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Full Paper

THE EFFECT OF VORTEX GENERATOR BASE LENGTH ON THERMAL HYDRAULIC PERFORMANCE ACROSS FIN-AND-TUBE HEAT EXCHANGER

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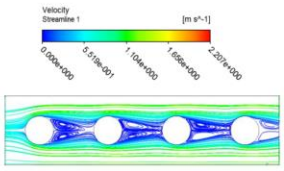
Graphical abstract



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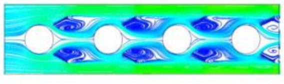

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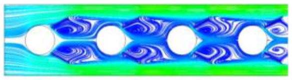

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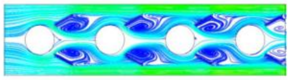

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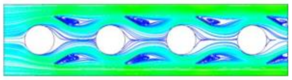
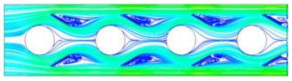
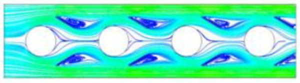


(e) CFU Default



(f) CFU Extended Front



(g) CFU Extended Back

Abstract

Heat transfer enhancement is believed can be achieved by using vortex generator. In the past decades, many researches have been performed to investigate the effect of various vortex generator geometry and parameters including vortex generator angle of attack and height. However, less study has been conducted to investigate the influence of vortex generator length at different arrangement towards the heat transfer performance across the fin-and-tube heat exchanger (FTHE). Therefore, the effects of different strategy on the rectangular winglet vortex generator (RWVG) base length towards the thermal hydraulic performance across the FTHE were numerically investigated in this study. Two types of RWVG arrangement known as common flow down (CFD) or common flow up (CFU) arrangement were used and placed behind four rows of tube in inline arrangement. Total of 7 cases were investigated including the default RWVG, extended front and extended back for both RWVG in CFD and CFU arrangement together with FTHE without vortex generator which was set as the baseline case. The Reynolds number ranged from 500 to 900. It was found that the size of the wake region behind the RWVG contributed to the additional pressure drop penalty across the FTHE. Meanwhile, different thermal characteristics were found for different base length strategy in CFD and CFU arrangement. For RWVG arranged in CFD and CFU arrangement, the extended back case shows the highest heat transfer enhancement with 5 – 25 % and 5 – 15 % increment compared to the baseline case respectively. Based on JF factor evaluation, default RWVG in CFU arrangement provide better heat transfer enhancement than the pressure drop penalty compared to other RWVG cases with average JF factor value is 0.8. Nonetheless, none of the tested cases shows higher JF factor value than the baseline case.

Keywords: Vortex generator, fin and tube, rectangular, common flow down, common flow up

1.0 INTRODUCTION

One of the methods for heat transfer enhancement on the gas side of the fin-and-tube heat exchanger (FTHE) is by implementing vortex generator which falls under the secondary flow enhancement technique. In this technique, the secondary flow produced by the vortex generator disturbs the growth of the boundary layer and create fluid swirling across the FTHE [1]. Thus, contributing to the overall heat transfer improvement.

According to Jacobi and Shah [2], vortex generator configuration can be divided into two types known as common flow down (CFD) and common flow up (CFU) arrangements. The orientation is called CFD arrangement if the transverse distance between the winglet pair for the trailing edges is more than the leading edges. Meanwhile, for the CFU arrangement, the transverse distance for the trailing and leading edges is vice versa. It was found that both arrangements improve the heat transfer rate across the FTHE [3, 4, 5, 6].

Other than that, many vortex generator geometric parameters have been investigated by previous researchers [7, 8, 9, 10, 11]. These include the effect of vortex generator height, angle of attack and location. An investigation performed by Zeng *et al.* [12] discovered that the heat transfer can be enhanced by increasing the vortex generator length, height and angle of attack but must be accompanied with higher pressure drop penalty. A study conducted by Tang *et al.* [13] described that improvement to the heat exchanger performance can be obtained by using vortex generator with larger angle of attack, smaller height and higher length. It is noted that heat exchanger performance is acquired from thermal hydraulic evaluation across the heat exchanger.

