Flow and Heat Transfer Characteristic on the Downstream Surface Using Solid Body and Vortex Generating Jet Turbulators

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Abstract

In this research, flow and heat transfer characteristics that employed solid and jet turbulator types to generate vortex flow were studied using computational fluid dynamics method. Four types of vortex flow generators that consisted of two solid turbulators, a cross fin with a row of circular pins, two vortex generating jets, and a slot jet with a row of circular jets, were installed prior to the heat transfer surface under constant heat flux condition inside the flow channel. The study was conducted under uniform mainstream flow velocity at 5 m/s. For a cross fin with a row of circular pins turbulators, considering as solid body turbulators, each of heat transfer and flow characteristic results were investigated. In case of two vortex generating jets, the results were investigated according to jet velocity to mainstream velocity ratios (VR) of 0.33, 0.6, 1.0, 1.3 and 3.0 to examine the heat transfer of downstream surface. Simulation results shown that all turbulators can generate the swirling flow and then directly affected to enhance heat transfer of downstream surface. A slot jet with a row of circular jets has been effectively produced the swirling flow that similarly to the use of solid turbulators. The results of this particularly study indicated that both slot and circular jets can increase the heat transfer that applied to the solid body turbulators.

Keywords: Eddy current jet, Vortex generated jet, Heat transfer enhancement, Turbulators, Film cooling

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Introduction

The principle of heat transfer on a flat surface is widely applied in heat exchanger devices i.e., fins, pipe wall, and plane wall. Due to the need of compact and economic of devices, heat transfer technique that focus to increase the heat convection ability have been broadly studied. This is because surface convection efficiency depends on many factors such as above surface velocity, flow characteristics and condition, surface pattern and roughness etc.

From the results of past studies, it was found that creating vortices flow on the surface can increase heat transfer. Conventional method to generate vortex flow was to obstruct the mainstream fluid, which flowed adjacent heat transfer surface, by attaching solid body such as pin and fin. For example, the studies from Fiebig (1998) and Aris et al., 2011 and Smulsky et al., 2012 exhibited the vortex flow behavior by installing fins. Vortex flow along downstream direction dominated flow adjacent the surface and shown its effected to increase heat transfer of downstream surface. The main reason of such heat enhancement was that the mechanism of vortex flow brought above fluid to flow impinging the surface, and then the thickness of boundary layer was disturbed and reduced consequently. On other hand, the emerged of vortex flow could increase heat transfer coefficient of the underneath surface. Strength of vortices flow gradually decayed according to distance from fin position. So, heat transfer enhancement ability represented the highest at downstream of pin location and reduced along downstream position. Nevertheless, Narato et al., 2021 proposed that the heat transfer characteristics could be dominated by various variables such as distance between pins, pin length, arrangement patters. In general, employed solid body to generate vortex flow over surface was concluded that could increase heat transfer efficiently, but the main disadvantages of this technique that obstructed of fluid flow led to consume more pumping power, increase flow friction, could not change heat transfer rate, generate hot spot area due to low heat transfer coefficient as reported by Axtmann et al., 2016 and Jacobi et al., 1995.

To avoid disadvantages from the effect of installing the solid body, Prince et al., 2009 exhibited that the injection the jet stream across mainstream flow direction was alternative method to generate vortex flow over surface to promote heat transfer rate. The type of generated flow was called counter rotating vortex pair, CRVP. The resulting of CRVP form shown various beneficial effects on surface flow such as reduction in separation flow and drag of aircraft wing surfaces, which reported by Zhang (2000). And Puzu et al., 2019 proposed the relation between flow behavior and heat transfer enhancement region. Jabbal and Zhong (2008) demonstrated the trajectory of jet stream after injecting into mainstream which could promote heat transfer of underneath vortex flow surface. Strength of CRVP closely associated ability to increase heat transfer. So, the area adjacent to jet hole had better heat transfer than that those away region. Similar to solid body, heat transfer enhancement by injecting jet stream to create like vortex flow also dominated by various such as injection velocity (referring to jet to mainstream velocity ratio, VR), hole configuration, injection angle, etc.

Although both of turbulators (solid body and jet) can create vortex like flow and promote heat transfer of downstream surface efficiently. However, the information from previous study has not yet been discussed the ability in enhancing heat transfer. This research therefore simulates the flow in a channel to compare the flow characteristics and heat transfer on the surface among of turbulators; 1. a cross fin 2. a row of circular pins 3. a slot jet, and 4. a row of circular jets employing CFD technique.

