6.3 Conclusion

The fluid flow thermal characteristics of a turbulent jet on wavy wall of amplitudes 0.2, 0.4 and 0.6 have been investigated experimentally and compared with the plane wall results. In addition to this, numerical simulation has been carried out using $k-\varepsilon$ RNG to get some of important information which are not available through the experiment. The conclusions drawn from the present study are:

- On normalizing the mean velocity profile using outer scaling method, self similar behaviour is noticed in the downstream The self similar behavior is delayed as the amplitude of wavy wall increases. The peak of the self similar profile is at $Y = 0.18$ for plane wall case, which shifts toward the wall at the crest and away from the wall at the trough with the increasing amplitude.

- During the development of flow over the wavy wall, the value of local maximum stream wise velocity increases with the increasing amplitude. At the first crest, the rise in U_{max} is 26%, 37% and 60% with respect to the plane wall jet. U_{max} follows the power law trend for crest and trough separately in the developed region.The spreading of jet $Y_{0.5}$ also become linear (similar to plane wall jet) at the crest and trough separately.

- The amplitude of wavy wall has great influence on the turbulence of the jet. Because in the near field, the turbulent intensity increases with the increasing amplitude. The maximum turbulent intensity in the case of plane wall jet is 14.5% which rises to 16.8%, 17.4% and 18.8% for the amplitude 0.2, 0.4 and 0.6 respectively. Which means the intermixing of jet fluid also increases with the increasing amplitude. This makes the use of wavy wall suitable in many industrial applications where heat transfer is important.

- Similar to the turbulent intensity, in the near flow field, the PSD rises with the amplitude. In far field locations, the influence of amplitude becomes mild, where the results of plane wall and wavy wall with all the amplitudes are nearly same.

- The self similar temperature profile follows the Gaussian curve for the plane wall jet and for the trough location of wavy wall, but for the crest location, self similar temperature profile does not follow the Gaussian curve.

- In the transition zone, the wall temperature decreases sharply in the case of wavy wall. In thermally developed region, the decay of wall temperature follows the power law $\theta_W = AX^{-n}$ with a constant decay rate n, and the decay rate increases as the amplitude of wavy wall increases.

- The temperature fluctuation is high near the exit of the jet (close to the wall) and it reduces as fluid moves forward and becomes almost flat in the thermally developed region. The influence of wavy wall on temperature fluctuation is felt only in near field till $X = 24.375$.

- The thermal potential core gets thinner and shorter with the increasing amplitude. In the case of 0.6 amplitude, it reduces by 26.67% in comparison to the plane wall jet.

- The turbulent heat fluxes <u't'> and <v't'> decrease as the fluid moves in the downstream direction in the case of plane and wavy walls.