CHAPTER 5

The flow and thermal characteristics of turbulent jet on isothermal modified wavy wall

The main aim of the present study is to reduce the re-circulation zone in the process of enhancing the heat transfer rate using wavy wall. The present study focuses on studying the partial wavy wall jet. In a partial wavy wall, the wall is made wavy in the beginning followed by a plane wall. This study will give a new approach to the scientific society for increasing the heat transfer rate by modifying the surface to a partial wavy wall. This kind of arrangement not only saves the material but also improves the overall performance of the turbulent wall jet. The effect of wavy portion on the heat transfer and fluid flow characteristics has also been explored numerically for two dimensional jets using $k-\varepsilon$ RNG model. The wavy wall portion is varied from 10% to 100% of the total length and amplitude is varied from 0.2 to 0.8. The wavy wall portion is considered to be sinusoidal with formula $Y = amplitude * sin(\frac{2\Pi}{7.5a}X)$ in which X is changed from 7.5a to 75a to get 10% (1 cycle) to 100% (10 cycles) wavy wall portion respectively.

5.1 Partial wavy wall

5.1.1 Results and discussion

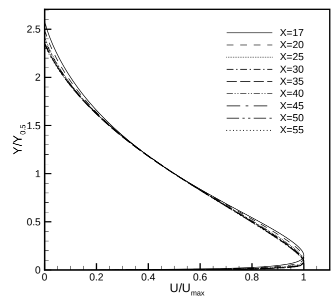
5.1.1.1 Mean streamwise velocity distribution

The streamwise velocity profile in wall normal direction at different X locations in plane wall region is shown in fig. 5.1 for the different cases. The velocity is normalized by U_{max} and the position normal to the wall is normalized by the jet half width $Y_{0.5}$. The self similar behaviour is clearly shown by all the cases of 0.4 amplitude as shown in fig. 5.1. For 0.4 amplitude, the velocity profile shows self similar behaviour from location $X = 25$, $X = 40$, $X = 47$ and $X = 60$ for 20%, 40%, 60% and 80% partial wavy walls, respectively. In the case of 0.8 amplitude, the self similar behaviour for different partial wavy walls, i.e. 20%, 40%, 60% and 80% is achieved after location $X = 30$, $X = 50$, $X = 65$ and $X = 70$, respectively. The flow is more disturbed in the case of 0.8, which leads to the delay in the self similarity of the velocity profiles.

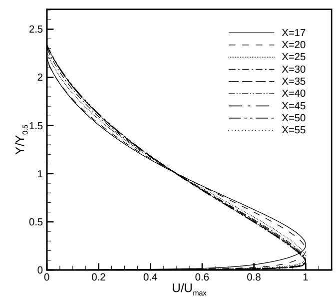
5.1.1.2 Flow Development

To explain the jet flow development, the trend of U_{max}, $Y_{0.5}$, Y_{max} and $Y_{0.5} - Y_{max}$ has been illustrated in fig. 5.2 . Figs. 5.2a and 5.2b show the decay of U_{max} for different wavy wall portions of amplitude 0.4 and 0.8 respectively. It is to be noted that U_{max} rises as soon as the jet comes out of the nozzle and the maximum value is attained at the first crest as the flow area reduces. As the fluid moves ahead from crest to trough, the area of flow increases so U_{max} falls to a minimum value near the trough. The trend of U_{max} remains wavy in wavy wall region. In the plane wall region, the decay of U_{max} becomes similar to the fully plane wall jet and starts approaching the result of fully plane wall jet. From figs. 5.2a and 5.2b, it can be noticed that in the case of 20% wavy wall the decay rate of U_{max} is least among all the cases for both 0.4 and 0.8 amplitudes. In the plane wall region, the decay rate of U_{max} increases when the portion of wavy wall increases from 20% to 100%. This means that the jet possesses high turbulence energy in the case of 20 % wavy wall, which will help in enhancing the heat transfer rate. Whereas in the case of fully wavy wall, the U_{max} reduces in far field and becomes even less than that in the case of plane wall in trough region for higher amplitudes, as discussed in the previous paper [56].

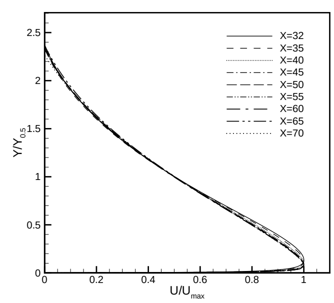
Figs. 5.2c and 5.2d show the growth of jet spread for different wavy wall portions for 0.4 and 0.8 amplitudes respectively. From figures, it can be seen that the growth of jet follows wavy pattern till the wall is wavy; once the fluid enters the plane wall region, the jet growth also becomes linear. In the case of 0.4 amplitude, the spread of jet for all the partial wavy



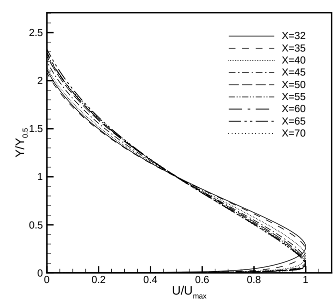
(a) 20% wavy wall 0.4 amp



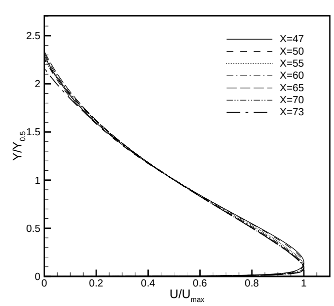
(b) 20% wavy wall 0.8 amp



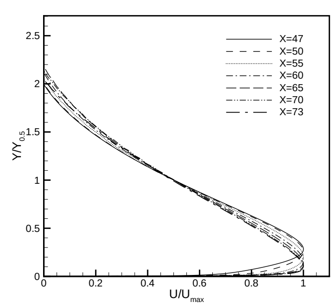
(c) 40% wavy wall 0.4 amp



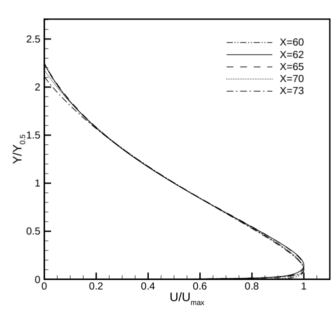
(d) 40% wavy wall 0.8 amp



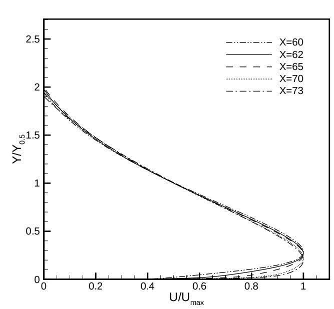
(e) 60% wavy wall 0.4 amp



(f) 60% wavy wall 0.8 amp



(g) 80% wavy wall 0.4 amp



(h) 80% wavy wall 0.8 amp

Figure 5.1: The normalized streamwise mean velocity profile for different wavy wall cases

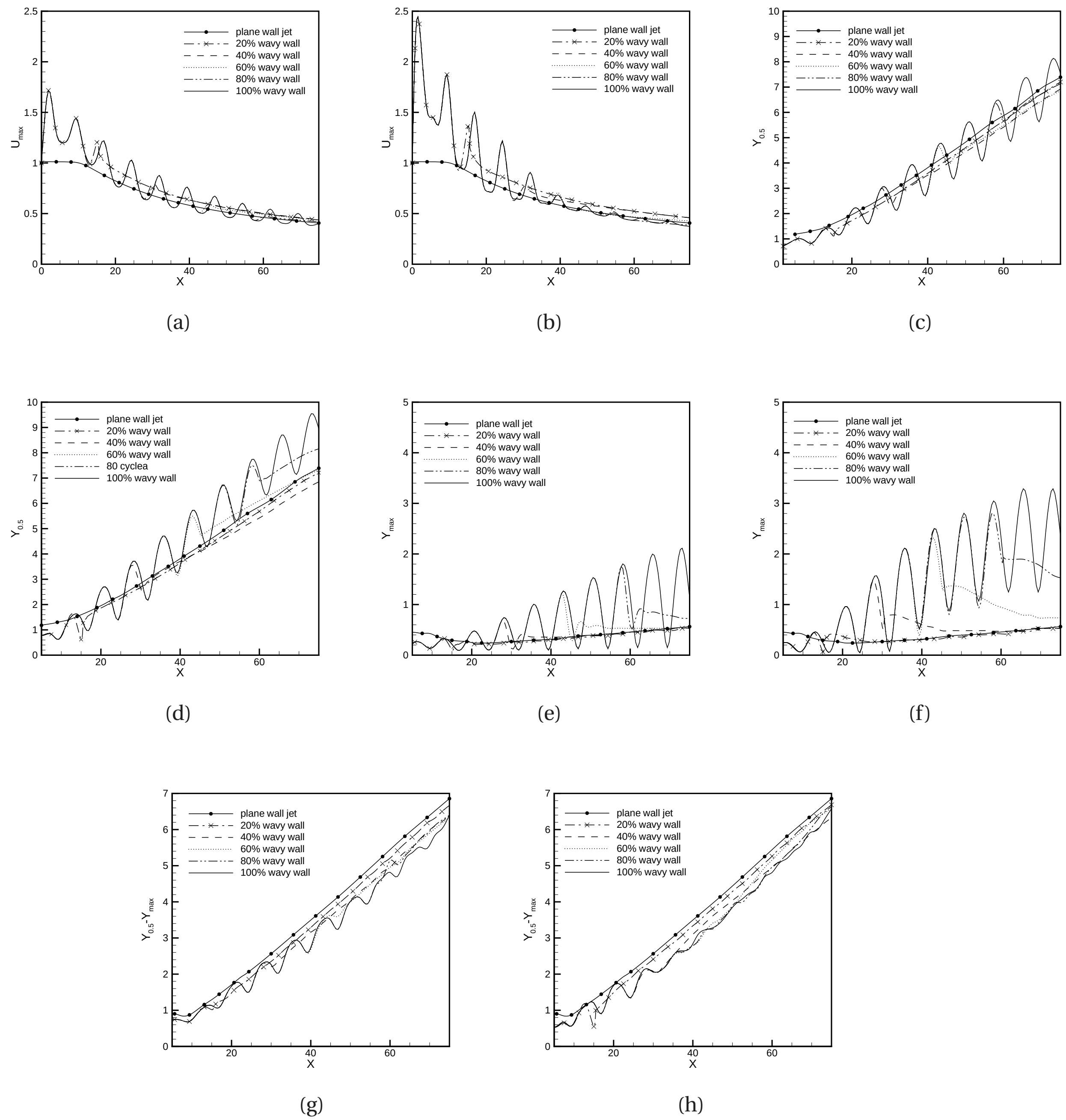


Figure 5.2: The decay of local maximum streamwise mean velocity for (a) 0.4 amplitude and (b)0.8 amplitude, the growth of jet spread for (c) 0.4 amplitude and (d)0.8 amplitude, the growth of inner shear layer thickness for (e) 0.4 amplitude and (f)0.8 amplitude and the growth of outer shear layer for (g) 0.4 amplitude and (h)0.8 amplitude.