Numerical analysis

1. Mathematical model

The numerical model of channel flow, as shown in Fig.1, was performed using the ANSYS FLUENT program by separating the control equation into an algebraic form. The SIMPLE algorithm (semi-implicit method for pressure linked-equations) and the k-ε model were used with the criterion to stop processing at an error value lower than 1.0E-5. The processing time was 30 to 60 hours depending on each case. Specification of lab top are Intel CORE i7 CPU 3.40 GHz.

The heat transfer on the surface is expressed as a dimensionless variable Nusselt number, as equation (1) is

$$N_u = \frac{hD}{k_f} \quad (1)$$

Where h is the convection coefficient on the surface at the considered position D. There are 4 cases composed of 1. Thickness of the fin 2. Jet slot width 3. Circular pins diameter 4. Diameter of jet hole which is equal to 4 mm and k_f is the thermal conductivity of air.

2. Study parameters

Fig. 2 shows the dimensions of the four numerical models, where the cross-sectional area of the channel is 300x26.4 mm^2, length 2,450 mm. The number of circular pins is 22, and the circular jet is 22 holes, which was placed across mainstream flow direction. The distance between the center of the pins or the jet holes is 12 mm. In the case of a jet, the parameter used to express the jet velocity is the velocity ratio (VR) which can obtained from the equation VR = V_j / V_m where V_j is the jet velocity and V_m is the average velocity of the mainstream. The details of the variable values are shown in Table 1.

Table 1. Details of parameters

Simulation	Velocity ratio, VR	Number of elements
Cross fin	-	2,276,550
Slot jet	0.33, 0.6, 1.0, 1.3, 3.0	2,848,500
Circular pins	-	3,446,490
Circular jets	0.33, 0.6, 1.0, 1.3, 3.0	3,421,516

