Geometry and Location Optimization of Wavy Flag to Improve the Heat Transfer Rate Vortex Generator

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ABSTRACT: This work demonstrates the effect of different shapes and positions of a wavy flag vortex generator on the heat transfer in a rectangular channel using Computational Fluid Dynamics (CFD) analysis. It covers the shape optimization as well as the position optimization of the shape optimized flag to achieve the best heat transfer enhancement. The result of post analysis shows that the shape optimized flag is the combination of rectangular and triangular flag and the optimized position is the flags arranged horizontally along the breadth of the channel. Average Nusselt number in shape optimized flag is 20 % higher than that in no flag condition, whereas in best optimized position in which 3 shape optimized flags are used it is 70 % higher when compared to no flag condition. This work also covers the experimental validation for the result of position optimization. Although, heat transfer enhancement by introducing additional turbulence had been widely studied but usage of flag, effect of different shapes of flag and the flag positions for improving the heat transfer has not been explored much in practical applications. This paper thus presents the use of flag for heat transfer enhancement.

Key words: Geometry, Optimization, HT, Vortex, Enhancement.

I. INTRODUCTION

All the industrial systems dealing with heat and fluid transfer involve fluid flow through channels and must deal with efficient heat dissipation problem at the same time. Heat transfer through channels is one of the classical problems in the heat transfer and fluid mechanics. The thermal behaviour of these channels has been described well by the correlations given by Dittus and Boelter [1]. These correlations imply that the Nusselt number of the fluid flowing inside the channel is a function of Reynolds and Prandtl number which represent the flow properties of fluid. Nusselt number is used to find the average heat transfer coefficient which gives the idea of amount of the heat carried by the air. Nusselt number can be easily varied by changing the Reynolds or the Prandtl number. As it is difficult to vary flow properties (i.e. change the Prandtl number), usually the Nusselt number is controlled by varying the Reynolds number. Vortex generators can be used as one of the methods to vary the Reynolds number in a channel. Vortex generator (VG) is aerodynamic device, consisting of a small vane like structure usually attached to a lifting surface. These are most often used to delay the local flow separation and aerodynamic stalling, in applications such as wings and control surfaces, flaps, elevators, aileronsand rubber. Various heat transfer enhancement techniques are used for enhancing the heat transfer in the channel. All these techniques come under active and passive techniques. They are used to enhance heat transfer by generating the vortex (whirl) in the flow. Passive techniques involve creating protrusions, dimples, corrugations etc. The flow can take place only in one direction as passive devices will be in-affective in case the flow direction changes. Active techniques involve external source like fans in which direction of flow can be altered, but the active techniques require an external source of energy which is a drawback. Another disadvantage is the size, as the fans cannot be introduced in small channels. The passive method has been more widely accepted than the active methods as they do not require any external power to produce whirl in the flow. Like these passive techniques, vortex generators can be used in the form of flags. Flag is a better solution to both active and passive techniques as they do not require the external source of energy and change in the direction of the flow doesn't affect its performance as it can change the direction of its fluttering with the change of course of flow. When the fluid flows over the flag, due to the fluttering of flag a whirl is produced which results in the mixing of the fluid. This mixing affects the thermal boundary layer and the temperature field which in turn increases the heat transfer. Software and numerical based analysis have been carried out to study the vortex generator's effect on the heat transfer. Ralph Kristoffer and Rajneesh N. Sharma conducted a study concluding that extensive and intensive experimental results are lacking to validate numerical and