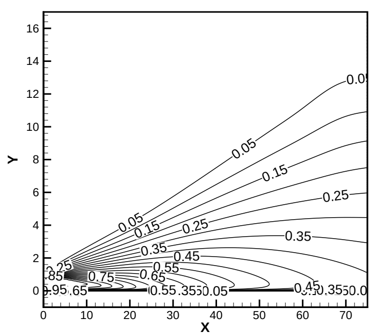
walls is less than the plane wall jet in plane wall region. However for 0.8 amplitude, in the plane wall region, the growth of jet spread is less than the fully plane wall jet only for 20% and 40% of the wavy wall portion; beyond this, the growth of jet spread is higher.

In order to explain the growth of inner shear layer of jet for different cases of amplitudes 0.4 and 0.8, the trend of Y_{max} has been shown in figs. 5.2e and 5.2f. The inner shear layer thickness grows along the downstream location and follows a wavy pattern in the wavy wall region with maxima at the trough and minima at the crest. In the plane wall region, the inner shear layer thickness reduces for some regions and then rises with a constant rate. Also, the trend of Y_{max} starts following the trend of plane wall jet for both the amplitudes, 0.4 and 0.8, with a wall having lesser wavy portion. The decrease in inner shear layer thickness is due to the transition zone resulting because of the interface between the wavy portion and the plane portion. Whereas in the case of fully wavy wall, the inner shear layer increases continuously as fluid moves in the downstream direction, as discussed by Kumari and Kumar [57]. During the transition phase, the inner shear layer and the outer shear layer are in adjusting mode and the surrounding fluid tries to push the fluid downward which leads to decrease in the inner shear layer thickness. In the case of fully plane wall jet, the transition zone is observed between $9 \leq X \leq 20$, where Y_{max} reduces. For 0.8 amplitude, the inner shear layer thickness is higher than the 0.4 amplitude for all the partial wavy wall cases.

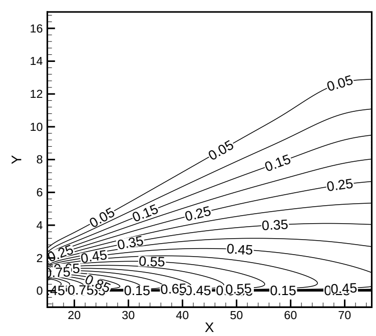
The growth of outer shear layer is shown in figs. 5.2g and 5.2h for different cases of amplitudes 0.4 and 0.8 respectively. From figs, 5.2g and 5.2h it can be seen that with the increasing wavy wall portion the growth of outer shear layer reduces in comparison to the fully plane wall case. In the case of 0.8 amplitude, the growth of outer shear layer is almost linear after 2 cycles of the wavy wall. This might be due to the formation of recirculation zone in trough region which is happening beyond 2nd cycle for 0.8 amplitude cases.

5.1.1.3 Velocity Contour

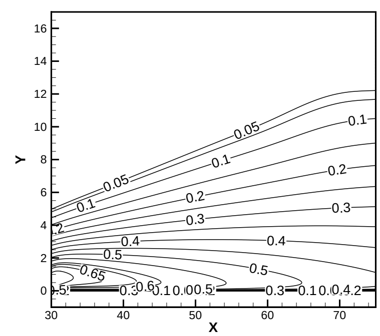
The velocity contour, normalized by the inlet velocity, has been shown in fig. 5.3 for plane wall region of the wavy wall of 0.8 amplitude and for fully plane wall jet. From fig. 5.3, it can be seen that the spreading of jet in the plane wall region of partial wavy wall is similar to the spreading of fully plane wall jet, where jet grows linearly and flow remains attached to the wall. Whereas, in the case of 100% wavy wall, flow gets separated for the wall amplitude of 0.8 in the downstream location. The spreading of jet in plane wall region of 20% and 40% wavy wall is relatively lesser than the spreading of jet in the case of a fully plane wall jet; the same is also observed in fig. 5.6d. Because in the plane wall region of



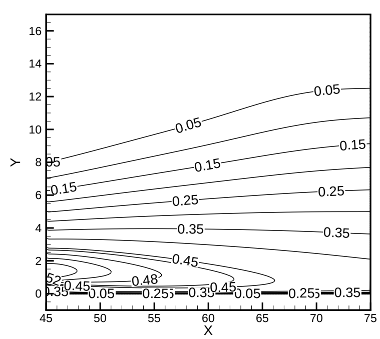
(a) Plane wall



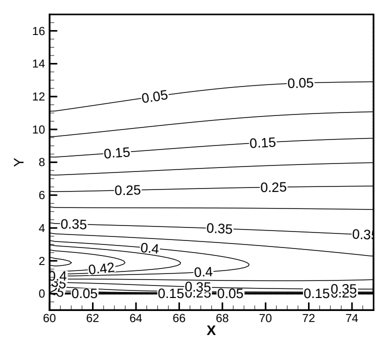
(b) 20% wavy wall



(c) 40% wavy wall

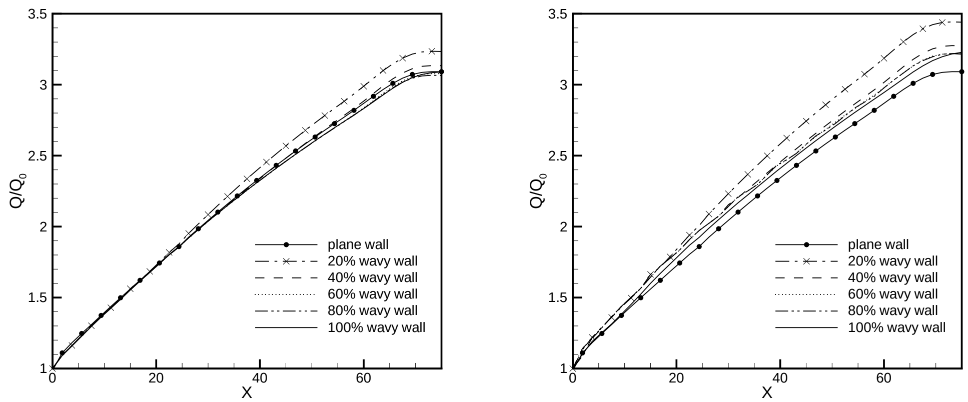


(d) 60% wavy wall



(e) 80% wavy wall

Figure 5.3: The velocity contour for the flow in the plane wall region, for plane wall and partial wavy wall of 0.8 amplitude.



(a) (b)

Figure 5.4: The entrainment of ambient fluid in the jet flow for (a) 0.4 amplitude and (b) 0.8 amplitude

20% and 40% partial wavy walls, the fluid moves with a higher velocity than it moves in the plane wall jet as shown in fig. 5.2b.

5.1.1.4 Entrainment

Fig. 5.4 shows the variation of normalized volume flow rate for the plane wall and different wavy wall portions for amplitudes 0.4 and 0.8, where Q is the volume flow rate in the streamwise direction for the unit depth at any specific location X. It can be calculated by $Q = \triangle_0^\infty \rho u d y$, and it is normalized by the inlet flow rate (Q_0). From fig. 5.4, it can be observed that the entrainment of the surrounding fluid in jet is highest for the 20% wavy wall portion for both the 0.4 and 0.8 amplitudes. The jet carries high momentum for 20% wavy wall portion for both the amplitudes, as the jet decay rate is slow (fig.5.2a and 5.2b), which leads to more entrainment of the surrounding fluid. For amplitudes 0.4 and 0.8, there is 4.6% and 11.2% more entrainment with respect to the plane wall jet in case of 20% wavy wall portion. In the previous study [56], the maximum entrainment of ambient fluid is 4.43% higher than the plane wall jet, which is comparatively less than the present study. From fig. 5.4, it can be observed that in the case of 0.4 amplitude, all the cases have nearly the same entrainment except the 20% wavy wall case. However, in the case of 0.8 amplitude, the entrainment of the surrounding fluid decreases as the portion of wavy wall increases from 20% to 100%. But, the entrainment is still higher than the entrainment observed in the fully plane wall jet.

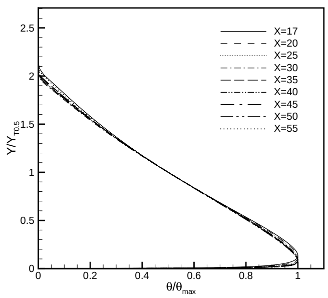
5.1.1.5 Temperature distribution

Fig. 5.5 shows the mean temperature profile at different locations for the cases of partial wavy wall with 0.4 and 0.8 amplitudes. The difference in temperature between the measuring point and the surrounding is normalized by the difference in maximum temperature and the surrounding at the specified location X, i.e. $\theta/\theta_{max} = (T - T_{\infty})/(T_{max} - T_{\infty})$. The transverse location Y is normalized by the temperature half width $Y_{T0.5}$, which is the transverse location from the wall where θ becomes half of the θ_{max}. In the case of 0.4 amplitude, for 20% wavy wall, the temperature profiles are following the self similar behavior throughout the plane wall region as shown in fig. 5.5a. For the other cases, in far field $X \geq 60$, the temperature profile does not follow the self similar behavior for the flow away from the wall ($Y \geq Y_{T0.5}$). In the case of 0.8 amplitude, the self similar behavior is seen for $X \geq 25$ for the 20 % of the wavy wall portion, and for higher wavy wall portion the self similar behavior is seen for the temperature profile near the wall $Y/Y_{T0.5} \leq 1$ only. This indicate that for partial wavy wall, the flow in far field is not thermally developed in the outer layer.

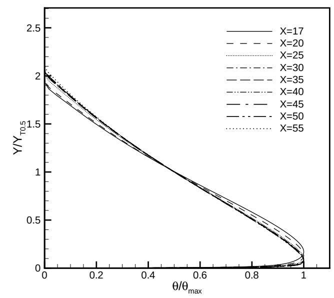
5.1.1.6 Thermal Development

The thermal development of jet in the case of partial wavy wall has been discussed in this section with the help of θ_{max}, $Y_{T0.5}$, and Y_{Tmax}. Figs. 5.6a and 5.6b show the decay of local maximum temperature, θ_{max}, in the downstream direction for different partial wavy wall of 0.4 and 0.8 amplitudes. The Holland and Liburdy [41] experimental result of plane wall jet has been used for the reference purpose. From figs. 5.6a and 5.6b, it can be observed that the decay rate of local maximum temperature is high for the partial wavy wall with respect to the fully plane wall jet. The thermal potential core length also reduces by 16% and 50% for 0.4 and 0.8 amplitudes respectively, in comparison to the fully plane wall jet. It is noticed that the percentage of wavy wall has almost no influence on the decay of θ_{max} as well as on the length of the thermal potential core. Due to the waviness, near the exit of the nozzle, the intermixing of fluid within the jet increases. This increases the heat transfer rate, leading to a decrease in the thermal potential core region and a rise in the decay of θ_{max}.