mainstream velocity (m/s); 5

mainstream Reynolds number; 15,090

mainstream, jet temperature (K); 300

Heat flux (W/m^2); 137.6

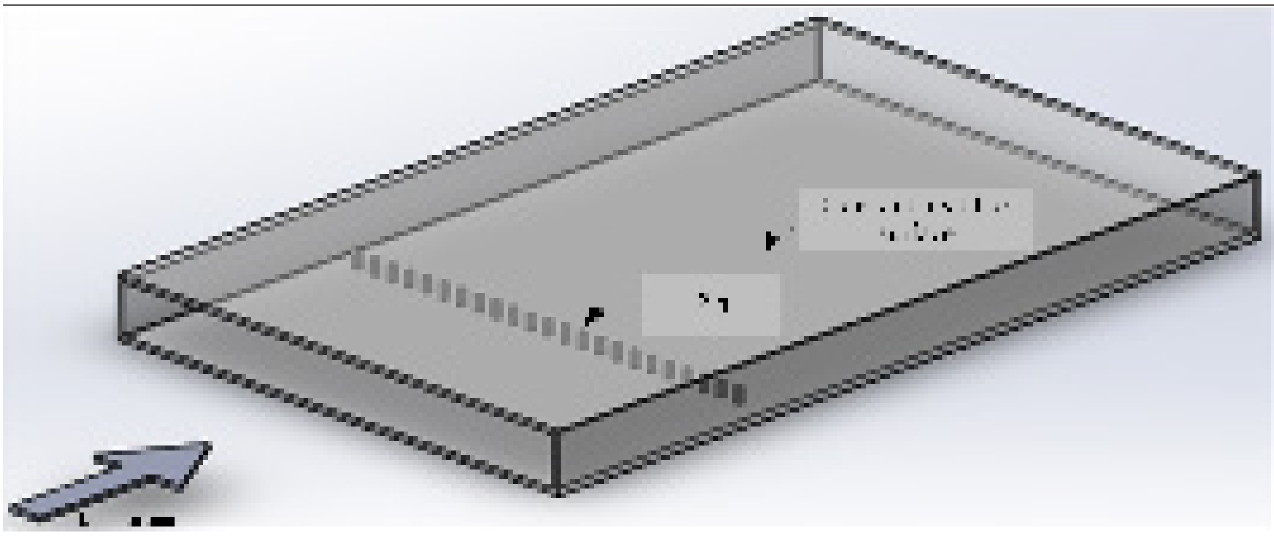

Figure 1. Numerical model of flow channel

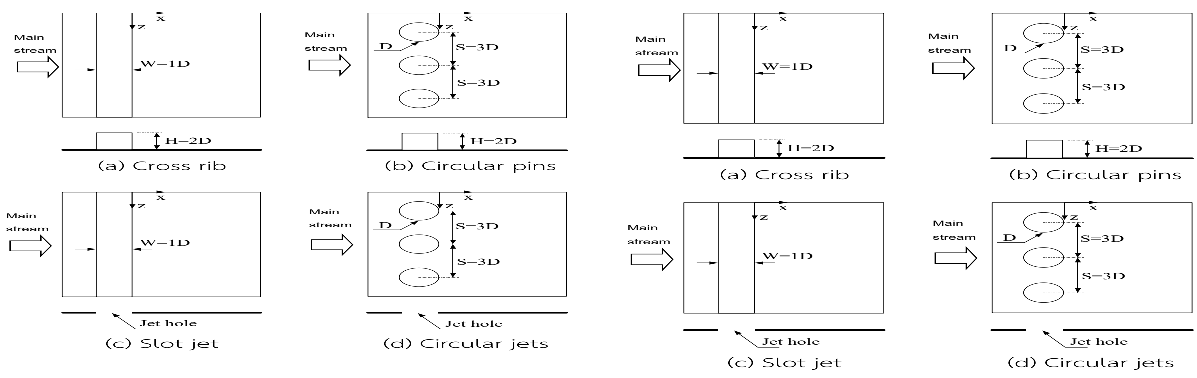

Figure 2. Dimensions of the turbulator in each case.

Results and discussions

Comparison of simulation results is divided into 2 cases; 1. cross fin and a circular pin, 2. Slot jet and circular jet. Vortex flow behavior and downstream surface temperature are focused to discuss the heat transfer results of both turbulators.

1. Flow characteristics of vortex

In the case of cross fin and slot jet. The swirling flow that occurs in both cases is the reverse flow behind the pin or the jet hole. Fig. 3a shows the velocity on the x-y plane at the center of channel of x/D= 4, 8, 16 and 32. For the mainstream velocity is 5 m/s, upstream fluid is lifted across the cross fin and pin while the bottom part hits the fin surface, and then CRVP are established. The cross-sectional area of the flow channel at the pin location is equal to 70 percent of the entire cross-sectional area, resulting in an average mainstream velocity higher than 5 m/s. For the velocities at the of x/D= 4 and 8, circulation flow associating reverse flow phenomena is established at the level of 5 and 6 mm from surface, respectively. But, at distance x/D= 16, negative velocity is absent, thus indicating that swirling does not present. This indicates that the point at which the fluid stream impinging the surface and then splitting into two parts is the reverse flow along the surface, which locates in the range of x/D=8 and 16. In this case, the center of impingement is at 56 mm of x/D=16 position. The velocity distribution of the mainstream begins to adjust to its original distribution before passing through the pins which can be seen that the velocity is reduced while the speed below increases with the distance from pin position.

In the case of slot jet, the velocity distribution characteristic depends on the velocity ratio (VR). When VR is low, VR=0.33, deformation of the velocity distribution is minimal near the bottom surface, as shown in Fig. 3b.

It will be noticed that the velocity closed to the pin position is less than at the away position due to the jet effect. While the upper velocity distribution is closed to each other in every position. It showed that the jet stream does not interfere the above mainstream due to low momentum jet injection cannot penetrate the much higher mainstream momentum flow. As the velocity ratio increases, the change in velocity distribution becomes more apparent. At VR=0.6, the velocity distribution that continuously develop can be investigated. When VR=1.0 at position of x/D=4, as shown in Fig. 3d, the reverse flow is appeared. The velocity difference of velocity profile at vertical direction of channel can be seen clearly. For VR=1.3 and 3.0, the strength of swirling flow is increased corresponding to higher jet velocity. At VR=3.0, the distribution of velocity along downstream direction is similar to the cross rib case. Nevertheless, there is a distinct difference that velocity distribution of the slot jet is not a smooth curve as the case of pins. When VR increase, the high-momentum jet can deeply penetrate mainstream fluid. The shear forces from different velocity layers between the jet and mainstream retards the velocity of mainstream, resulting in the different distribution of velocity to the case of fins. This phenomenon decreases at the positions further away from the jet exit due to decrease in jet momentum, and finally jet stream is engulfed by mainstream.