However, to the authors' best knowledge, less study has been conducted to examine the influence of different vortex generator length and various vortex generator arrangement placed behind the tubes across the FTHE. Therefore, this study mainly focused on the thermal hydraulic properties across the FTHE with and without rectangular winglet vortex generator (RWVG) at Reynolds number ranged from 500 – 900.

2.0 METHODOLOGY

2.1 Governing Equations

In this study, incompressible fluid with constant thermo-physical properties is considered. From the previous study [14, 15, 16, 17], the governing equations for the numerical simulation method used in this research are written as follows.

$$\frac{\partial}{\partial x_i}\left(\rho u_i T\right)=\frac{\partial}{\partial x_i}\left(\frac{k}{C_p}\frac{\partial u_i}{\partial x_i}\right) \quad (1)$$

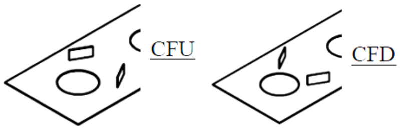
$$\frac{\partial\left(\rho u_i\right)}{\partial x_i}=0 \quad (2)$$

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right)=\frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_j}{\partial x_i}\right)-\frac{\partial p}{\partial x_i} \quad (3)$$

Eq. (1) – (3) shown are the general equations used in numerical calculations to analyze the fluid dynamics and thermal characteristics. Note that the fluid used at the gas side of the FTHE in this study is air.

2.2 Physical Model and Computational Domain

In this study, two different vortex generator length is tested at two vortex generator arrangement together with a baseline case where no vortex generator is introduced. The RWVG arrangement used in this study is shown in Figure 1.



(a) (b)

Figure 1 RWVG arrangement used in this study (a) common flow up (CFU) and (b) common flow down (CFD)

The dimension for the FTHE was referred from a study performed by Gholami *et al.* [14]. The FTHE applied in this study consists of four tube rows organized in inline arrangement. The RWVG geometry used was a design based on the study by Gholami *et al.* [14] which was set as the default RWVG where the RWVG center point was designated. The FTHE geometry and the RWVG height were kept constant in this study. The RWVG base length was extend in two ways which is the extended front and extended back with respect to the default RWVG center point. The value of the extended length is 1.5 mm. Figure 2 shows the geometry and the dimension of the RWVG used in this study. Meanwhile, the computational domain of the FTHE used in this study is presented in Figure 3.