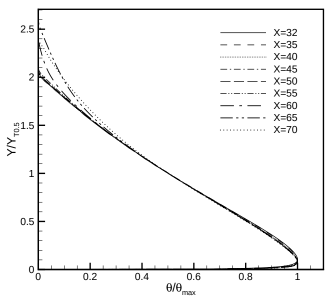
The thermal spread of the jet for different cases of amplitudes 0.4 and 0.8 has been shown in figs. 5.6c and 5.6d, respectively. For 0.4 amplitude, the jet thermal spread is less than that in the plane wall jet. In the plane wall region, as the portion of wavy wall increases, the thermal spread of jet reduces. In the case of 0.8 amplitude, in the wavy wall



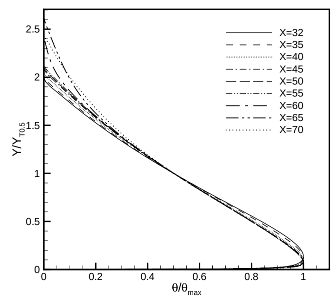
(a) 20% wavy wall 0.4 amp



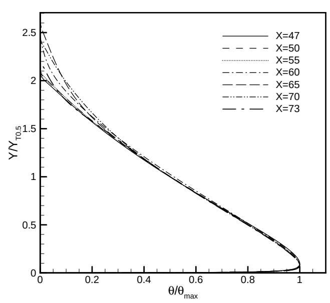
(b) 20% wavy wall 0.8 amp



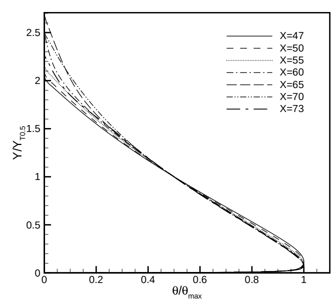
(c) 40% wavy wall 0.4 amp



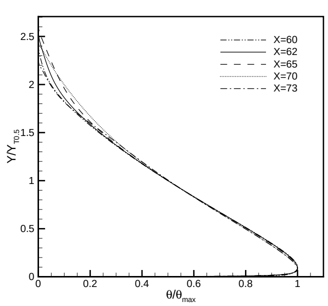
(d) 40% wavy wall 0.8 amp



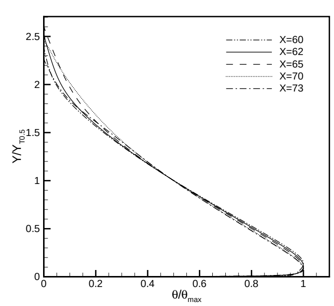
(e) 60% wavy wall 0.4 amp



(f) 60% wavy wall 0.8 amp



(g) 80% wavy wall 0.4 amp



(h) 80% wavy wall 0.8 amp

Figure 5.5: The normalized temperature profile for different wavy wall cases

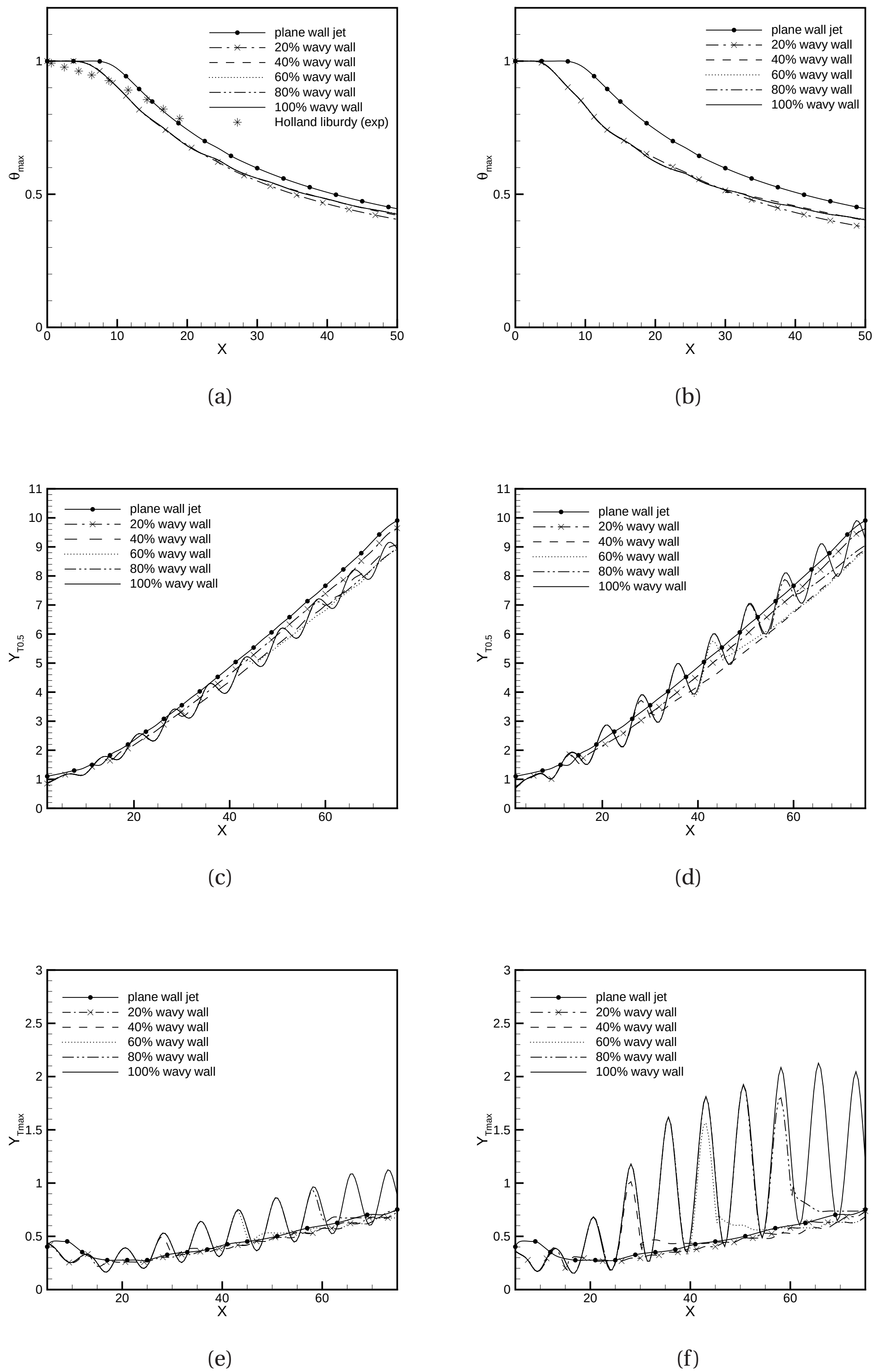


Figure 5.6: The decay of local maximum normalized temperature for (a) 0.4 amplitude and (b)0.8 amplitude, the growth of jet thermal spread for (c) 0.4 amplitude and (d)0.8 amplitude and the growth of thermal wall boundary layer thickness for (e) 0.4 amplitude and (f) 0.8 amplitude

portion, the $Y_{T0.5}$ is more for the crest region (except 1st crest) and in plane wall region the growth of $Y_{T0.5}$ remains less than the fully plane wall jet.

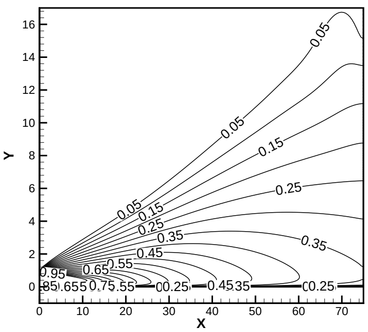
The growth of Y_{Tmax} has been explained for different cases in figs. 5.6e and 5.6f for the amplitudes 0.4 and 0.8, respectively. The inner shear layer thickness grows and the pattern remains wavy in the wavy wall region with maxima at the trough and minima at the crest, similar to the growth of inner shear layer thickness. When the fluid moves from the wavy wall to the plane wall region, Y_{Tmax} decreases for some length due to the formation of transition zone. Once the transition zone ends, the trend of Y_{Tmax} starts following the trend of fully plane wall jet. The growth of Y_{Tmax} is high for 0.8 amplitude in comparison to the 0.4 amplitude.

5.1.1.7 Temperature Contour

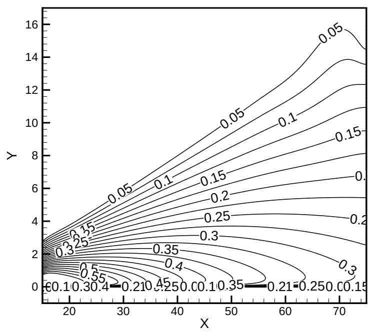
In fig. 5.7, the normalized temperature contour $\theta = \frac{T-T_\infty}{T_0-T_\infty}$ has been shown for a fully plane wall jet and in the plane wall region of the partial wavy wall with 0.8 amplitude. The temperature distribution in the plane wall region of partial wavy wall is similar to the distribution in fully plane wall jet, with a linear growth. Similar to the velocity contour, the thermal spreading in plane wall region of the partial wavy wall is relatively less than the fully plane wall jet. This has also been observed in fig. 5.6d.

