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Novel Method to Improve Heat Transfer Rate Through Delta Swirl Tape for a Swirl Jet Impingement Study

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ABSTRACT

With advancement of electronic equipment's, there is a need to have an efficient method or mechanism that helps remove heat from the system. Air jet impingement is generally implied method for effective heat removal from these equipment's. There are several types of air jet impingement techniques used and among them swirl air jet is one of most prominent and proven method. In this study, a novel method is proposed to improve heat transfer of a swirling air jet impingement. Experimental study has been performed with swirl tape and novel delta tape having twist ratio (T.R) = 2 for jet to plate distance of z/d=2 to 8 and Re varying between 1500 to 9000. This study is basically carried out to improve the heat transfer at low Re conditions. Thermal imaging technique is used to derive centerline Nu values for different jet to plate distances (z/d=2 to 8). Study shows that novel delta tape adds significant improvement in heat transfer for above mentioned conditions.

1. INTRODUCTION

When we speak about jet impingement heat transfer, image that comes into mind is cooling techniques that gets used to achieve better heat transfer enhancement. These techniques include both passive and active method of cooling without affecting system performance. Most of application of these techniques involve gas turbine cooling, electronic component cooling, material processing etc. Thus, jet impingement plays important role in all sectors of industrial application and most importantly help achieve efficient heat dissipation products.

References [1-11] explains out various methods and parameters that determine heat transfer enhancement. These parameters include Reynolds number (Re), jet exit to plate distance (z/d), jet type, target plate surface type, Prandtl number, inclination of target plate, type of nozzle, cross flow etc. Better way to improve heat transfer is by increasing turbulence intensity of flow. The studies [12, 13] explain out this method of increasing turbulence intensity from swirling flow achieved by swirl tape when compared to a conventional jet impingement method. Gupta et al. [14] have explained importance and significance of spiral motion to achieve better heat transfer rate in their study. Uniformity of flow is key parameter for heat transfer enhancement. This can be achieved through swirling flow is explained by Huang and El-Genk [15]. Experimental investigation was conducted by Kumar et al. [16] who showed that heat transfer initially increased with the increase in twist ratio (2 to 4.5) and there after reduced with the increase in the twist ratio (4.5 to 7.5). Heat transfer rate was maximum at z/d = 1 for all twist ratios and Reynolds number.

Following below points list out summary of literature work conducted:

- Literature points out one main factor about heat transfer enhancement which is achieved by use of swirling mechanism experimentally.
- It is also seen that increasing turbulence intensity of flow improves heat transfer. Basically, turbulence intensity of flow is dependent on amount of swirl generation which in turn improves heat transfer. Thus, swirl generation plays important role in increase in turbulence intensity.
- One more very important factor in heat transfer enhancement is uniformity of impingement. More the flow uniformly impinges on target plate better is heat transfer enhancement.
- It is important to note that Twist ratio of swirler used in experiment plays important role in heat transfer enhancement. Smaller the twist ratio better the heat transfer enhancement.

Motive behind present work is to point out that, swirl generation technique used in literature can be more effectively modified to further improve the heat transfer. Hence a unique methodology is established in this study that showcases better improvement in turbulence intensity thus yielding better heat transfer enhancement.

Present work focuses on Re which varies between Re=1500 to 9000. Swirl jet impingement on flat plate experiments is performed at above mentioned Re by varying the jet to plate distance (z/d) using twisted tape of twist ratio of T. R=2. In present work a novel swirl generating method is established using a delta twisted tape of T. R=2 and Nu distribution on flat plate is derived using thermal image technique. Results got are compared with results of traditional swirl jet impingement. Overall objective of the present work is to showcase following:

- Heat transfer enhancement for a swirl jet impingement using delta twisted tape.
- Heat transfer results are derived using thermal image technique and centerline Nu are plotted for Re varying between 1500 to 9000.

- Comparison of results of novel swirl method is done with the traditional swirl generation thus showcasing the effectiveness of heat transfer enhancement.

Overall structure of this work is explained below:

- Present work uses delta swirl tape (existing swirl is modified to achieve better turbulence intensity) into the nozzle through which air jet impinges on to the heated flat plate.
- Experiments are performed for flow Re varying between 1500 to 9000 for z/d=2 to 8. Using thermal imaging technique, it is shown that delta swirl tape improves heat transfer compared to conventional swirl generation technique by almost up to 25%.