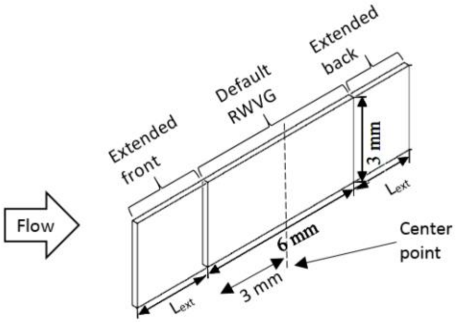


Figure 2 Detail dimension for RWVG

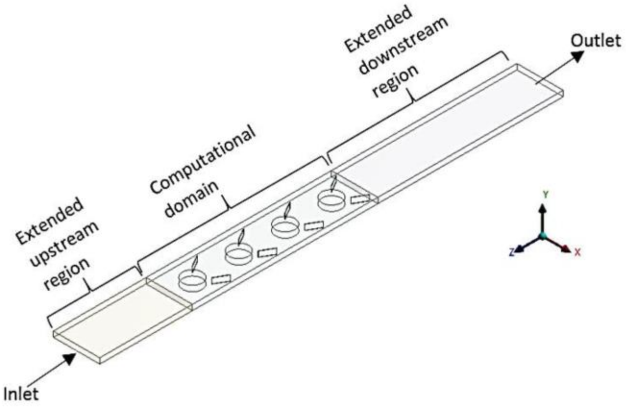


Figure 3 Computational domain of FTHE model

2.3 Boundary Conditions

The fluid used in the numerical study was assumed to have constant physical properties, steady state condition and laminar flow condition. The thermal contact resistance between the fin and the tube is ignored. Uniform velocity of $U = U_{in}$ and constant temperature of $T_{in} = 300$ K is set at the inlet. The U_{in} is obtained with respect to the tube collar diameter. Meanwhile, thin wall thermal resistance parameters and no slip condition is prescribed to the top and bottom surface of the fin wall. At the tube walls, no slip condition and the temperature is set constant at $T_{tube} = 333$ K. For the extended upstream and extended downstream wall, adiabatic condition is considered. Symmetry boundary condition is set to the computational domain sides to reduce the computational domain size in spanwise direction.

2.4 Numerical Method

The velocity field and pressure characteristic were solved using COUPLED solution algorithm scheme in this study. The convergence criterion in this numerical study for the residual of the continuity and velocity component was less than 10^{-3}. While the residual of the energy less than 10^{-5} was considered as the converged solution.

3.0 RESULTS AND DISCUSSION

The objective of current study is to analyze the effect of different vortex generator base length across the FTHE in terms of flow characteristic and thermal hydraulic performance. The baseline case in this study was set for the case of FTHE without the presence of the vortex generator. Meanwhile, RWVG arranged in default CFD and CFU arrangement were fixed as the reference point to evaluate the extended front and extended back of the RWVG base length. The Reynolds number used was ranged from Re = 500 to 900. The analysis for the heat transfer performance across the FTHE has been made by the establishment of commonly used factor which is f - friction factor and j – Colburn factor. Further discussion on the reliability of the heat transfer augmentation to the pressure drop penalty for each vortex generator geometry and arrangement is described by JF factor or also known as the area goodness factor.

3.1 Validation of Numerical Results

There are five different grid systems tested to validate the solution independency for Reynolds number ranged from 500 to 2500. The result obtained is presented as in Figure 4. Due to minimum percentage of difference among the tested grid systems, the grid system of 3780001 has been selected.

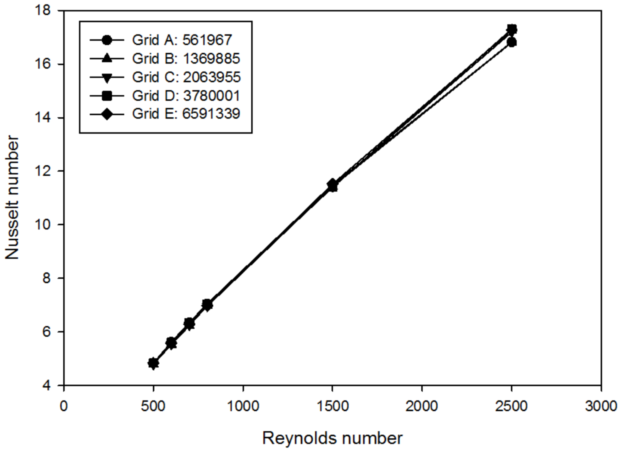


Figure 4 Nusselt number for different grid systems

Meanwhile, validation of the computational simulation method has been performed to measure the result accuracy obtained in this study. Current simulation method was evaluated using the geometry and conditions from a study done by Wang and Chi [18]. As shown in Figure 5, the result obtained from the current numerical simulation and experimental result from previous literature is shown. It was found that the percentage of difference for Nusselt number are within the acceptable limit, ranged from 1.7 to 11.6 %.

Besides that, a flow visualization study across the FTHE channel of inline arrangement using dye injection technique has been performed by Salleh *et al*. [19]. Comparison between the experimental study done by Salleh *et al*. [19] and current numerical simulation study on the flow characteristic across the FTHE without the presence of vortex generator is shown in Figure 6 for Re = 500. Flow characteristic obtained from current numerical simulation was found to be closed to the result retrieved from the experimental study done by Salleh *et al*. [19].