5.1.1.8 The heat transfer rate

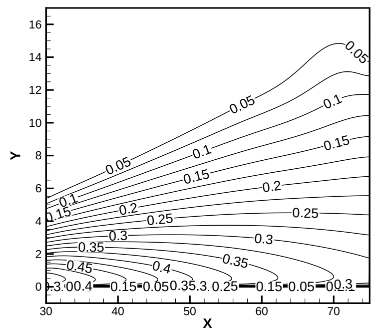
The local Nusselt number at any specific location X on the wall is designated by Nu_x. The trend of local Nusselt number along the partial wavy wall for different amplitudes, 0.2 to 0.8, has been plotted in figs. 5.8a- 5.8d and the results are compared with the results of fully plane wall. The Nu_x is maximum at the leading edge of the wall and it reduces till the trough as the fluid moves forward; the Nu_x rises as the fluid moves from the trough to the crest. The trend of Nu_x remains wavy till the wall is wavy. In the plane wall region, the trend of Nu_x becomes similar to the trend of fully plane wall jet with a little fluctuation at the interface region where the plane wall region starts. In the plane wall region of the partial wavy wall, the local Nusselt number remains almost the same as the fully plane wall jet in the case of 0.2 and 0.4 amplitudes. For the amplitudes 0.6 and 0.8, as the wavy wall portion increases, the Nu_x reduces. The graph of average Nusselt number for different partial wavy walls for different amplitudes along with the plane wall jet is shown in fig. 5.9. A sudden increment in the average Nusselt number is seen for all the amplitudes as the plane wall is replaced by 10% wavy wall; for higher amplitudes, the increment in average Nusselt number is high. For the amplitudes 0.2 and 0.4, the average Nusselt number keeps



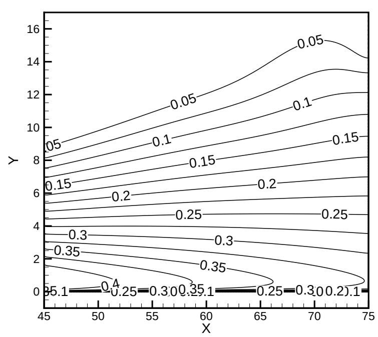
(a) Plane wall



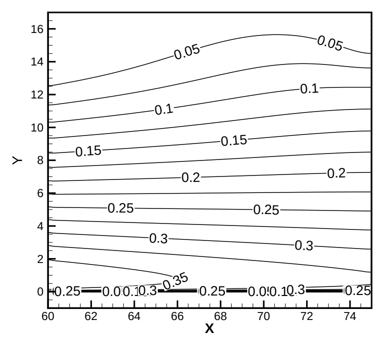
(b) 20% wavy wall



(c) 40% wavy wall



(d) 60% wavy wall



(e) 80% wavy wall

Figure 5.7: The temperature contour for the flow in the plane wall region,for plane wall and partial wavy wall of 0.8 amplitude

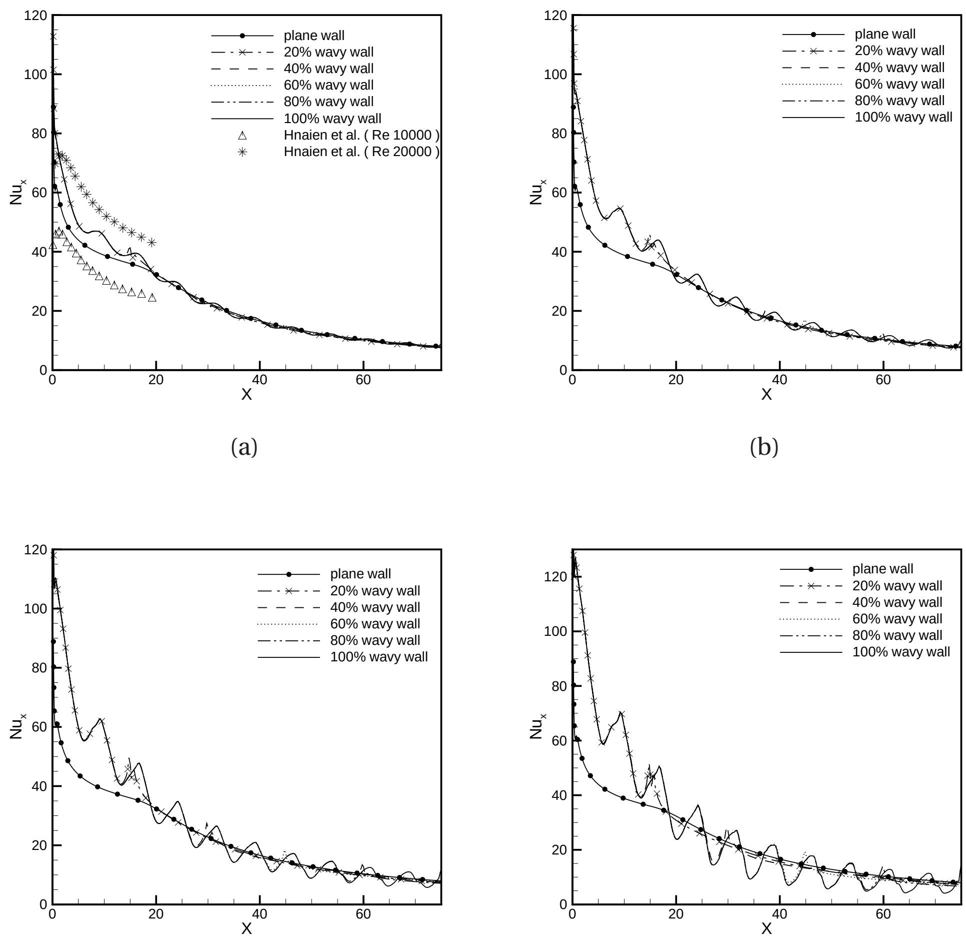


Figure 5.8: Variation of local Nusselt number at the surface for (a) 0.2 amplitude, (b) 0.4 amplitude, (c) 0.6 amplitude and (d) 0.8 amplitude for different partial wavy walls

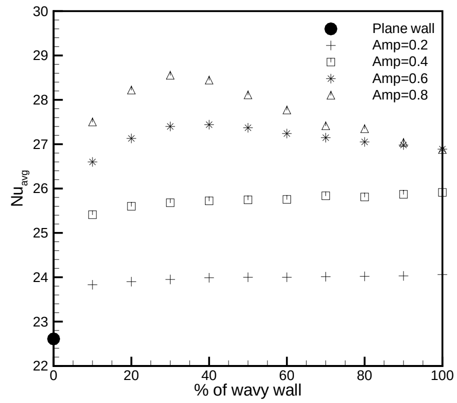


Figure 5.9: Variation of average Nusselt number for different cases

Table 5.1: The percentage increment in average Nusselt number for different cases with respect to plane wall jet.

% wavy wall\Amp	0.2	0.4	0.6	0.8
10%	5.40	12.4	17.69	21.7
20%	5.70	13.2	20.00	24.84
30%	5.90	13.57	21.18	26.27
40%	6.10	13.76	21.36	25.8
50%	6.15	13.86	21.06	24.32
60%	6.15	13.91	20.48	22.82
70%	6.20	14.27	20.07	21.25
80%	6.24	14.35	19.64	20.51
90%	6.30	14.42	19.33	19.57
100%	6.42	14.61	18.92	18.80

on increasing with a slow rate as the portion of wavy wall increases till the wall becomes 100% wavy. However, in the case of 0.6 and 0.8 amplitudes, the maximum average Nusselt number is achieved for 40% and 30% wavy walls respectively; beyond this, the average Nusselt number reduces as the % of wavy wall increases. The percentage increment in Nu_{avg} for the different cases with respect to the plane wall jet has been listed in table. 5.1. The maximum increase in Nu_{avg} is 26.27%, which is much higher than the maximum heat transfer achieved in the previous paper [56], i.e. 19.08% for the fully wavy wall case. In the case of higher wavy wall portion, the average Nusselt number reduces due to the increment in the re-circulation zone which causes separation.

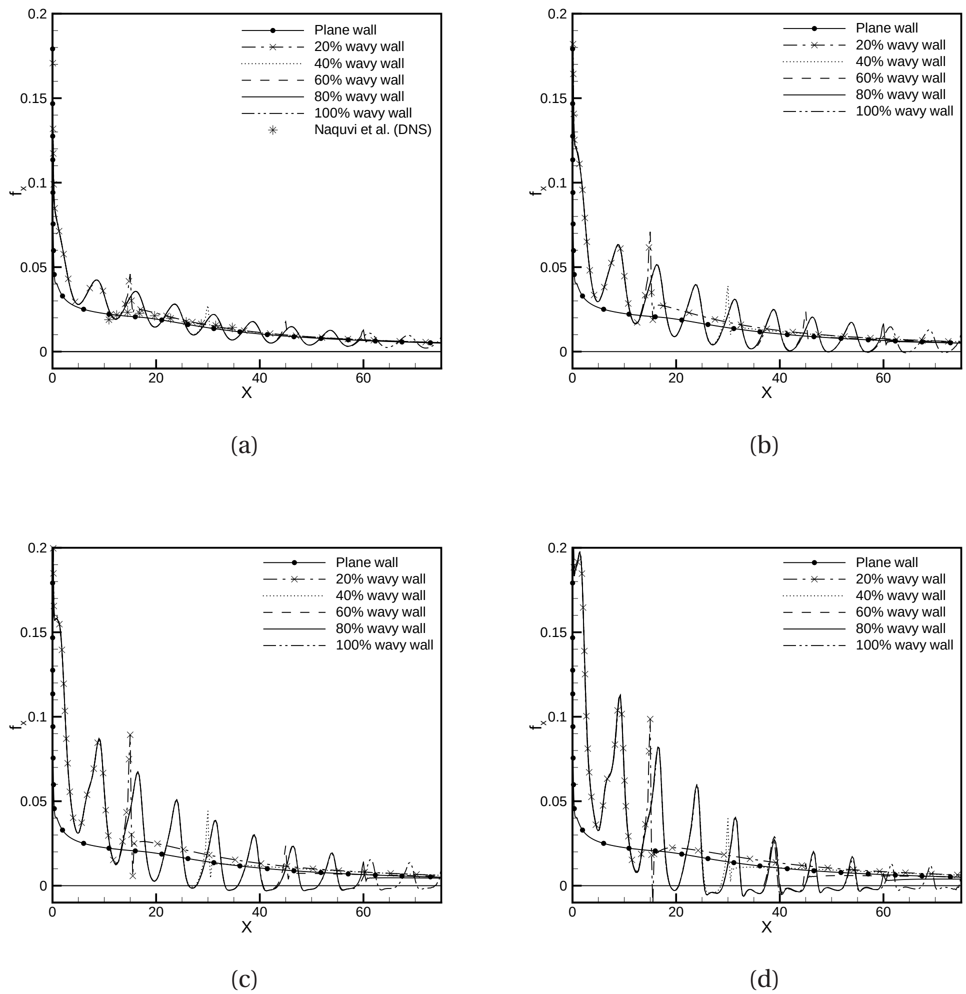


Figure 5.10: Variation of friction factor coefficient for (a) 0.2 amplitude, (b) 0.4 amplitude, (c) 0.6 amplitude and (d) 0.8 amplitude for different partial wavy walls

5.1.1.9 Friction coefficient and re-circulation zone

The local friction coefficient, f_x is a non-dimensional parameter. The variation of local friction factor coefficient for different cases is shown in figs. 5.10a-5.10d for amplitude 0.2, 0.4, 0.6 and 0.8. It can be seen from the fig. 5.10 that in the crest location, f_x is more and in the trough location it is less because the derivative of streamwise mean velocity is high in crest and low in trough location for wavy wall. At the interference point, a sudden fluctuation in f_x is noticed. For the same amplitude, the intensity of fluctuation reduces as the % of wavy wall increases and for the same % of wavy wall portion, the intensity of fluctuation increases with the increasing amplitude. In the plane wall portion, the local friction factor decreases at a constant rate similar to the fully plane wall jet. From fig.