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theoretical predictions. They presented a review of with different flag arrangements, flag positions and number of flags to find out heat transfer enhancement when compared to no such flags in the channel flow pipes [2]. Jae Bok Lee et al used a penalty immersed boundary method in performing the study of flag as vortex generator for heat transfer enhancement. They studied the heat transfer performance by varying the bending rigidity, channel height, Reynolds number of the flags which are installed on the flow channel [3].HyungJin Sung et al. concentrated on the study of flag with asymmetric configuration and symmetric configuration using penalty-based immersion boundary method. Results showed that asymmetric configuration creates more wakes in the channel flow than symmetric configuration. Asymmetric configuration flags had fewer ratios between cross sectional area of flag and the channel height compared to symmetric configuration [4].Zheng Li et al. investigated on the effects of young's modulus of the elastic thin sheet used as vortex generator on the oscillations of the elastic sheet, vorticity fields, and heat transfer performances. This paper gave a scope to go further research in the materials of the flags which are used as vortex generators considering the material rigidity as major factor [5].Atul Kumar Soti et al. used fluid structure interface solver to carry out the study between interaction of fluid with the flag installed in the channel. Fluid structure method is based on the sharp interface immersed boundary and finite element method. Results showed that decreasing boundary layer thickness leads to increase in the Nusselt number in flow channel [6]. Hyung Jin Sung et al. investigated on flapping flag dynamics of inverted flag in a uniform flow using immersion method. Area to length ratio influence of the inverted flag in the heat transfer enhancement has been studied. Boyoung Kim et al. modelled an inverted flag where one side is free end and the other end is fixed to a cylinder. Six pairs of vorticial structures are generated in the wake of the inverted flag formedwhich influence the thermal boundary layer and the temperature fields. Flapping mode is the best one for heat transfer among the straight and deflected modes [8].Herrault et al. [9] and Hidalgo and Glezer [10,11] used oscillating reeds in order to induce small-scale motions and demonstrated local heat transfer enhancement up to 300% in channels. Shoele and Mittal [12] numerically modelled the flow-induced fluttering motion of a flexible reed and shown that it significantly increased the mean heat flux through the channel. This work focuses on the various possibilities of enhancing the heat transfer by using different shapes of the flag (rectangle, triangle, ellipse, combination of rectangular and triangular). It further includes the position optimization of the shape optimized flag in a region to obtain maximum heat transfer. It also includes the experimental validation of the CFD results of the position providing the highest heat transfer enhancement.

PROBLEM STATEMENT

Shape and position optimization of a static wavy flag for best heat transfer:

- To establish flag as a substitute for active and passive vortex generators.
- Forced convective heat transfer using wavy flag vortex generator in a closed rectangular channel and to optimize the shape and position using CFD analysis and its experimental validation.

OBJECTIVE

- Effectiveness of wavy flag as heat transfer enhancement device.
- Influence of shape and position of the flag on heat transfer.

Parameters	Specifications
Channel cross section area	110 X 150 mm^2
Channel length	150 *mm*
Heater capacity	20 *W*
Heater thickness	3.5*mm*
Surface area of Flag	300 mm^2
Fluid	Air

TABLE 1: SPECIFICATIONS OF THE PARAMETERS INVOLVED IN THE PROCESS

SCOPE

- This work can be used as a reference while selecting flags as vortex generator for improving thermal management in larger systems like data centers, chillers, air conditioners, dryers, refrigerators and other industrial heat exchangers.
- Other applications include micro scale cooling systems in portable devices like laptop computers, sensors, etc.

II. METHODOLOGY

- Modeling and Meshing has been done in ANSYS ICEM 18.1
- Computational fluid dynamics technique in ANSYS FLUENT 18.1 to compare and quantify the temperature distribution of the fluid in the channel.
- Calculations and graphs are to be obtained in M.S. Excel
- Experimental validation of CFD results.

This paper aims to present a brief review of flag vortex generators for thermal enhancement. Although flag dynamics is widely reported, the review reveals that this heat transfer technique is not widely explored, specifically

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on the heat transfer performance of flags. Extensive and intensive experimental results are lacking to validate numerical and theoretical predictions. This paper further provides a non-exhaustive list of existing gaps, challenges, and potential research areas in using flags as vortex generators for thermal enhancement, which aims to guide future research directions in this thermal fluid-structure problem. There is a need to conduct further investigations on this technique to fully establish its thermal characteristics.The use of flexible plates or "flags" as vortex generators inside a channel was successfully demonstrated as an alternative heat transfer enhancement technique.The use of flexible plates or "flags" as vortex generators inside a channel was successfully demonstrated as an alternative heat transfer enhancement technique.Recent innovations in thermo-fluid systems and electronics are geared towards improved system performance.