Comparison of the quantitative and qualitative data between the present study and previous studies has shown a good agreement. Therefore, the results for current numerical simulation study are validated.

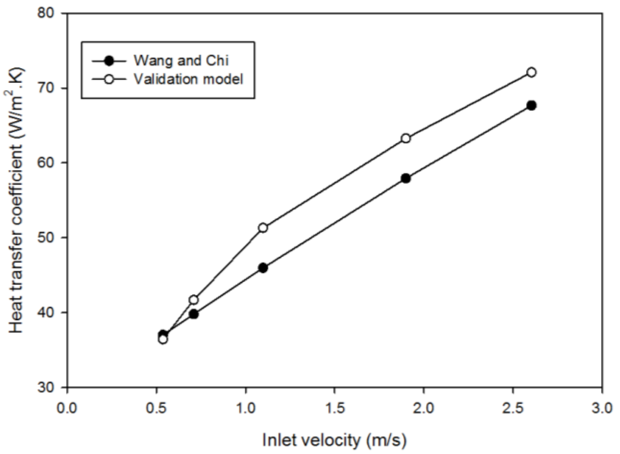
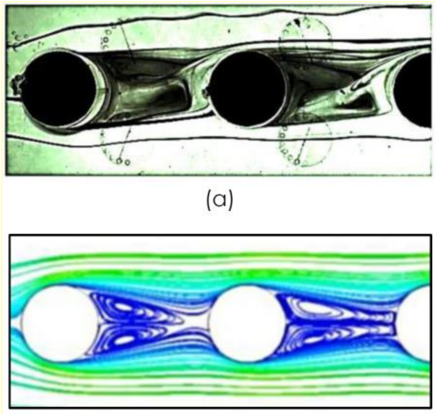


Figure 5 Validation between current simulation methods with previous experimental data [18]



(a)

(b)

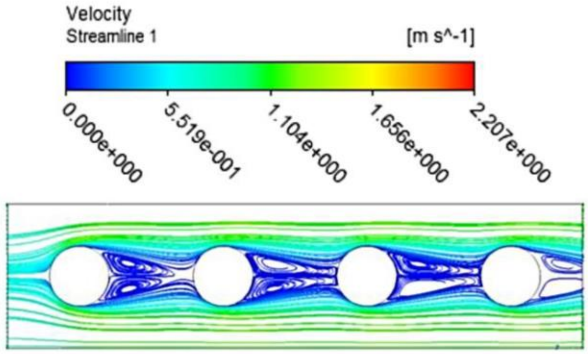
Figure 6 Comparison of flow characteristic across FTHE between (a) flow visualization experiment [19] and (b) current numerical simulation

3.2 Streamlines

The streamlines for each tested FTHE with and without vortex generator is shown in Figure 7. The streamline presented indicate the influence of different RWVG base length towards the flow characteristic across the FTHE.

The biggest wake region behind tubes was found formed at baseline case compared to other tested cases as shown in Figure 7(a). The recirculation zones behind tubes represent a poor heat region across the FTHE. This is due to low overall heat transfer resulted from the low mixing region where the high temperature region was found [2, 3].

As the default RWVG in CFD and CFU arrangement was applied, the size of the wake region behind tubes was observed to become smaller. The main flow was found directed to the rear region of the tube which minimizing the poor heat transfer zone behind tubes. Additional wake region behind the RWVG were found formed. The biggest wake region size behind RWVG was observed for the CFD arrangement than CFU arrangement.