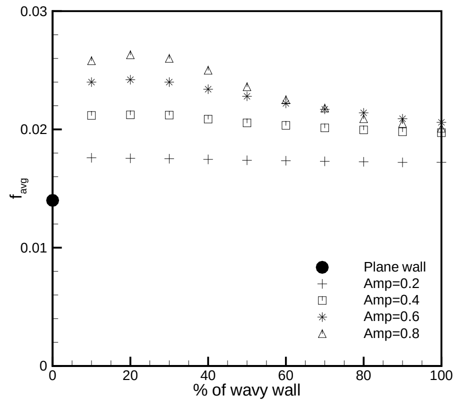


Figure 5.11: Variation of average friction coefficient for different cases

5.10a, it can be seen that in the case of 0.2 amplitude, the influence of % of wavy wall portion on the local friction factor in plane wall portion is negligible. As the wavy wall amplitude increases from 0.4 to 0.8 (figs. 5.10b, 5.10c and 5.10d), the influence of % of wavy wall portion in plane wall region becomes significant. In the plane wall region, for the amplitude 0.2 to 0.8 and the 20% wavy wall case, f_x is a little higher in comparison to the fully plane wall jet. The average friction coefficient f_{avg} is calculated by integrating the local friction coefficient f_x throughout the length of the bottom wall. The graph of average friction coefficient for different partial wavy walls for different amplitudes along with the plane wall jet is shown in fig. 5.11 . From fig.5.11 it can be seen that the f_{avg} increases as the amplitude increases in the case with smaller portion of wavy wall.The percentage increment in average friction factor with respect to the plane wall jet is listed in table. 5.2 for all the cases. From table. 5.2, it can be observed that for the 10% wavy wall case the average friction factor increases drastically with respect to the plane wall jet and for higher amplitude the increment goes up to 87.6% for 20% wavy wall. In the case of 0.2 amplitude, the increment in average friction factor remains almost same for all the wavy wall percentages. But for the higher amplitudes (0.4 to 0.8), the friction factor starts reducing as the wavy wall portion increases beyond 20%. When the f_x becomes negative, the separation starts and the zone is known as the re-circulation zone. From fig. 5.10, it can be seen that there is no re-circulation zone for 0.2 amplitude whereas for the other amplitudes, separation starts with 80%, 40% and 30% wavy wall portions respectively. The % of wall under the re-circulation zone for different partial wavy wall has been listed in table. 5.3 . From the table. 5.3, it can be seen that once the separation initiates for a given amplitude, the % of wall under the re-circulation zone keeps on increasing with the

Table 5.2: The percentage increment in average friction factor for different cases with respect to plane wall jet.

% wavy wall\Amp	0.2	0.4	0.6	0.8
10%	25.4	51.3	71.4	84.0
20%	25.4	51.6	72.8	87.6
30%	25.1	51.5	71.2	85.5
40%	24.7	49.1	67.5	78.4
50%	24.2	46.8	62.9	68.8
60%	23.9	45.3	58.4	60.5
70%	23.6	43.8	54.7	55.5
80%	23.3	42.6	52.8	49.5
90%	22.9	41.4	49.2	46.4
100%	23.0	40.8	47.3	43.7

Table 5.3: The % of wall under the re-circulation zone in different cases.

% wavy wall\Amp	0.2	0.4	0.6	0.8
10%	-	-	-	-
20%	-	-	-	-
30%	-	-	-	2.4
40%	-	-	1.6	6.4
50%	-	-	4.93	12.4
60%	-	-	8.6	18.9
70%	-	-	12.9	21.2
80%	-	2.0	17.5	26.5
90%	-	3.7	22.2	38.7
100%	-	6.3	28.0	45.7

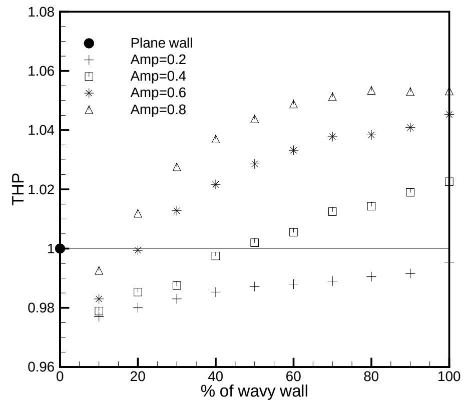


Figure 5.12: The variation of THP for different amplitudes and wavy wall %

increasing % of wavy wall.

5.1.1.10 Thermal hydraulic performance

Fig. 5.12 shows the thermal hydraulic performance for different amplitudes against the different % of wavy walls. For the amplitude 0.2, 0.4 and 0.6, the thermal hydraulic performance increases with increase in the wavy portion of wavy wall. In the case of 0.2 amplitude, the THP remains less than 1 for all the different wavy wall portions, which indicates that the friction losses dominate and therefore it can not be a good choice for efficient cooling. The maximum increment in THP of 5.3% has been obtained for 0.8 amplitude and 70% of wavy wall; the THP remains almost same thereafter. So, in order to get maximum heat transfer, it is not necessary to make the complete surface wavy, as done in a previous work [56].

5.2 Partially linearly decaying (LD) wavy wall

To minimize the problem of formation of recirculation region, in the present work, the portion of wavy wall has been made of linearly decaying amplitude in the downstream direction where the recirculation is more severe. The wavy wall is made partially linearly decaying by first having a wavy wall with a constant amplitude of 0.8 from the leading edge followed by a linearly decaying wavy wall from 0.8 to zero amplitude. The portion of LD wavy wall is changed from 0% (0 cycle) to 100% (10 cycle) and the influence of LD wavy wall portion on the flow and thermal characteristics has been studied numerically. The frequency $\omega_{10} = 2\pi N/L$ is kept constant for all the cases by keeping number of cycle $N =$

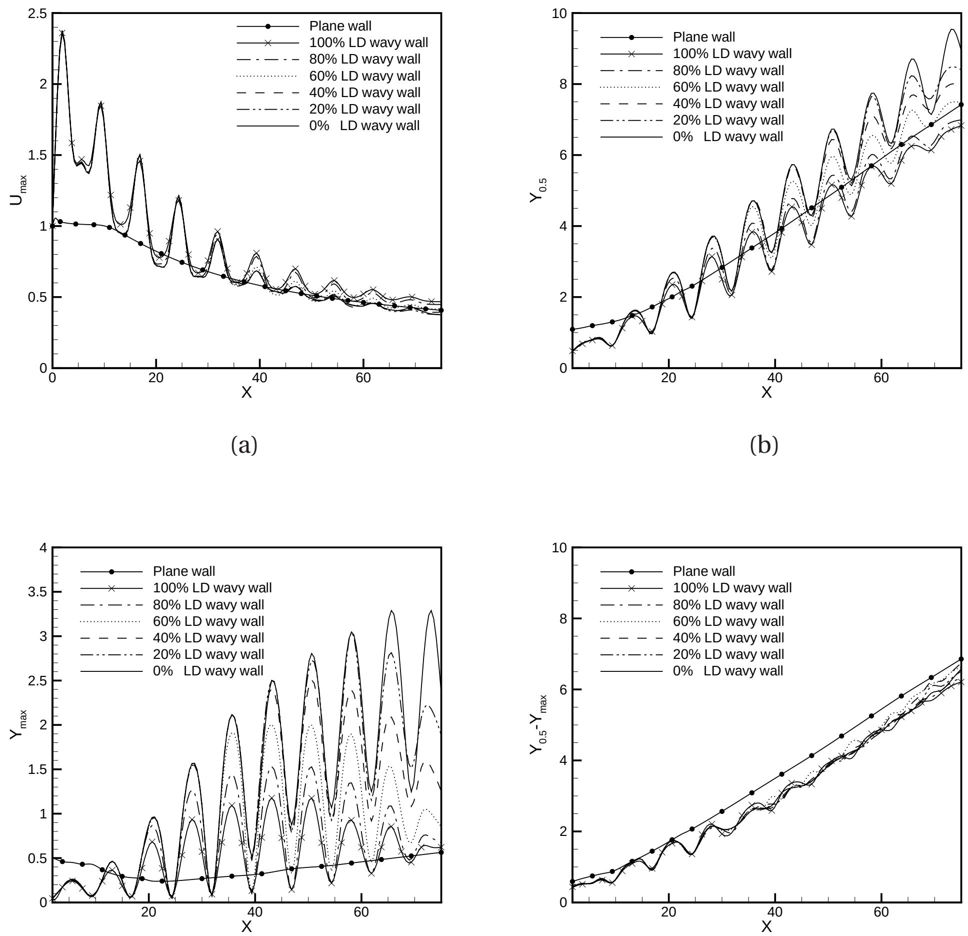
10 and length of wall $L = 75a$. In the case of 100% LD wavy wall, the amplitude is varied throughout the length and for 0% LD wavy wall, the amplitude is constant throughout the length. For 10% (1 cycle) LD wavy wall, the amplitude remains constant (0.8) for 90% of the wall followed by LD wavy wall in the remaining 10% of the wall. The equations used for different cases are mentioned in Chapter 3.

5.2.1 Result and discussion

5.2.1.1 Flow Development

The variation of the local maximum streamwise velocity U_{max} along the flow has been shown in fig. 5.13a for the different % of LD wavy wall and the plane wall. The potential core gets distorted in the case of wavy wall, which means that the transition zone starts from the beginning and intermixing of fluid is initiated between the upper shear layer and wall shear layer. The curvature of wavy wall from the leading edge to the first crest restricts the area of the jet flow. To satisfy the continuity, the velocity of the jet increases and becomes maximum at the first crest. When jet moves forward from crest to trough, the area of the jet flow increases, leading to a decrease in the jet velocity. This pattern of increase and decrease in velocity near the crest and trough locations persists throughout the wavy wall, but the intensity decreases as the fluid moves downstream. The decay in U_{max} is same for the portion of wavy wall with constant amplitude. In the portion of linearly varying amplitude, the decay of U_{max} is minimum for the 100% LD wavy wall, and the decay rate increases as the portion of LD wavy wall decreases. Because with the decrease of % of LD wavy wall, when fluid moves from crest to trough region, the conversion of the kinetic energy into pressure energy is higher due to a larger slope. Moreover, there is an increase in the total arc length as the % of LD wavy wall decreases. In the case of 100% LD wavy wall the jet has to effectively travel to 77.67a, which increases to 82.78a in the case of 0% LD (100% constant amplitude) wavy wall.