2. EXPERIMENTAL SETUP

Figure 1 shows experimental setup used to generate swirl flow. Most of components of this setup remain same as already explained in literature [17] apart from the pulse generation unit. This jet impingement circuit consists of a compressor attached to a pipe through which air is blown at some specified speed controlled by a valve attachment. A circular nozzle of diameter is attached to other end of pipe and flow is made to impinge on target plate through this nozzle. Jet air flow rate is measured using a digital Testo smart hotwire anemometer [17-19]. Hot wire anemometer used in the experiment is shown in Figure 2.

Figure 3 shows methodology adopted to measure the air flow from the jet. Flow and Reynolds number calculations are explained by the literature [17-19]. Same methodology is adopted in present work too.

Most of experimental methods use U-tube manometer technique to measure the flow through use of some theoretical correlations. However, possibility of losses due to leakages is higher in this method which would end up with higher uncertainties in flow measurement and Re. Hence to reduce the uncertainties and have better accuracy, hot wire anemometer is used in present experiments.

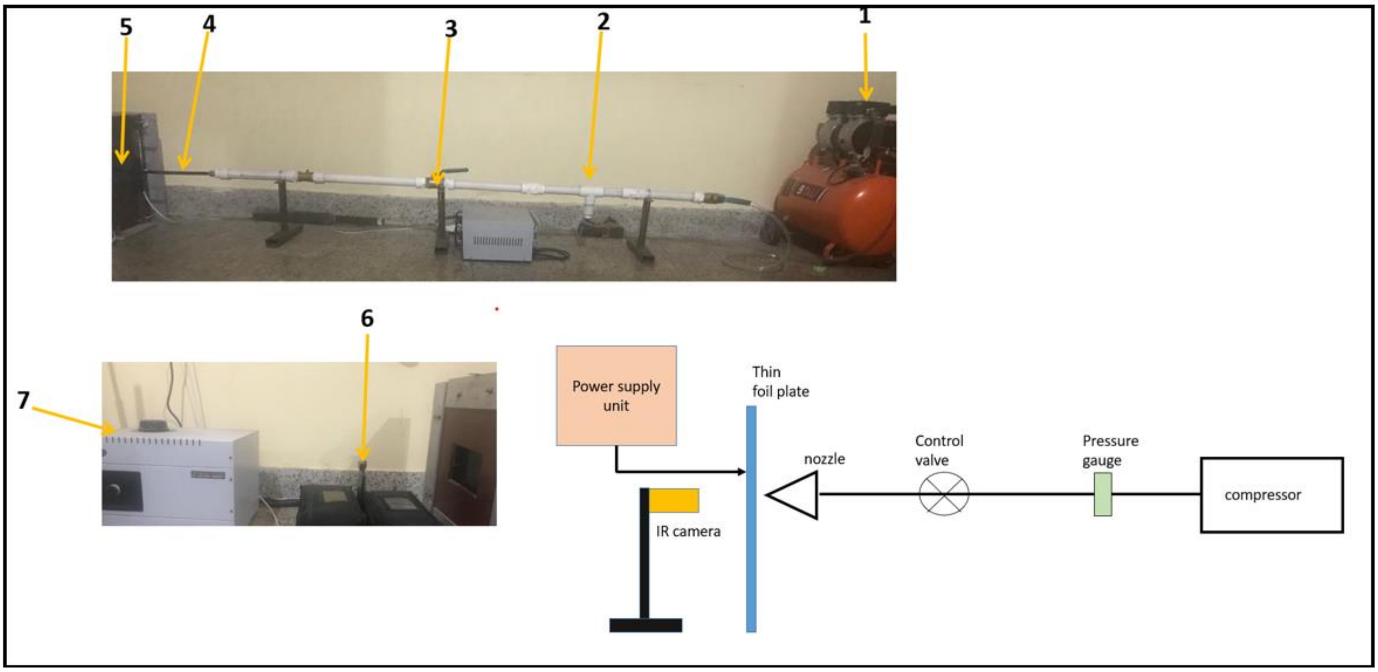

Figure 1. Actual setup and schematic diagram of experimental setup (1-Compressor; 2-Pressure Gauge; 3-control valve; 4-Nozzle; 5-Thin foil plate; 6-IR camera; 7- Power supply unit)