One of the key areas of research is improving their cooling systems for optimum thermal and economic performance. Due to the demanding nature of their applications, modern electronics and energy systems need compact and more efficient means of heat transfer. Heat transfer in channels is one of the classical problems in heat transfer and fluid mechanics. Numerous experimental, theoretical and numerical studies have already described the thermal behavior of the channel. Correlations like the one proposed by Dittus-Boelter are widely used to describe this thermal behavior. In these correlations, the Nusselt number inside a channel is a function primarily of the flow Reynolds number and the fluid properties represented by the Prandtl number. Unless these flow properties are modified, insignificant heat transfer enhancement is attained and one way to circumvent it is by introducing additional turbulence to the flow. Indeed, heat transfer enhancement by introducing additional turbulence had been widely explored. The use of vortex generators (VG) for heat transfer enhancement is a common approach. Vortex generators are generally categorized as passive or active. Passive VG techniques include modifying the channel surface to generate turbulence in the flow. These may be done by creating protrusions, dimples, corrugations, etc. in the channel walls. Re-center views and studies by Sheikholeslami et al. and Ahmed et al. provide brief yet comprehensive reports on the advances made in passive VGs. Reviews on passive techniques which include inserts like twisted tapes and other channel surface modifications features are also widely reported. Active vortex generators need an external energy source to create turbulence. Piezo-fans and magnetic fans belong to this category. The third category of VG maybe derived by combining passive and active techniques. To create additional turbulence, conventional VG involves modifications to the channel wall surfaces or inclusion of features that alter the overall channel geometry. Although recent advances in manufacturing made complicated geometries possible, the geometry of these enhanced surfaces and features posed challenges on the construction of the system. On the other hand, power requirements remain one of the causes of limitations of active systems. Space considerations also matter. In piezo fans, for example, the presence of the piezoelectric patch limits their spatial applications, i.e. they are seldom inserted inside the channels. Indeed, most piezofans are used for thermal enhancement of heat sinks. Alternative techniques to conventional passive VG involve inserting flexible materials like small flags and reeds inside the channel to enhance turbulence. These systems combined the prominent advantages of both the passive and active systems. Unlike the active systems, the motion of the flag or reed is caused by the flow, eliminating the need for an external power source. The flow-induced motion of the flag creates the turbulence which enhances the channel heat transfer without the need for complicated geometry and features. Thin flags or reeds can also be installed in smaller channels. Inserting flags in channels is a promising technique for heat transfer enhancement. In recent experimental studies, Herrault et al. and Hidalgo and Glezer reported the beneficial effects of inserting flexible plates or flags in between heat sink fins to enhance its heat transfer. They reported that as high as 300% enhancement in local heat transfer may be attained by using flags. The same qualitative results were reported by Shoele and Mittal and Soti et al. through their numerical analyses. Flag VG's have huge potential in a wide array of applications owing to the flexibility of modifying the different flag material properties, channel dimensions and flow characteristics to suit different operating conditions. Indeed, the technology is readily scalable, i.e., it can be used for both micro and macro scale applications. Micro scale cooling systems in portable devices like laptop computers, sensors, etc. will derive benefits from this technology. Likewise, thermal management in larger systems like data centers, chillers, air conditioners, dryers, refrigerators and other industrial heat exchangers may be improved through the flag VG system. Undoubtedly, the technologies which will be derived from this research effort will have profound commercial benefits to the thermal management industry. The dynamic behavior of the flag immersed in the flow and the influences of channel properties contribute to the complexities of this system that merit extensive and intensive research efforts. Although the use of inserts had been a prevailing theme in various VG studies, very little information appears to be available on the characteristics flag or reed inserts as vortex generators for heat transfer augmentation. This paper presents a non-exhaustive review of experimental, theoretical and numerical studies regarding the use off-lags as vortex generators for heat transfer enhancement. Since the motion of the flag primarily governs the thermal performance of the system, a section on flag dynamics was included and another section was devoted to heat transfer enhancement using flags.

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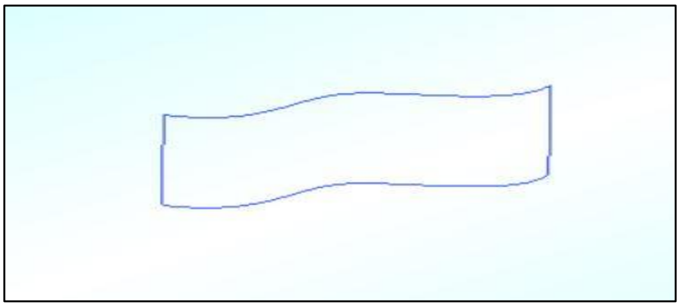
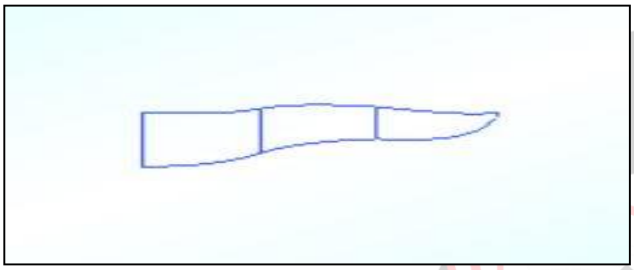
FLAG GEOMETRY AND POSITION DESCRIPTION