The growth of jet has been discussed with the help of jet half width $Y_{0.5}$. The jet half width is defined as the location normal to the wall where the streamwise velocity becomes half of the maximum streamwise velocity U_{max} at any particular location X. Fig. 5.13b shows the comparison of jet growth for the different % of LD wavy walls and plane wall along the downstream direction. In the case of wavy wall, the trend of $Y_{0.5}$ is also wavy for a cycle; the jet spread is minimum at the crest and maximum at the trough. In the near flow field $X \leq 11.25$, $Y_{0.5}$ remains the same and less than the corresponding value for the plane wall jet. To satisfy the continuity, the growth rate of jet decreases as the % of LD wavy wall increases. In the far field, the walls with 100% and 80% LD wavy wall have lesser jet



(a) (b) (c) (d)

Figure 5.13: (a)The decay of local maximum streamwise velocity(b) the growth of jet half width (c) the growth of inner shear layer and (d) the growth of outer shear layer, along the flow for different % of LD wavy wall and plane wall jet

growth in comparison to the plane wall jet. However, the wavy wall with a smaller portion of LD wavy wall has higher growth rate than the plane wall jet.

In fig.5.13c, the development of the inner shear layer has been explained with the help of Y_{max} in the downstream direction; Y_{max} is the wall normal distance where the local maximum streamwise velocity U_{max} is found. In the case of plane wall jet, Y_{max} is almost constant till the potential core and it reduces in the transition zone as the upper shear layer comes in contact with the inner shear layer. The entrainment from the top pushes the inner shear layer towards the bottom wall, but once the flow enters the developed zone, Y_{max} grows linearly. The pattern of inner shear layer is also wavy similar to the jet spread, with minima at the crest and maxima at the trough. The growth of inner shear layer decreases as the % of LD wavy wall increases from 0% to 100%. In the near flow field, when the jet comes in contact with the wavy wall the flow area of jet gets restricted in crest region, which accelerates the fluid and the thickness of inner shear layer decreases. In the case of 0% LD wavy wall, the inner shear layer grows throughout the wall and the growth rate at the trough is higher than the growth rate at the crest.

The growth of the outer shear layer $(Y_{0.5} - Y_{max})$ for different % of LD wavy wall jets and the plane wall jet has been shown in fig. 5.13d. For the plane wall jet, the growth of the outer shear layer is almost linear in the developed zone. In comparison to the plane wall jet, the growth of outer shear layer remains less throughout the flow domain, for all the wavy wall cases. And the influence of % LD wavy wall on the growth of outer shear layer is insignificant.

5.2.1.2 Entrainment of ambient fluid

The growth of volume flow rate Q due to the entrainment of surrounding fluid has been shown in fig. 5.14 for different % of LD wavy walls and it is compared with the case of plane wall jet. Here, the volume flow rate is calculated by using $Q = \Delta_0^\infty \rho u dy$, and it is normalized by the volume flow rate at the inlet of the nozzle Q_0. The velocity discontinuity of the jet with the surrounding fluid and the momentum of jet at the exit of nozzle are the two factors responsible for the entrainment of ambient fluid. The growth of volume flow rate in the downstream direction is almost linear in all the cases of wavy wall and the plane wall jet. The growth of volume flow rate is higher in the case of wavy wall and the wavy wall with 100% LD wavy wall is having highest volume flow rate. In the case of 100% LD wavy wall, the entrainment of ambient fluid is 6.13% higher than the entrainment in plane wall jet. The U_{max}, in the case of 100% LD wavy wall, is the highest among all the cases due to which the discontinuity between the jet and the surrounding fluid is more. So, the entrainment is also maximum.

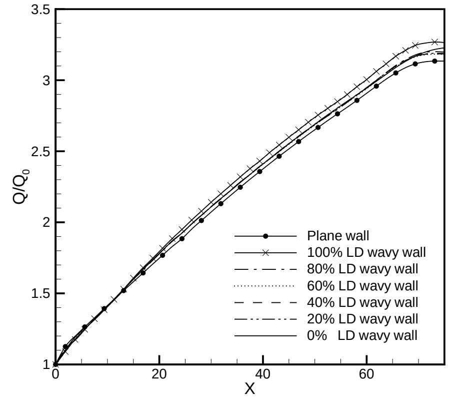


Figure 5.14: The variation of volume flow rate for different % of LD wavy walls and the plane wall.

5.2.1.3 Reynolds stresses

The distribution of Reynolds stresses, <u’u’>, <v’v’> and <u’v’> in the cross-stream direction has been illustrated in fig. 5.15. The Reynolds stresses at the 6th and 8th crests (X = 39.375 and X = 54.375) and troughs (X = 43.125 and X = 58.125) have been plotted for 100%, 50% and 0% LD wavy wall for the discussion. It can be observed from the figures that Reynolds stresses decrease as the fluid moves forward, in all the cases. The peaks of Reynolds stresses at the trough location shift upward as the % of LD wavy wall decreases. This might be due to increase in the cross-stream area at the trough location. There are two peaks in the profile of Reynolds normal stresses, <u’u’> and <v’v’>, one in the inner shear layer, with a lesser value and the second one in the outer shear layer with a higher value. In between the two peaks, the value is minimum at the location of maximum streamwise velocity, as the velocity gradient is minimum at this position. Whereas, the X Reynolds stress remains negative near the wall and becomes positive in the outer shear layer. The magnitude of negative shear stress is more in the trough location for <u’u’> and <u’v’>. The value of stresses decreases as the % of LD wavy wall decreases. The 100% LD wavy wall shows a higher value of <u’u’>, <v’v’>, and <u’v’> at all the locations because of higher turbulence.

5.2.1.4 Turbulent kinetic energy

In fig. 5.16, the variation of turbulent kinetic energy in the cross-stream direction has been shown. The TKE has been compared for 100%, 50% and 0% LD wavy walls at the 6th and 8th crests (X = 39.375 and X = 54.375) and troughs (X = 43.125 and X = 58.125).

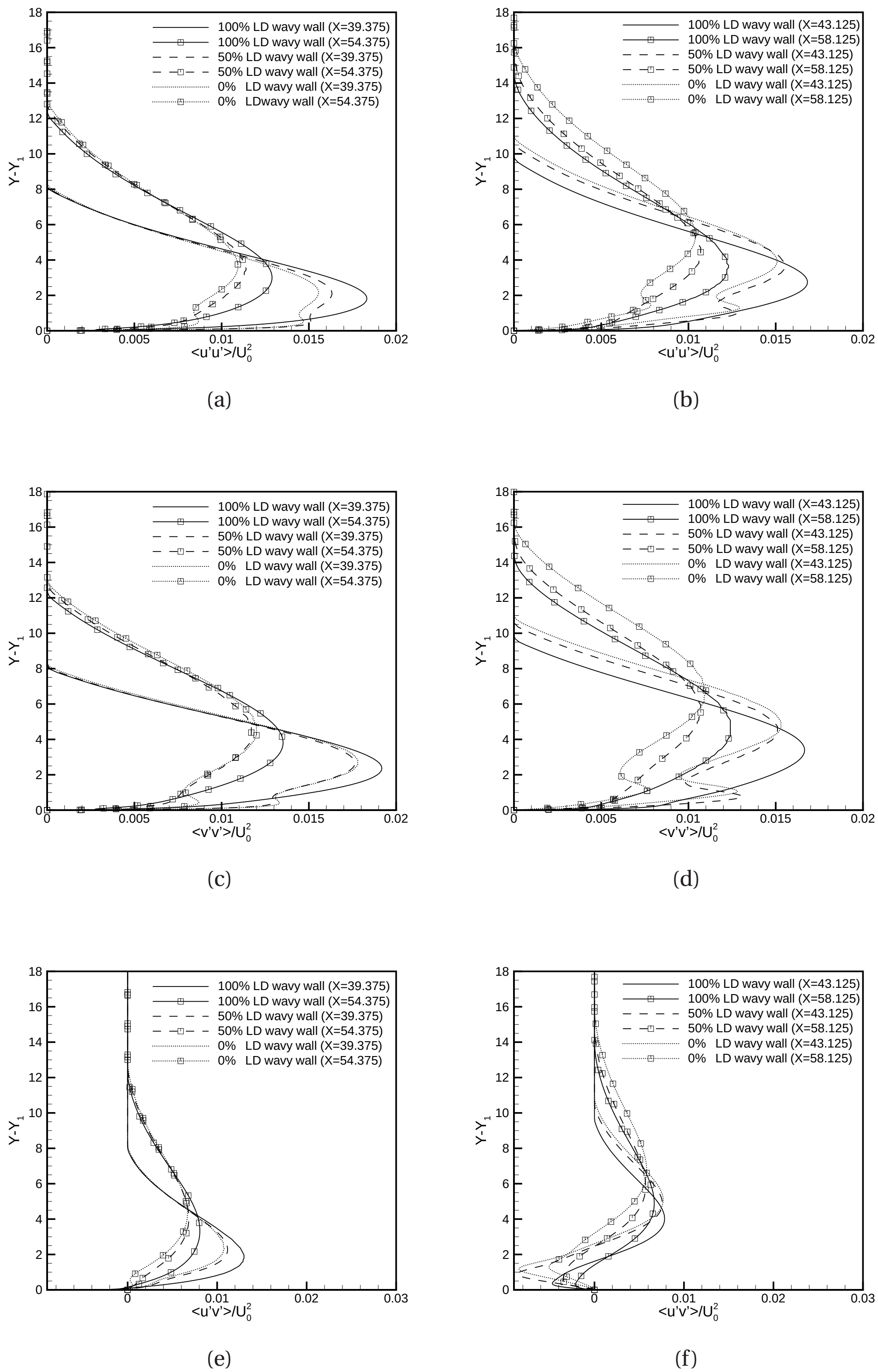
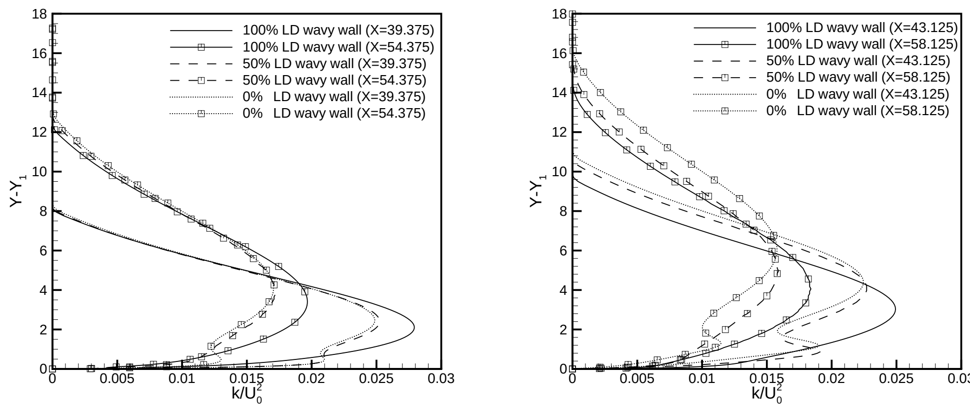


Figure 5.15: The cross-stream distribution of X normal Reynolds stress at (a) crest and (b) trough, Y normal Reynolds stress at (c) crest and (d) trough, and Reynolds shear stress at (e) crest (f) trough.