Figure 2. Testo hot wire anemometer probe

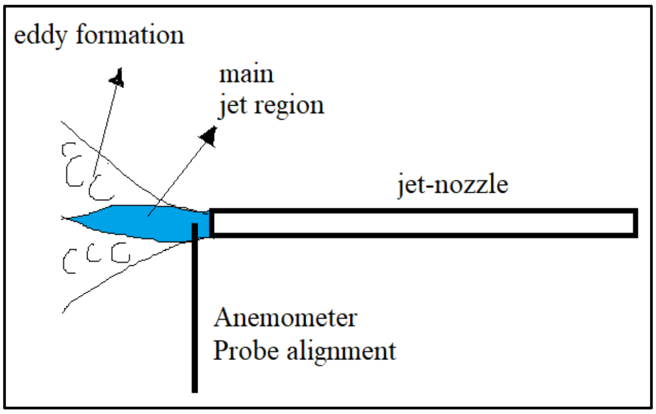

Figure 3. Probe position and alignment in jet flow

It is worth noting that accuracy of hotwire anemometer is in the range of +/- 0.5%. Once the flow is set for a particular Reynold number anemometer is removed and heat transfer readings are taken on surface area of interest.

Heat transfer measurement methodology used in this study is explained in literature [17]. Stainless steel plate of 0.06 mm thickness and dimension 215 mm x 145 mm is used in present work for heat transfer studies.

For swirl generation, twisted tapes made from brass material is inserted into the nozzle. Length of these tapes are 650 mm, diameter 10 mm and thickness of 0.9 mm respectively. A non-dimensional number called as twist ratio (T.R) is defined as:

$$T.R = \frac{\text{tape pitch}}{\text{tape width}} \tag{1}$$

Twisted tape is manufactured by fixing one end of the tape to lathe machine, while another end is slowly rotated at a fixed axis. It is made sure that distance between two points on twisted tape after 180 deg rotation defines the pitch (p) of the tape. We represent “p” and “w” as pitch and width of the tape which is shown in Figure 4. In present work, heat transfer measurements are done using twisted tape with twist ratio (T.R) of 2 as shown in Figure 5.

An IR camera is placed behind the target plate on to which jet impingement happens. IR camera used in this study is FLIR-C3. IR camera captures the thermal images of jet impingement. Thermal images show the temperature distribution of plate at that instant of time. As the thickness of plate is 0.06 mm temperature measured at the back face and front face are merely same and hence IR methodology of temperature measurement depict the actual behavior of temperature variation across the plate with minimal error. Black Matte Finish Asian paint with 0.99 emissivity is used to paint the plate surface. It is worthwhile to note that IR technology used in temperature measurement is more accurate than temperature measurement by thermal sensors.

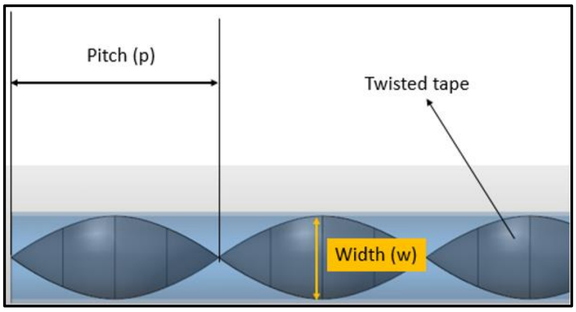

Figure 4. Twisted tape in the nozzle

Figure 5. Twisted tape with T.R=2

With the help of literature [20] it is found that uncertainty of parameters measured in this experiment lie between 3-4% for present work.

3. RESULTS AND DISCUSSION

3.1 Experimental validation

Centerline Nu distribution for Re=1500, p/w = 2 & z/d=1 is obtained for a swirling jet flow on target plate is compared with results obtained by Kumar et al. [16] as shown in Figure 6 present results show good agreement with literature. Stagnation Nu vary by 4% compared to results of Kumar et al. [16].