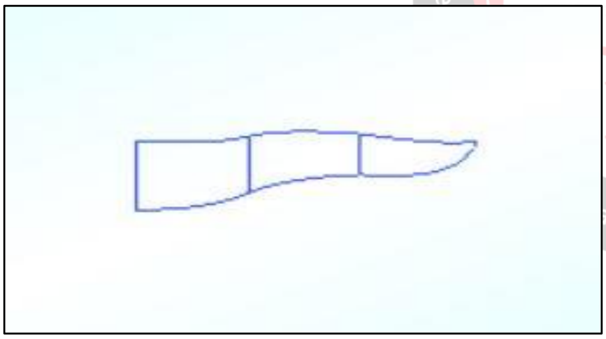
Flags of six different shapes are selected which includes regular geometries such as rectangular, triangular and elliptical. The remaining three shapes are the combination of the regular geometries which include rectangular flag combined with a triangular flag, rectangular flag with two triangular ends and a rectangular flag with semi-circular top and bottom edges. All the six geometries have been shown below in fig 1. It also contains the symbolic name of each flag for the convenience in writing purpose.



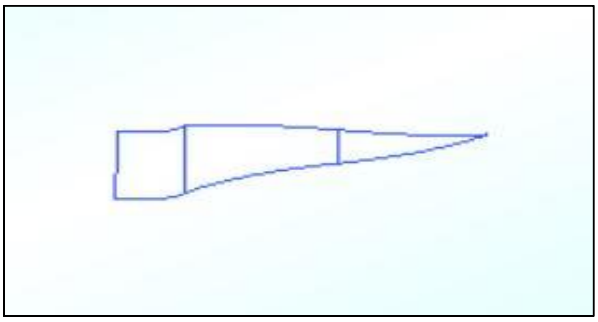
a) Rectangular Flag (RF)



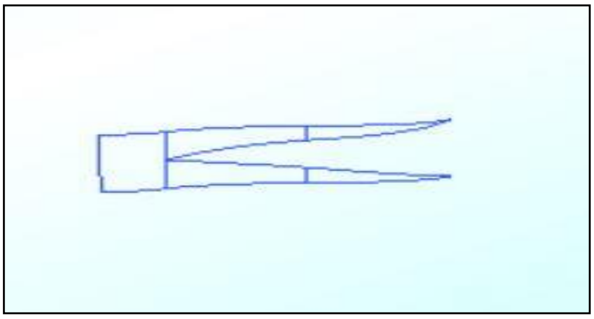
b) Triangular Flag (TF)



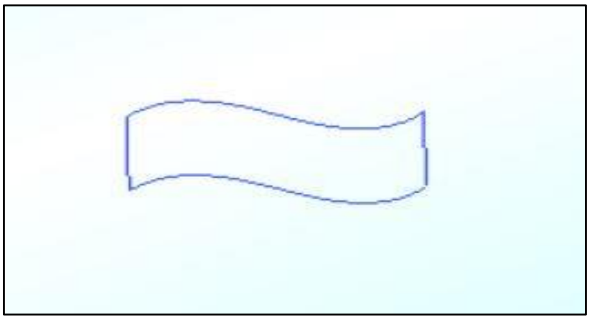
c) Elliptical Flag (EF)



d) Rectangular flag combined with triangular flag (ROTF)



e) Rectangular flag combined with two triangular flags (RTTF)



f) Rectangular flag with semicircles on its top and bottom edges (RSTF)

Fig 1: Flag Geometries

For the analysis these flags are attached on the top surface of the aluminium sheet one by one. The position of flagpole for every flag is kept same. The height of the flag from the aluminium sheet is kept same for every flag i.e., 2.5 mm. To bring uniformity the surface area of each flag is kept constant i.e.,300 mm^2 with the maximum error of 1.66% i.e., 5 mm^2. Flags width is kept constant i.e., 10 mm. Flags are of wavy and in nature. Since the flags are of static nature (no fluttering) so the total no of crest in each flag is kept constant i.e.,3.