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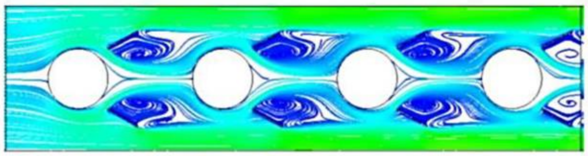
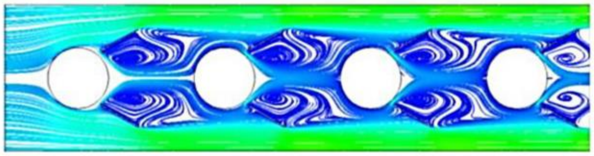
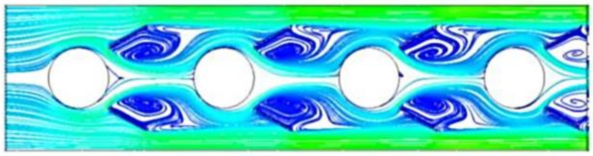


(b) CFD Default



(c) CFD Extended Front



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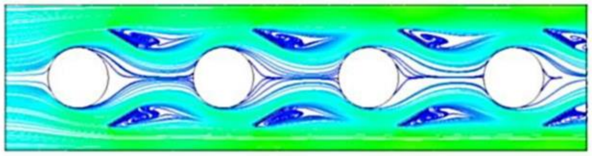
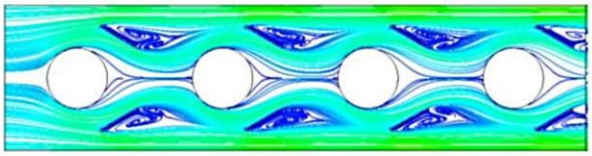
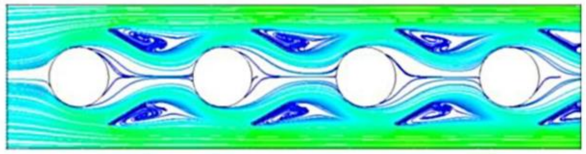


(e) CFU Default



(f) CFU Extended Front



(g) CFU Extended Back

Figure 7 The streamline pattern in the various vortex generator geometry and arrangement at Re = 500

Further investigation on the effect of different RWVG base length extension has shown that RWVG in CFD arrangement results in the largest wake region size at the rear region of the RWVG. The CFD extended front was found to produce the largest wake region behind the RWVG compared to other cases. While, the default RWVG in CFU arrangement has been observed to generate the smallest wake region behind the vortex generator.

3.3 Thermal Hydraulic Performance

The result obtained from the numerical simulation were analyzed in terms of j – Colburn factor, f – friction factor and JF factor evaluation as shown in Figure 8, Figure 9 and Figure 10 respectively. In relation with the streamlines presented in previous sub section and the f – friction factor as in Figure 9, it was found that the size of the wake region behind the vortex generator contribute to the value of the pressure drop penalty imposed across the FTHE. Wake region behind extended front RWVG in CFD arrangement was observed to be the biggest among other tested cases. The f – friction factor obtained was also the highest with 109 – 141% increment with respect to the baseline case. Meanwhile, the lowest pressure drop penalty was found to occur at the default RWVG in CFU arrangement, having the smallest wake region size behind the RWVG with 27 – 41% increment from the baseline case. Therefore, it can be said that the pressure drop penalty increases as the wake region size behind the RWVG increases.

Other than that, the j – Colburn factor for RWVG in CFD configuration was generally observed to be 1 – 6% greater than the CFU configuration. While the f – friction factor for RWVG in CFU arrangement was observed to be 37 – 80% lower than RWVG in CFD arrangement. In terms of heat transfer augmentation, vortex generator in CFD arrangement placed behind tubes enhanced the heat transfer higher than the vortex generator placed behind tubes in CFU arrangement. However, the pressure drop penalty is also higher.

The effect of different RWVG base length on the heat transfer improvement is separately analyzed for the CFD arrangement and the CFU arrangement cases based on Figure 8. For the cases of CFD arrangement, it was found RWVG with extended front minimally enhance the heat transfer than default CFD base length and RWVG with extended back with 0.8 – 17% increment with respect to baseline case. While RWVG with extended back provide the best heat transfer enhancement compared to default RWVG in CFD arrangement with 5 – 25% increment to the baseline case. This scenario shows that the distance between the tube and the tip of the RWVG in CFD arrangement should not be too close to prevent any interference to the horseshoe vortices development which enhanced the heat transfer further downstream. While, longer RWVG base length downstream in CFD arrangement will further enhance the heat transfer with stronger secondary vortices created due to the higher area facing the main flow.