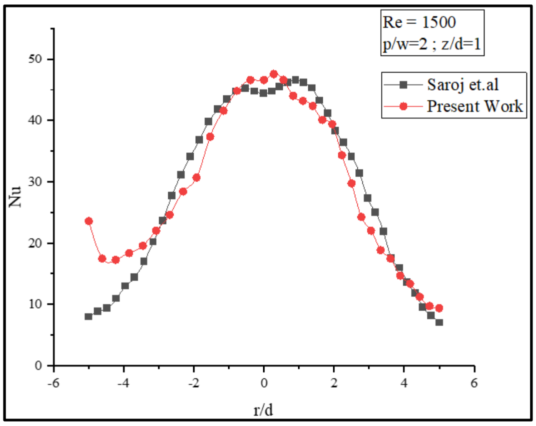

Figure 6. Experimental validation study

3.2 Traditional swirl generation using twisted tape

This section discusses results got using traditional approach of swirl generation for twisted tape of T.R=2. Reynolds number for this study is varied between 1500 to 9000. Jet to plate distance is varied between 2 to 8 for all the cases very similar to the distance that was adopted in literature [17]. Figure 7 shows centerline Nu distribution across the plate for above mentioned condition.

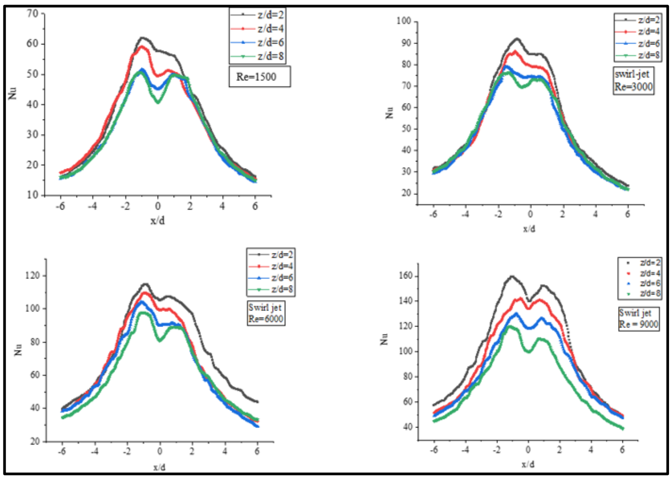

Figure 7. Centerline Nu distribution

Following observation are highlighted from above study:

- Jet to plate distance z/d=2 shows more heat transfer compared to z/d = 4 to 8.
- As z/d increases heat transfer effectiveness decreases.
- Shift of peak Nu is seen in all the case with sudden decrease in Nu in the stagnation region.

Figures 8-11 show contour plot of Nu generated on target plate. For z/d = 2,4,6,8 and Re varying between 1500 to 9000.