Fluid Properties and Boundary Conditions

Fluid present in the channel is air. Since the temperature of the air entering the channel inlet is between 25 and 30 degrees Celsius so the density of air is taken as 1.174 kg/m^3, viscosity if the air is taken as 15.85 µ Pa.s, thermal conductivity as 0.0242 w/m-k and specific heat as 1006.43 j/kg-k. The density, specific heat and thermal conductivity of aluminium is kept as 2719 kg/m^3, 871 j/kg-k, 202 w/m-k respectively. Velocity inlet boundary condition is used at the inlet. CFD analysis is carried out at three different velocities i.e., 1.1m/s, 1.65m/s and 2.45m/s. At the outlet of the channel pressure-outlet boundary condition is applied with pressure as 1 atm. At walls of the channel and the flag surface no slip boundary condition is applied. The heater attached at the bottom of the aluminium sheet provides constant heat flux of 888.88 w/m^2.

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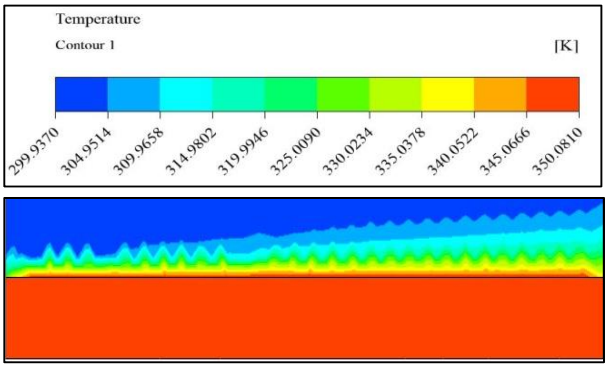
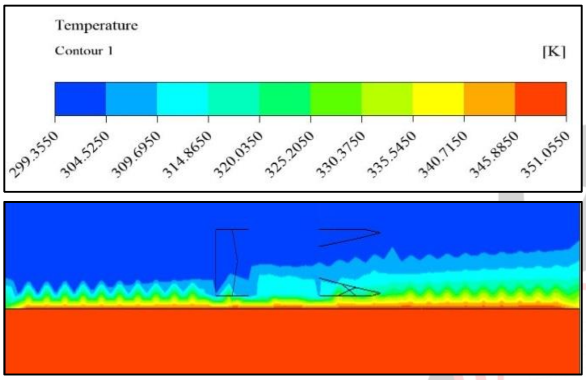
III. SHAPE OPTIMIZATION

Based on the CFD simulations and the results obtained after the calculations, flag which gives the maximum heat transfer is selected.

CFD Simulations



a) No Flag



b) Rectangular flag combined with two triangular flags

Fig 2: Thermal boundary layer in different flags

Fig 2:Shows the thermal boundary layer in NF and RTTF condition respectively. The thermal boundary layer obtained in different cases has different boundary layer thickness.

Procedure Followed During Calculations

Fig 3 shows lines plotted along the length of the channel. Temperature values of the air along these lines are obtained and an average temperature of the air from those values is obtained. Number of lines are more in the region where the flag is present because there is high rate of temperature change.

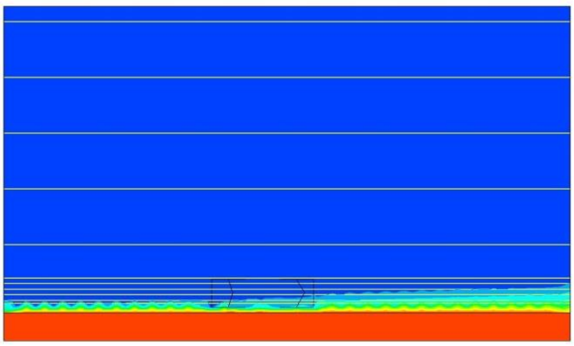


Fig 3: Lines plotted along the length to obtained temperatures along these lines

The lines are well distributed in the channel from top to bottom and hence give good idea of the average temperature of air moving out of the channel. The difference between the air temperature at the inlet and at the outlet gives the overall change in the temperature of the air flowing through the channel

Following procedure is then followed to find out the average Nusselt number in each case:

Step 1

Mass flow rate $(\dot{M}) = \rho \times A_c \times V$

Step 2

Temperature change in fluid $(T_d) = T_o - T_i$

$$(Q) = \dot{M} \times Cp \times T_d$$

Step 3

Heat carried away by the fluid

Step 4

Average temperature difference between surface and fluid

Step 5

Average heat transfer coefficient $(h) = \dfrac{Q}{A_s \times T_a}$

Step 6

Nusselt no $(Nu) = \dfrac{h \times D_h}{k}$

Step 7

Reynolds no $(\mathrm{Re}) = \dfrac{\rho \times V \times D_h}{\mu}$

IV. RESULTS AND DISCUSSION

Velocity (m/s²)	Nu	Re
	No flag condition	
1.1	239	8236
1.65	249	12354
2.45	267	18344
	RF	
1.1	274	8236
1.65	288	12354
2.45	315	18344
	TF	
1.1	249	8236
1.65	268	12354
2.45	306	18344
	EF	
1.1	229	8236
1.65	236	12354
2.45	247	18344
	ROTF	
1.1	261	8236
1.65	297	12354
2.45	314	18344
	RTTF	
1.1	288	8236
1.65	301	12354
2.45	324	18344
	RSTF	
1.1	225	8236
1.65	226	12354
2.45	238	18344

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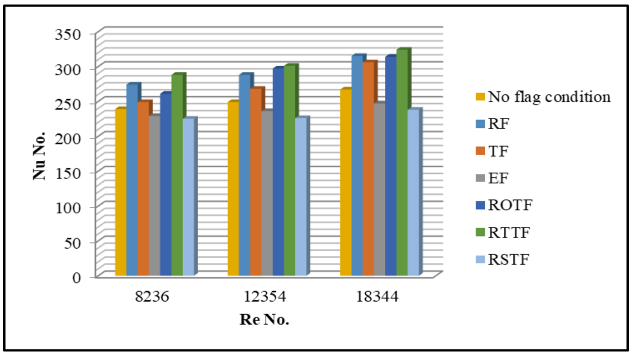
Table 2 shows the Nusselt number at different Reynolds number in different flags. The RTTF condition shows the highest Nusselt number at all the different velocities. Graph I is plotted between the Nu and Re. It clearly represents the RTTF having the highest Nusselt number at all the three different velocity conditions.



Graph I: Nusselt number vs Reynolds number for different flag shapes

V. EXPERIMENTAL VALIDATION

To establish the credibility of CFD studies, the result of shape and position optimization i.e., best heat transfer achieved in case of RH position is validated with the help of experiment. The rectangular channel used in the experiment is made up of acrylic sheet material and rest of the conditions are kept same as that in the CFD analysis.

The average Nusselt number obtained after experiment in each case is higher than that obtained in CFD simulation. At the velocity of 1.1 m/s in case of flags, average experimental Nusselt number is greater than the CFD Nu by 6.73%. At 1.65 m/s, it is greater by 8.37% whereas at 2.45m/s it is greater by 7.14%. For no flag condition, at 1.1 m/s, the experimental Nusselt number is greater than the Nusselt number obtained using CFD is 6.29%. At the velocity of 1.65 m/s, it is greater by 9.23%. and for 2.45 m/s, the experimental value is greater by 8.98%. The difference between the experimental and CFD Nusselt number is lower at the lower speeds, whereas at the higher speeds the difference between the results are higher. This can establish the fact that the difference between experimental and software results increases at high Reynolds number. The table V shows the Nusselt number at different Reynolds number during the experiment.

Table-5: Comparison between Nusselt number obtained by experimental validation for the most optimized result

Velocity (m/s^2)	Nu. No.	Re. no.
RH		
1.1	416.60	8236.
1.65	453.71	12354
2.45	495.99	18344
No flag		
1.1	254.99	9244.58
1.65	272.25	13866.87
2.45	291.96	20590.20

Comparison of RH Between CFD And Through Experiment:

Table 6: Comparison of Nu No. in CFD and experimental results

Velocity (m/s^2)	Nu. No.	Re. no.
RH-EXPERIMENTAL		
1.1	416.60	8236.
1.65	453.71	12354
2.45	495.99	18344
RH-CFD		
1.1	390	8236
1.65	418	12354
2.45	462	18344

From CFD analysis and experimental investigation, we conclude that in experimental validation there is only 6%-8% increase in the Nu No. compared to CFD results. This decrease in Nu No. may be due to instrumentation error and experimentation error.