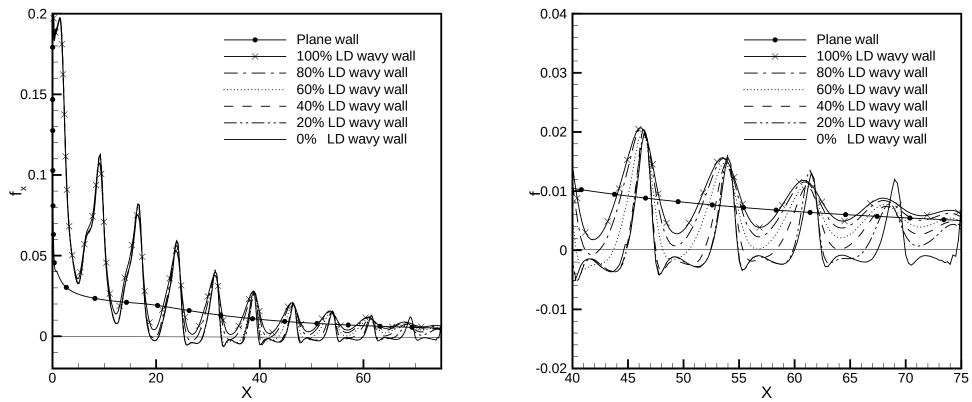
(a) (b)

Figure 5.16: The cross-stream distribution of turbulent kinetic energy at (a) crest and (b) trough

Similar to the Reynolds normal stresses, the TKE profile also has two peaks: the first and the smaller one is near the wall in inner shear layer and the second and bigger one is in the outer shear layer. In all the three cases of LD wavy wall, the TKE decreases as fluid moves forward in the downstream direction. At a fixed location, the turbulent kinetic energy in the outer shear layer is maximum for the 100% LD wavy wall due to the high entrainment of ambient fluid, and for 50% and 0% of LD wavy wall, a very small difference is noticed. The second peak in the inner shear layer becomes shallow and moves closer to the wall in the case of 100% LD wavy wall. In the case of 100% LD wavy wall, the amplitude is decreasing continuously from the beginning, leading to a relatively smooth surface in comparison to the 50% and 0% LD wavy wall. That is why in the inner shear layer, the turbulence grows gradually and remains less than that in the other cases.

5.2.1.5 Friction factor coefficient

The distribution of wall friction factor coefficient has been shown in fig. 5.17a for different % of LD wavy walls and the plane wall jet. The f_x is maximum at the beginning when jet comes in contact with the wall, as the streamwise velocity gradient is very high. In the case of plane wall jet, the f_x decreases very fast in near flow field $X \leq 5$ and beyond this, the decay of f_x slows down and becomes linear. In the wavy wall case, f_x is higher near the crest location and lower near the trough location for every cycle. Because at the crest, the streamwise velocity is high which gives rise to a higher velocity gradient du/dy. In the trough region, f_x decreases with increase in the % of LD wavy wall, in the LD portion.



(a) (b)

Figure 5.17: The variation of wall friction factor coefficient for the different % of LD wavy wall cases and plane wall jet

Whereas in the crest location, f_x remains almost same for all the cases. The zoomed view of the variation of f_x in the far field location, i.e. $X \geq 40$ has been shown in fig. 5.17b. The trend of f_x also tells about the separation and re-circulation zones. When f_x crosses the zero line and goes to negative value, the flow gets separated and the region where f_x remains negative is the region of re-circulation. From fig. 5.17a, it can be observed that in the case of 100% LD wavy wall, the jet remains attached throughout the wall similar to the case of a plane wall jet. The re-circulation occurs in 80% LD wavy wall and it increases as the % of LD wavy wall decreases. For the 0% LD wavy wall, 45.7% of the total wall experiences re-circulation. When fluid moves from crest to trough, some of the kinetic energy is converted to pressure energy and adverse pressure gradient ($dp/dx \geq 0$) is generated, which gives favorable conditions for the separation. In the case of higher percentage of LD wavy wall, the amplitude of wavy wall is reduced continuously along the downstream location, which also reduces the adverse pressure gradient ($dp/dx \geq 0$) responsible for the separation. The % increment in the average friction factor with respect to the plane wall jet for different % of LD wavy walls has been shown in fig. 5.18. It can be seen that the wall friction factor is maximum for the 100% LD wavy wall which is 81.2% more than the value obtained in the case of plane wall jet, and it reduces as the % of LD wavy wall reduces.

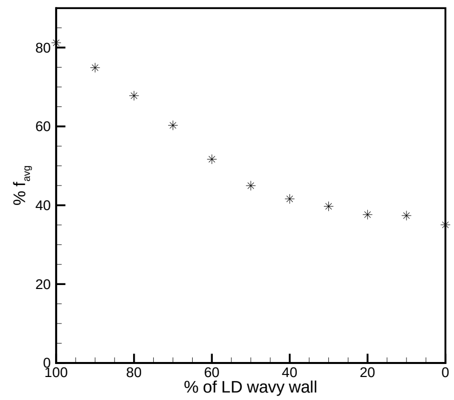
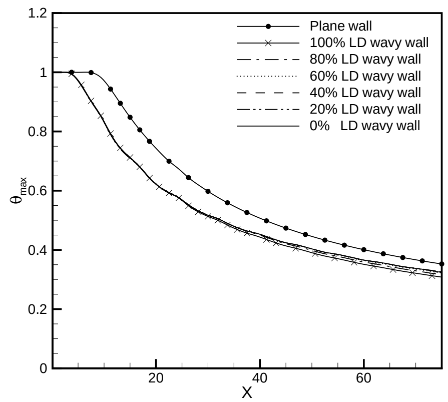


Figure 5.18: The % increment in the average wall friction factor with respect to the plane wall jet, for different % LD wavy walls

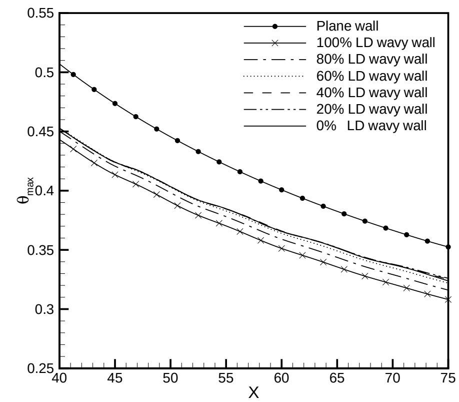
5.2.1.6 Thermal development

The thermal development of jet on LD wavy wall has been discussed with the help of normalized local maximum temperature θ_{max}, thermal jet half width $Y_{T0.5}$ and Y_{Tmax} as shown in fig. 5.19. The decay of θ_{max} for different % of LD wavy walls and the plane wall has been illustrated in fig. 5.19a. For LD wavy walls, the thermal potential core reduces by about 50% of the thermal potential core in the plane wall jet. In the case of wavy wall, the velocity potential core is distorted from the beginning due to which the jet is in the transition zone from the starting, where the intermixing of fluid within the jet is high. Because of this, the colder stream of jet in the outer region mixes thoroughly with the hot jet and the thermal potential core is exhausted early. The thermal decay rate of jet is also higher in the case of LD wavy wall jet. There is almost negligible influence of the % of LD wavy wall on the length of thermal potential core and the thermal decay of jet in near flow field. However, the thermal decay rate of jet is higher for the higher % (80% and 100%) of LD wavy wall in the far field as shown in the fig. 5.19b. In the far field, U_{max} is higher for the higher % of LD wavy wall which increases the transfer of heat from the bottom wall and consequently θ_{max} decreases.

The growth of thermal spread of jet for wavy wall with different % of LD wavy walls and the plane wall has been shown in fig. 5.19c. In the beginning, the thermal growth of jet remains almost same for all the wavy wall cases, but as the fluid moves forward, $Y_{T0.5}$ starts reducing for the wavy wall with higher % of LD wavy wall. The thermal spread of jet is minimum for the 100% LD wavy wall, similar to the velocity spread of the jet as shown in fig. 5.13b. In the case of 100% LD wavy wall, the thermal growth of jet is 11.9% less in comparison to the plane wall jet. The development of Y_{Tmax} as fluid moves forward has



(a)



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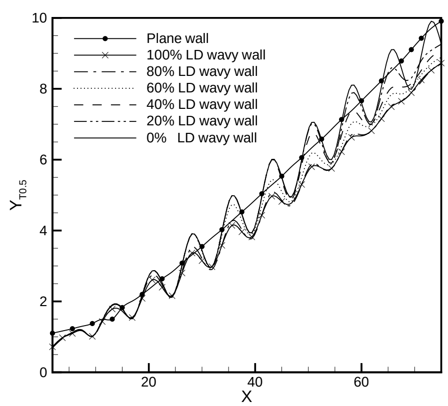

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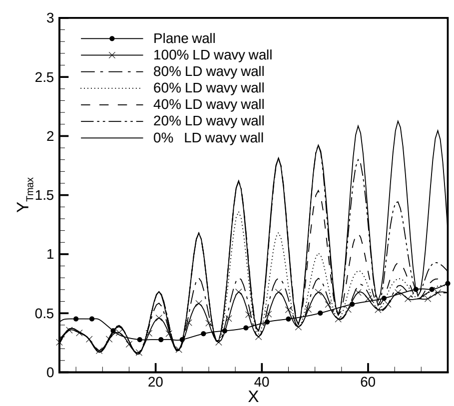
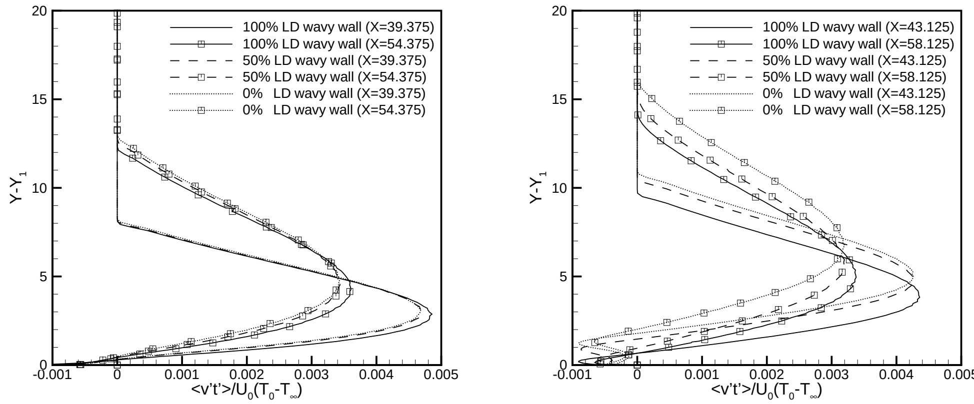