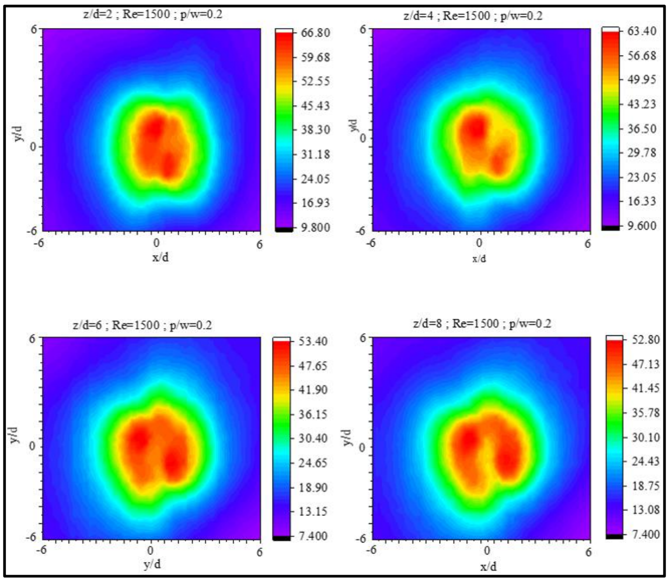

Figure 8. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=1500

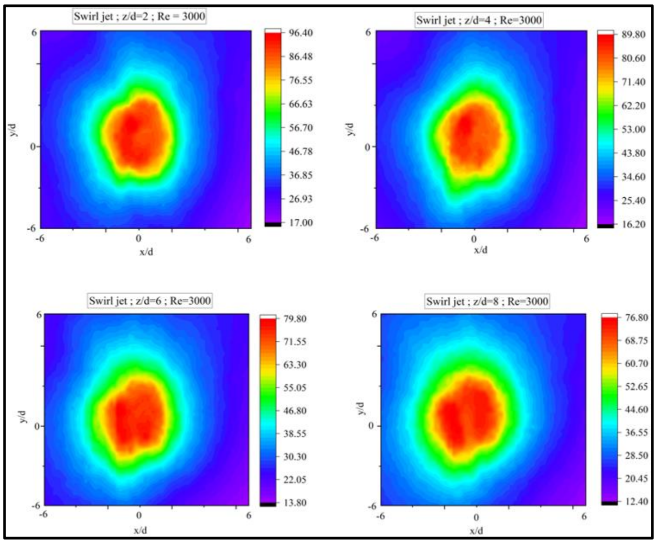

Figure 9. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=3000

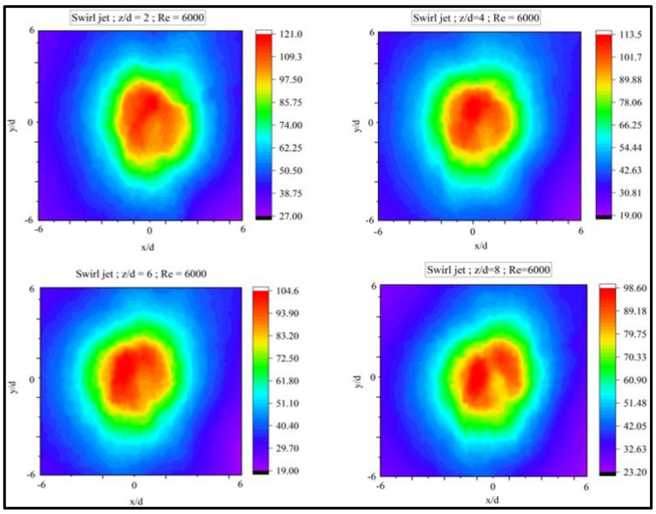

Figure 10. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=6000

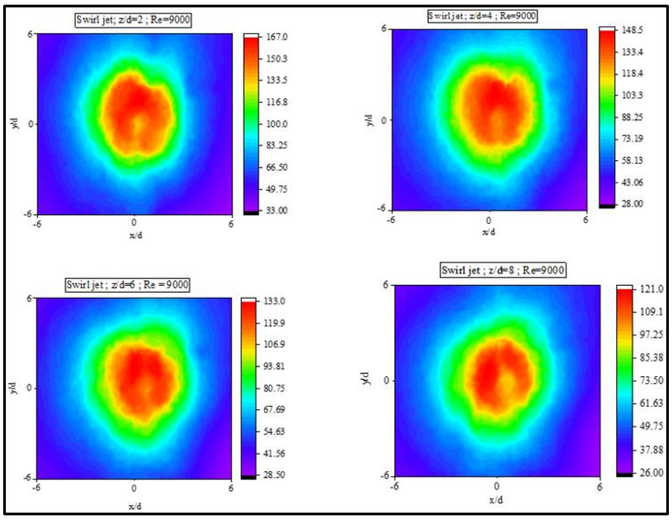

Figure 11. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=9000

It is clear from contour plots that due to presence of swirl tape; peak Nu is seen to be shifted axially. We observe a drop in Nu at center of plate, that is due to stagnation region development. The flow gets distributed into two lumps of fluid with formation of stagnation region at the center. Thus, we see sudden dip in centerline Nu at stagnation region.

4. USE OF DELTA TAPE TO IMPROVE HEAT TRANSFER

This method uses a delta tape as shown in Figure 12 with T.R = 2.

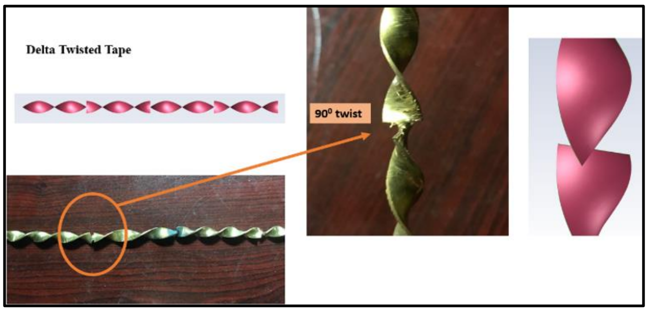

Figure 12. Delta Twisted tape

The main principle behind adopting this method is that, swirling flow gets detached due to sudden change in angle of twist. This leads to increase in turbulent intensity of flow thus resulting in increase in heat transfer.