VI. CONCLUSION

As the effect of different shapes of flag and the flag positions for improving the heat transfer has not been explored much in practical applications. This work thus demonstrated the effect of different shapes and positions of a static wavy flag vortex generator on the heat transfer in a rectangular channel using Computational Fluid Dynamics (CFD) analysis. CFD analysis was carried in order to find out the shape providing the maximum heat transfer enhancement and further position optimization was carried out using three shape optimized flag. Further for the validation of the CFD results, experimental analysis was carried out. For the shape optimization, three standard flag shapes and three combinations of the standard shapes were considered. Average Nusselt number in each case was compared in order to find out the shape providing maximum heat transfer enhancement. RTT flag showed the highest Nusselt number in each different velocity condition. As compared to the no flag condition, the average Nu is greater by 20% in RTTF condition. Position optimization is carried out using the RTT flag. For the position optimization, four different flag positions are used. Due to

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space constraint, total number of flags used for position optimization were kept three. At the lower value of Re, RS position showed the highest Number whereas RH position had a higher value of Nusselt number than RS position at the highest Re. A single position can be selected if the velocity of air in the channel is constant. But in order to find a single best position at the variable velocities, further averaging of the Nusselt number was done. RH position showed the maximum average Nu number. Compared to the no flag condition, the average Nu number was 70 % higher in RH condition. An experiment was conducted in order to validate the CFD result of RH condition. The experimental results were like the CFD results with maximum variation of 8-9 % in average Nu at each different velocity. Thus, RTTF was considered the most optimized shape and RH was considered the position showing the maximum heat transfer enhancement.

REFERENCES

[1] TL, Incropera FP. Fundamentals of heat and mass transfer, 7. Hoboken, N.J: John Wiley; 2011.

[2] Ralph Kristoffer B. Gallegos, Rajnish N Sharma, "Flags as vortex generators for heat Bergman transfer enhancement: Gaps and challenges," in Renewable and Sustainable energy reviews, 76(2017) 950-962

[3] Jae Bok Lee, Sung Goon Park, Boyoung Kim, Jaeha Ryu, Hyung Jin Sung, "Heat transfer enhancement by flexible flags clamped vertically in a Poiseuille channel flow," in International Journal of Heat and Mass Transfer,107 (2017) 391–402

[4] Jae Bok Lee, Sung Goon Park, Hyung JinSung,"Heat transfer enhancement by asymmetrically clamped flexible flags clamped in achannel flow," inInternational Journal of Heat and Mass Transfer,116 (2018) 1003-1015

[5] Zheng Li, Xianchen Xu, Kuojiang Li, Yangyang Chen, Guoliang ,Huang , Chung-lung Chen,Chien-Hua Chen, "A flapping vortex generator for heat transfer enhancement in a rectangular airside fin,'' in International Journal of Heat and Mass Transfer,118 (2018) 1340–1356.

[6] Atul Kumar Soti, Rajneesh Bhardwaj, John Sheridan, "Flow-induced deformation of a flexible thin structure as manifestation of heat transfer enhancement" in International Journal of Heat and Mass Transfer,84 (2015) 1070–1081.

[7] Jaeha Ryu, Sung Goon Park, Boyoung Kim, Hyung Jin Sung, "Flapping dynamics of an inverted flag in a uniform flow", in Journal of fluid and structures 57 (2015) 159-169.

[8] Sung Goon Park, Boyoung Kim, Cheong Bong Chang, Jaeha Ryu, Hyung Jin Sung, "Enhancement of heat transfer by a self-oscillating inverted flag in a Poiseuille channel flow in "International Journal of Heat and Mass Transfer,96 (2016) 360–370".

[9] Herrault F, Hidalgo PA, Ji C-H, Glezer A, Allen MG, "Cooling performance of micromachined self-oscillating reed actuators in heat transfer channels with integrated diagnostics", in Micro Electro Mech. Syst. (MEMS), 2012 IEEE In: Proceedings of the 25th International Conference, IEEE, 2012, p. 1217–20.

[10] Hidalgo P, Glezer A, "Direct actuation of small-scale motions for enhanced heat transfer in heated channels", in ASME-JSME-KSME 2011 Jt. Fluids Eng. Conference, American Society of Mechanical Engineers, 2011, p. 3123–9.

[11] Hidalgo P, Glezer A, "Small-scale vorticity induced by a self-oscillating fluttering reed for heat transfer augmentation in air cooled heat sinks", in InterPACK/ ICNMM2015, San Francisco, CA. 2015

[12] Shoele K, Mittal R, "Computational study of flow-induced vibration of a reed in a channel and effect on convective heat transfer", in Phys Fluids 2014;26:127103

 DOI : 10.35291/2454-9150.2022.0250