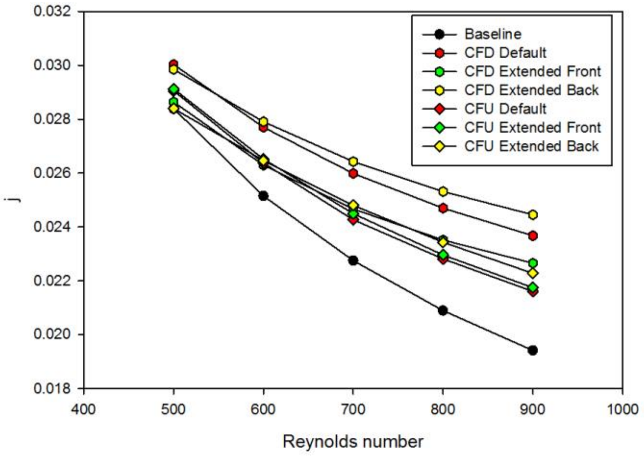


Figure 8 Numerical simulation result on j – Colburn factor

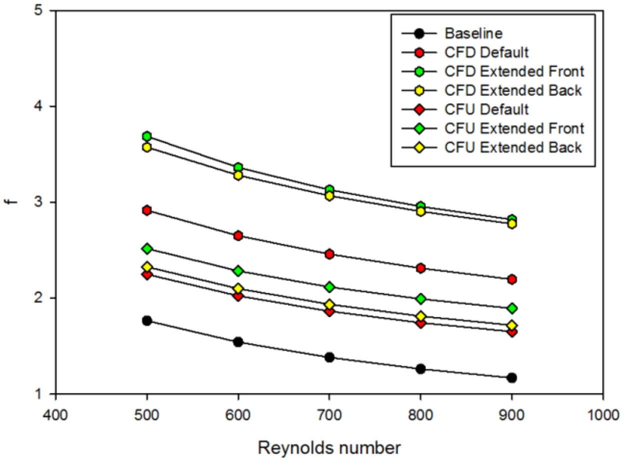


Figure 9 Numerical simulation result on f - friction factor

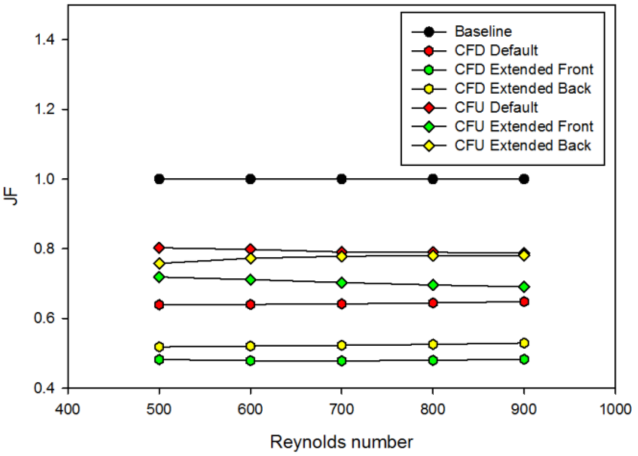


Figure 10 Numerical simulation result on JF factor evaluation

For RWVG in CFU arrangement, the extended front case was found to slightly enhance the heat transfer across the FTHE compared to the default CFU arrangement where the heat transfer enhancement were 2 – 12% and 2 – 11% higher than the baseline case respectively. Meanwhile, the extended back case was found to enhance the heat transfer better than the extended front case and the default CFU case with 5 – 15% enhancement with respect to the baseline case. This phenomenon was due to extended back case directed the main flow towards the rear region and further eliminate the poor heat transfer region behind tubes.