Above conducted experiments are repeated with this approach and results got are compared with the traditional swirl approach. Section below explains the comparison.

4.1 Traditional swirl versus Delta swirl results comparison

Figures 13-16 show centerline distribution of Nu comparison for traditional twisted tape swirl versus delta twisted tape for z/d=2 to 8 and Re=1500 to 9000.

It is evident from comparison that, delta swirl tape is more effective and results in higher heat transfer enhancement over all range of Reynolds numbers that are studied in present work and jet to plate distance.

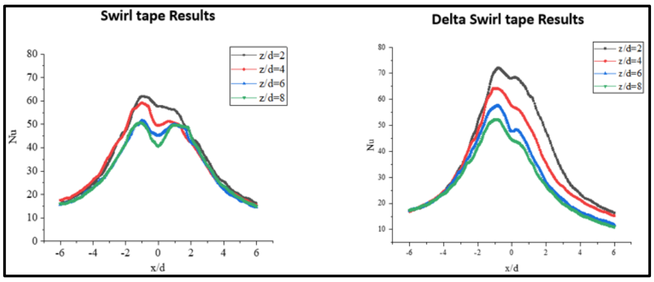

Figure 13. Centerline Nu distribution comparison for z/d=2 to 8 and Re=1500

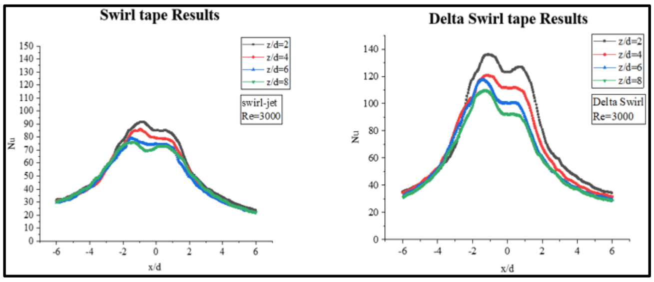

Figure 14. Centerline Nu distribution comparison for z/d=2 to 8 and Re=3000

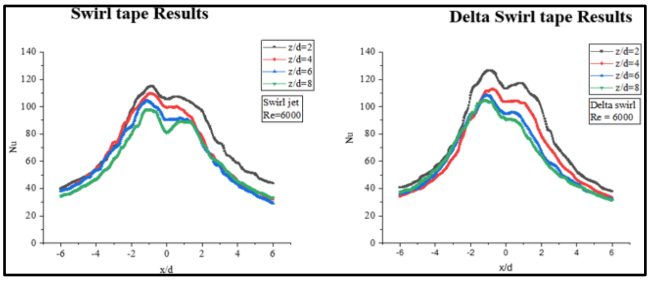

Figure 15. Centerline Nu distribution comparison for z/d=2 to 8 and Re=6000

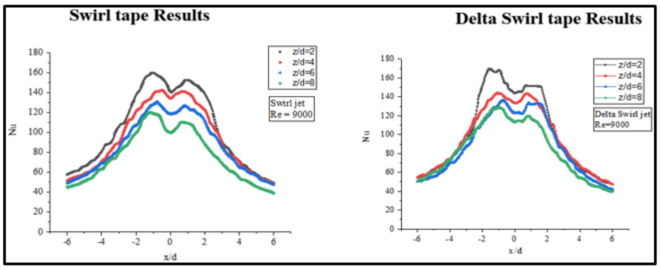

Figure 16. Centerline Nu distribution comparison for z/d=2 to 8 and Re=9000

Figures 17-20 show contour plot Nu distribution across the test plate for above mentioned conditions.

Following observation can be made from above contour plots:

- Delta tape has a 90 deg twist which increases the turbulence when primary swirl flow comes in contact with it. There is a shift in peak Nu observed in contour plots. This peak Nu is primarily more towards the area where there is mixing of swirl flow and secondary flow generated due to twist in delta tape.
- As jet to plate distance increases, we observe effect of secondary flow gets nullified and hence Nu shift is observed in a symmetric manner.