(d)

Figure 5.19: (a)The decay of local maximum temperature (b) Zoomed view of the decay of local maximum temperature in far flow field (c) the growth of thermal spread of jet and (d) the growth of thermal wall boundary layer along the flow, for different % of LD wavy walls and plane wall jet



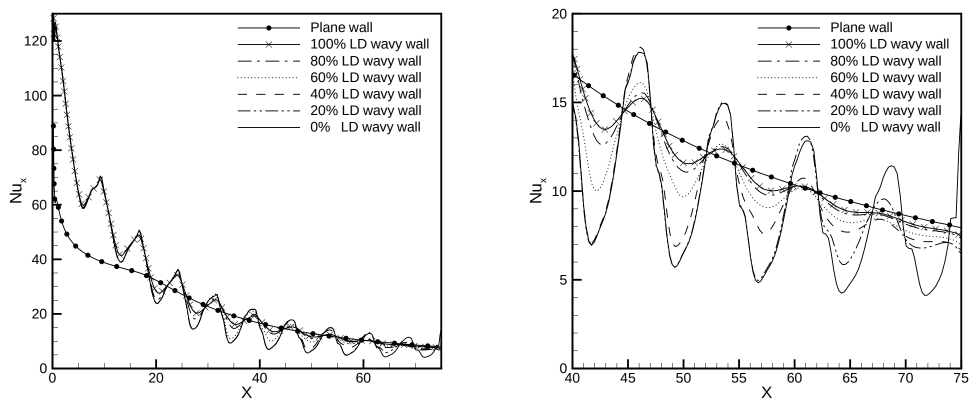
(a) (b)

Figure 5.20: The cross-stream distribution of turbulent heat flux at (a) crest and (b) trough

been shown in fig. 5.19d for different % of LD wavy walls and the plane wall jet. In the near flow field till $X = 11.125$, Y_{Tmax} remains same for all the wavy wall cases which is less than the value obtained for the plane wall jet. As the fluid moves forward, Y_{Tmax} remains same for all the % of LD wavy walls, near the crest location. However, in the trough region, the growth of Y_{Tmax} reduces as the % of LD wavy wall increases.

5.2.1.7 Turbulent heat flux

Fig. 5.20 shows profile of cross-stream turbulent heat flux <v't'> along the cross stream direction at the 6th and 8th crests ($X = 39.375$ and $X = 54.375$) and troughs ($X = 43.125$ and $X = 58.125$) for 100%, 50% and 0% LD wavy walls. The cross-stream turbulent heat flux <v't'> is calculated by using the formula <v't'> = $-(\nu_t/pr_t)(dt/dx_i)$, where ν_t is the turbulent viscosity and pr_t is the turbulent Prandtl number and it is normalized by the inlet parameter $(U_0(T_0 - T_\infty))$. The <v't'> remains negative near the wall ($Y \leq Y_{Tmax}$), because in this region the temperature gradient dt/dy is positive. For the flow above Y_{Tmax}, the <v't'> becomes positive as the temperature gradient dt/dy is negative. From fig. 5.20, it can be seen that for a given location the turbulent heat flux <v't'> is maximum for 100% LD wavy wall. In the case of 50% and 0% LD wavy walls, the results are almost same because the thermal decay of jet is also same for 0% to 60% of LD wavy wall. For a given case, the turbulent heat flux <v't'> reduces as fluid moves forward at the crest as well as at the trough. This is due to increase in the jet spread when the fluid moves in the downstream direction.



(a) (b)

Figure 5.21: The variation of local Nusselt number for different % of LD wavy wall cases and plane wall jet

5.2.1.8 Nusselt Number

The variation of local Nusselt number Nu_x for different % of LD wavy wall cases and the plane wall jet is shown in fig. 5.21. The Nu_x remains same for all the wavy wall cases in the near flow field till $X = 12$, which is relatively higher than the plane wall jet because of the high intermixing of fluid in the case of wavy wall. As the fluid moves further in the downstream location, Nu_x increases with increase in the % of LD wavy wall in the trough location, because the thermal boundary layer reduces (fig. 5.19d) and the formation of recirculation zone also gets reduced. The overall increment in the heat transfer rate with respect to the plane wall jet has been shown in fig. 5.22, where $\% Nu_{avg} = [(Nu_{avg}/Nu_{avg0})] \times 100$ and the Nu_{avg0} is the average Nusselt number for the plane wall jet. The 100% LD wavy wall is having the maximum increment in the heat transfer, which is 27.9% higher than the plane wall jet. The increment in the average Nusselt number decreases as the % of LD wavy wall decreases. In the case of 0% LD wavy wall (constant amplitude throughout), which has been previously studied by Kumari and Kumar [56], there was an increment of 18.8% in the average Nusselt number. This suggests that the modified wavy wall with LD wavy wall gives better result for heat transfer in comparison to the wavy wall with a constant amplitude throughout.

5.2.1.9 Thermal hydraulic performance (THP)

From the above discussion, it is clear that the average Nusselt number increases with the increase in the portion of LD wavy wall and that is the main motive of the present work.

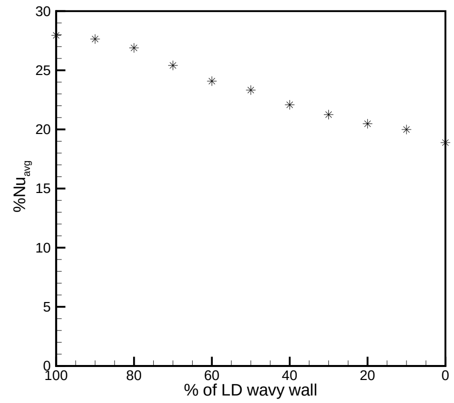


Figure 5.22: The % increment in the average Nusselt number with respect to the plane wall jet, for different % LD wavy walls

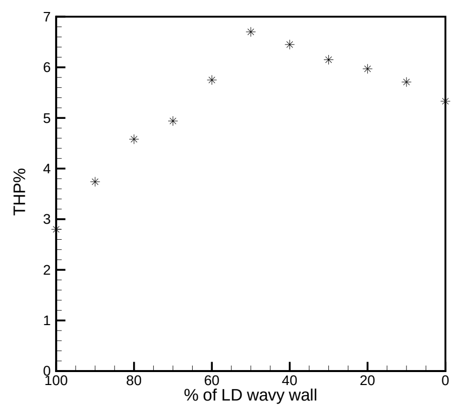


Figure 5.23: The thermal hydraulic performance for different % LD wavy walls

But, along with the average Nusselt number, the wall friction factor also increases with the increase in the % of LD wavy wall leading to increase in the losses. To come up with the best outcome by considering the heat transfer and friction losses together, the thermal hydraulic performance (THP) has been calculated. Fig. 5.23 shows the THP for different portions of LD wavy wall. The maximum increment of THP with respect to the plane wall jet is 6.7%; it is noticed for the 50% of the LD wavy wall. In the case of wavy wall with a constant amplitude throughout (0% LD wavy wall), there is a maximum increment of 5.3% in THP [56]. This shows that after considering the losses, 50% LD wavy wall performance is better than the wavy wall with a constant amplitude throughout.

5.3 Conclusion

The following conclusions are drawn from the discussion of different flow and thermal characteristics of turbulent jet on partial wavy wall.

- In the case of velocity profile in plane wall region, there is a delay in the formation of developed zone for 0.8 amplitude in comparison to the 0.4 amplitude, for a given % of partial wavy wall.
- In the case of temperature profile, the similar behaviour is noticed near the wall only, i.e. $Y \leq Y_{T0.5}$. This indicates that the flow is not thermally developed in the outer shear layer, in the plane wall region of the partial wavy wall.
- In the plane wall region of the wavy wall, the local maximum streamwise velocity U_{max} is maximum for 10% wavy wall and it reduces further as the % of wavy portion increases indicating that the turbulence of jet is also maximum for 10 % wavy wall and it reduces further, on increasing the % of wavy wall.When the fluid moves from wavy to plane wall region, the fluid enters into the transition zone before getting developed because Y_{max} falls in that region which is similar to the trend of Y_{max} in the transition zone of fully plane wall case.
- The entrainment of surrounding fluid in jet flow is maximum in the case of 20% wavy wall portion for both 0.4 and 0.8 amplitudes. And, the entrainment of ambient fluid decreases as the % of partial wavy wall increases.
- The partial wavy walls have almost similar θ_{max} decay profile for the same amplitude. But in comparison to the plane wall jet, the local maximum temperature decays at a higher rate in the case of partial wavy wall. Moreover, the thermal potential core vanishes early, i.e. it reduces by 16% and 50% for 0.4 and 0.8, respectively with respect to the plane wall jet.
- The maximum heat transfer is observed for 30% wavy wall with amplitude 0.8, which is 26.27% higher than the fully plane wall jet. It starts reducing with the increase in the % wavy wall portion as the re-circulation zone increases drastically thereafter.
- The THP increases with the increasing wavy wall portion for 0.2 and 0.4 amplitudes. In the case of 0.2 amplitude, the THP remains less than 1, which makes it unsuitable for heat transfer enhancement. The maximum THP is 5.3% for 0.8 amplitude and 70% of wavy wall and it remains constant thereafter with increase in the wavy wall portion.

The following conclusions are drawn from the discussion of different flow and thermal characteristics of turbulent jet on partially linearly decaying wavy wall.

- In the downstream location, the decay of U_{max} reduces as the % of LD wavy wall increases and it is minimum for the case of 100% LD wavy wall. The growth of jet spread and the growth of inner shear layer are also minimum in the case of 100% LD wavy wall.
- The entrainment of ambient fluid is maximum in the case of 100% LD wavy wall, which is 6.3% higher in comparison to the plane wall jet. Other than this case, the entrainment remains almost the same and relatively higher than the plane wall jet.
- At a given location, in the region of LD wavy wall, the Reynolds stresses and heat flux increase with the increasing % of LD wavy wall.
- The thermal potential core remains the same for all the wavy wall cases which is 50% less than the case of plane wall. The thermal decay rate of jet is higher for the higher % of LD wavy wall in the far field.
- Similar to the velocity spread and the growth of inner shear layer of jet, the thermal spread and growth of Y_{Tmax} of jet also reduce with the increase in the % of LD wavy wall. In the case of 100% LD wavy wall, the thermal spread of jet is 11.9% less than that obtained in the case of plane wall jet.
- The average wall friction factor is maximum for 100% LD wavy wall and it reduces as the % of LD wavy wall portion reduces. But for all the cases, it remains higher than the plane wall jet.
- There is an increment of 27.9% in the heat transfer rate for the wavy wall with 100% LD wavy wall in comparison to the plane wall jet which is higher than the previous study on a fully wavy wall jet.
- By considering the losses, wavy wall with 50% LD wavy wall gives the best THP among all the cases, which is 6.7%.