JF factor evaluation used in this study considers both heat transfer enhancement and pressure drop penalty across the FTHE as in Figure 10. The heat transfer enhancement across the FTHE is larger than the pressure drop penalty when the JF value is larger than 1 and vice versa [20, 21]. The baseline case was set as the JF factor reference in this study with the JF factor value is 1. It was found that the pressure drop for all the tested cases in this study is higher than the heat transfer enhancement across the FTHE. JF factor for the default RWVG in CFU arrangement was found to be the highest among other tested cases with average JF factor is 0.8. Meanwhile, the lowest JF factor was shown by the extended front RWVG in CFD arrangement with the average JF factor value is 0.5.

Gholami *et al.* [14] had performed a numerical study investigating the heat transfer enhancement and pressure loss penalty of wavy RWVG across the FTHE. There were two wavy RWVG configurations used known as wavy down RWVG and wavy up RWVG. Note that, wavy RWVG were placed behind the tubes in CFD arrangement. Figure 11 shows the comparison between the present study and the previous study done by Gholami *et al.* [14] with respect to Re = 500. For present study, all the extended cases were selected for the comparison together with the default case of the RWVG in CFU arrangement.

From Figure 11, the extended cases of RWVG in CFD arrangement show lower JF factor performance than the wavy RWVG cases. For similar arrangement behind tubes, the cases of extended RWVG in CFD arrangement provide higher pressure drop penalty than the heat transfer enhancement due to larger vortex generator area facing the main flow compared to wavy RWVG. Nonetheless, RWVG in CFU arrangement shows greater heat transfer enhancement than the pressure drop penalty compared to wavy RWVG cases despite the base length extension. This achievement proved that different vortex generator arrangement behind tubes affect the thermal hydraulic performance across the FTHE. Thus, further parametric study for the RWVG which can be consider as simple geometry is needed to find the optimum parameter that can provide higher heat transfer augmentation and lower pressure drop penalty across the FTHE such as the location of the vortex generator behind tubes.

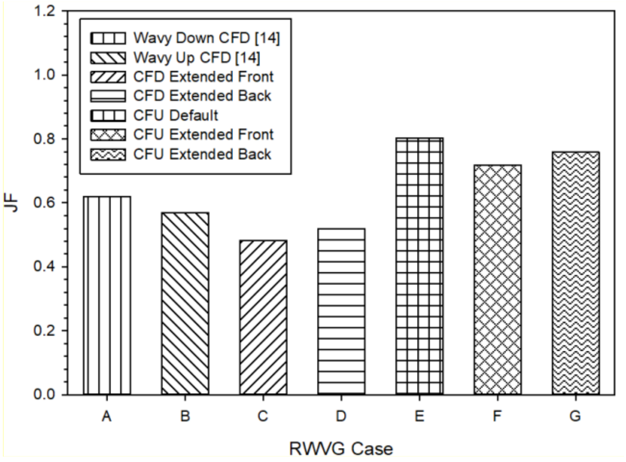


Figure 11 The JF factor for present study and previous study done by Gholami *et al*. [14] for Re = 500.

4.0 CONCLUSION

The flow characteristic and thermal hydraulic performance across the FTHE with different RWVG base length and arrangement behind tubes has been numerically investigated for Reynolds number ranged from 500 to 900. The conclusions for the present study are as follows:

1. The highest heat transfer enhancement for RWVG placed behind tubes is given by CFD arrangement followed by CFU arrangement and FTHE without vortex generator.
2. The size of the wake region behind RWVG plays major role towards the value of pressure drop penalty.
3. Longer RWVG base length downstream in CFD arrangement will further enhance the heat transfer but it comes together with pressure drop penalty increment.
4. Shorter distance between the tube wall and the leading edge of the RWVG in CFD arrangement resulted in lower heat transfer enhancement with higher pressure drop penalty.
5. RWVG in CFU arrangement with longer base length downstream enhance the heat transfer with slight increment in pressure drop penalty than default CFU arrangement.
6. Based on JF factor, RWVG in any cases shows lower heat transfer enhancement across the FTHE than the pressure drop penalty.

Acknowledgement

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