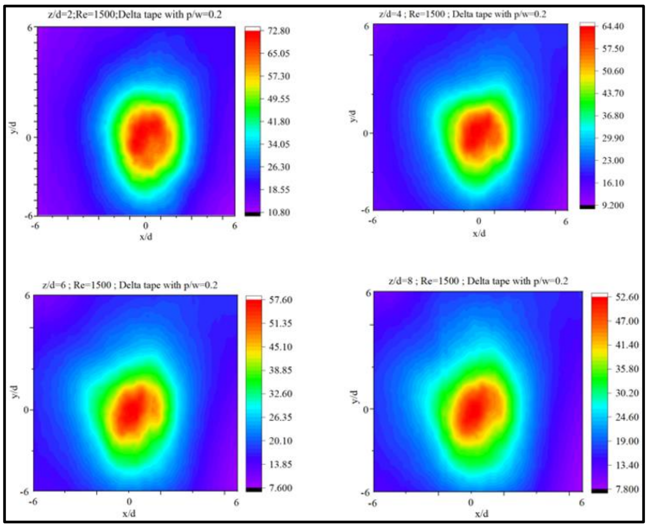

Figure 17. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=1500

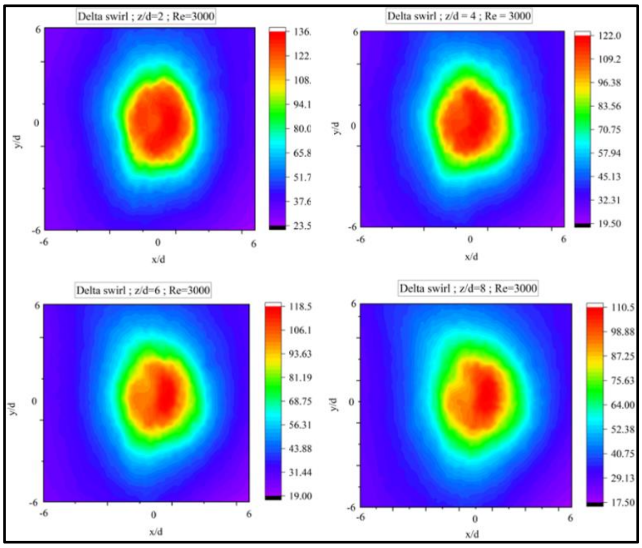

Figure 18. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=3000

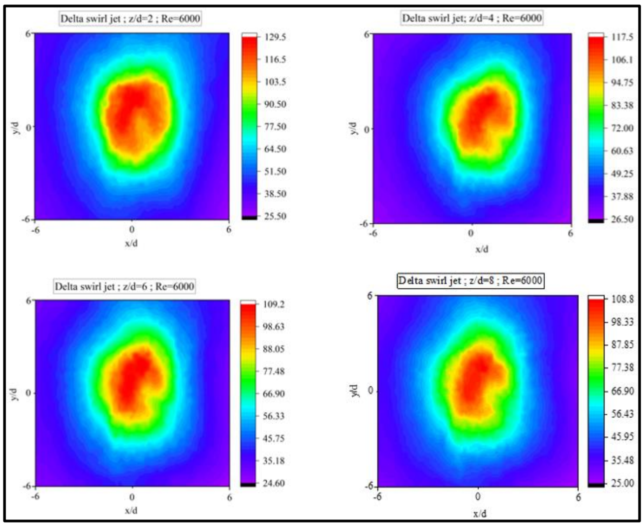

Figure 19. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=6000

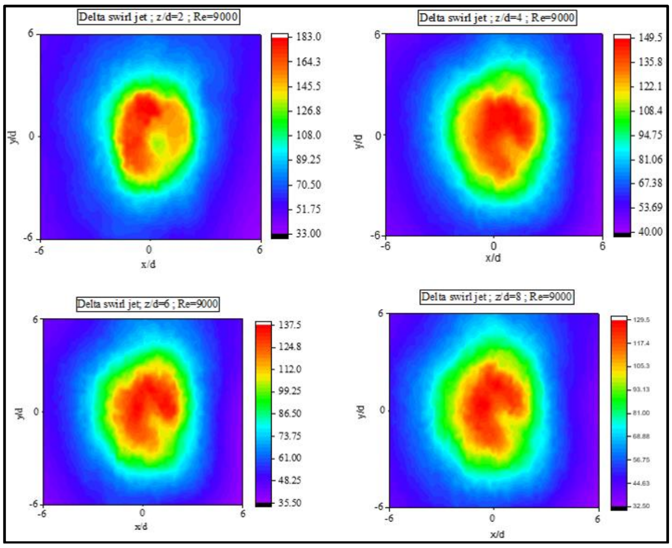

Figure 20. Contours of Nu distribution on target plate for z/d=2 to 8 and Re=9000

Figure 21 shows peak Nu comparison for normal swirl case and swirl generated due to presence of delta tape. It is evident that delta tape helps in heat transfer enhancement as we see higher value of peak Nu is all the above-mentioned cases.

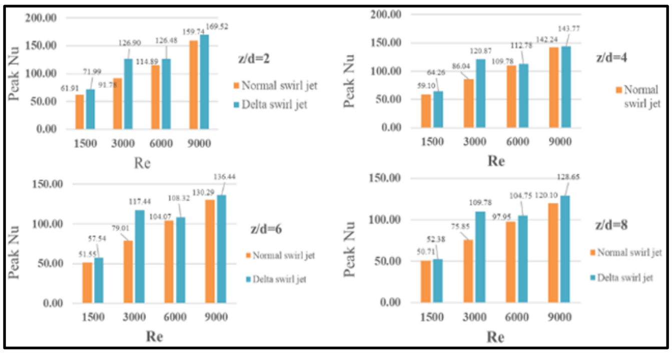

Figure 21. Peak Nu comparison for normal and delta tape case for z/d=2 to 8 and Re=1500 to 9000

5. CONCLUSION

Swirl jet impingement is achieved by use of swirl tape of T.R=2 which help generate heat transfer distribution on flat plate surface experimentally. This study is conducted for jet to plate distance of z/d=2 to 8 and Reynolds number between 1500 to 9000. Following conclusion are made from this study:

- Heat transfer effectiveness is higher for z/d = 2 when compared to z/d=8 regardless of any Reynolds studied in the present case.
- Nu shift is observed in a symmetric manner which indicate that swirl generated due to present of swirl tape distributes effectively on to the plate symmetrically.
- The strength of swirl decreases as jet to plate distance increases thus we observe decrease in peak Nu value.

Local heat transfer distribution on flat plate surface for swirl flow generated due to delta twisted tape of T.R=2 for z/d=2 to 8 and Re=1500 to 9000 are studied experimentally. Results obtained are compared with traditional swirl generation method of twisted tape. Following conclusion is made from this study:

- Delta twisted tape increases the heat transfer rate for all the above-mentioned cases compared to standard method.
- For z/d =2 and 4 we observe that peak Nu is shifted more towards one side. This is because of sudden 90deg twist that is built-in on the tape. This generates additional secondary flow and increases mixing or turbulence due to primary swirl. The strength of swirl is more in such cases and this helps in increase of heat transfer rate.
- As the distance from jet to plate increases, we observe more of a symmetric shift in peak Nu as seen in case of standard swirl jet impingement case.
- Effectiveness of heat transfer is more for laminar case (Re=1500-3000) when compared to the transitioned turbulence case (Re=6000 to 9000). Delta tape is able to create more turbulence or disturbance of primary flow in laminar case thus increasing overall heat transfer.

Authors would like to provide limitations and future research directions of present work which are listed below:

- In present work Re studied was in the range of 1500 to 9000 as setup was limited with capacity of compressor availability. Hence it would be interesting to see the present work being extended for much higher Re by utilizing higher hp compressor. Re in the range of 9000 to 20000.
- Present work can be further extended numerically to understand physics of heat transfer improvement by modeling the delta tape and carrying out numerical studies using commercial CFD software's.
- One of application of present work is in electronic cooling. However, we know that electronic devices are also subjected to secondary ambient flow or cross flow. Thus, the present work can be extended to study heat transfer on flat surface subjected to different cross flow velocity.

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NOMENCLATURE

A	Jet impingement surface area (m^2)
d	Jet diameter (m)
h	Heat transfer coefficient (W/m^2K)
K	Thermal Conductivity of air (W/mK)
Nu	Nusselt Number
Re	Reynolds Number
P	twisted tape pitch
W	twisted tape width
p/w	Twist Ratio (T.R)
μ	Dynamic Viscosity
ρ	Density (kg/m^3)
t	Plate thickness
z/d	Jet to plate distance