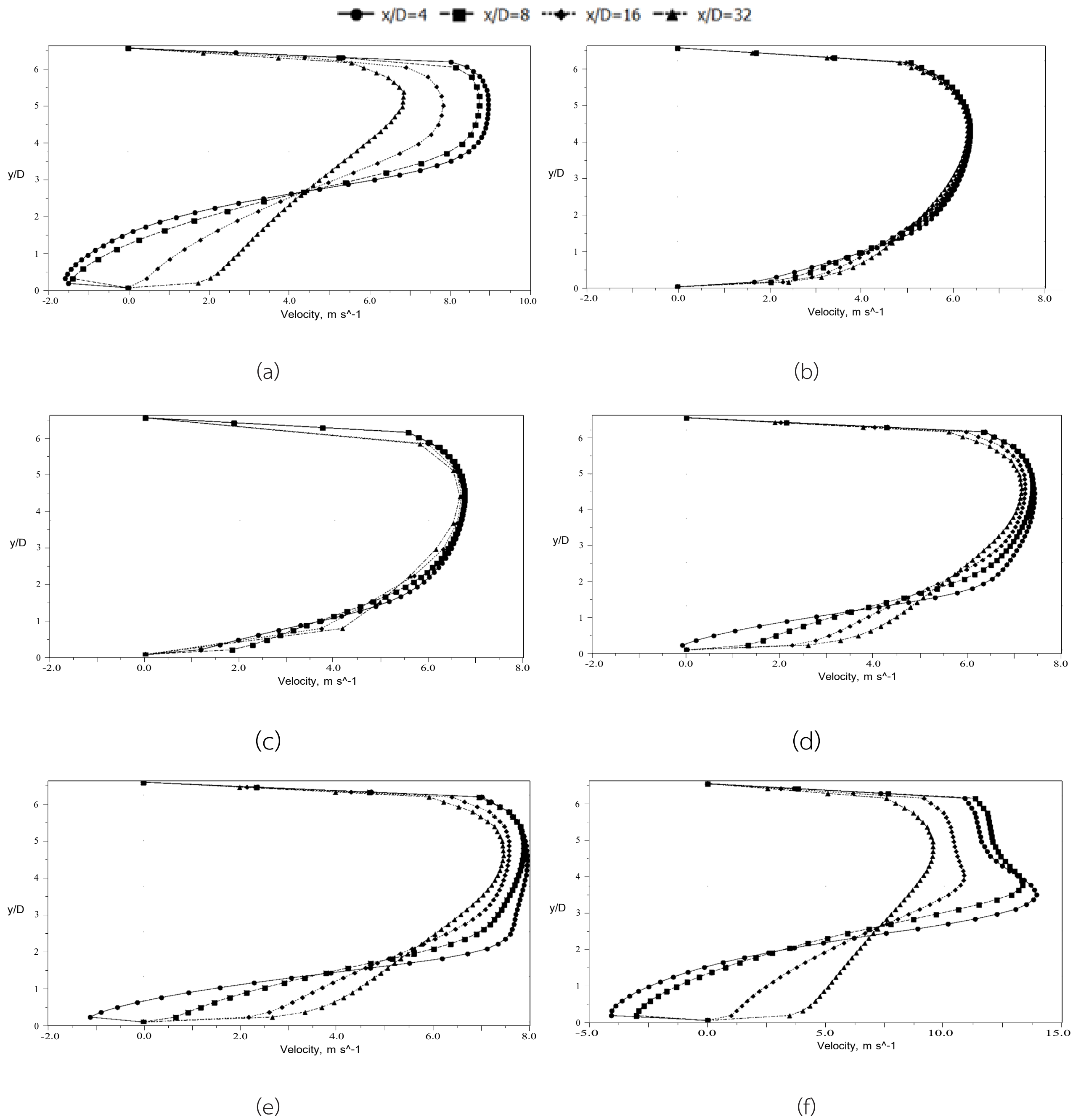

Figure. 3 The velocity distribution of the mainstream at distances x/D= 4, 8, 16 and 32 in each case by (a) cross fin (b) slot jet at VR=0.33. (c) slot jet at VR=0.6 (d) slot jet at VR=1.0 (e) slot jet at VR=1.3 (f) slot jet at VR=3.0

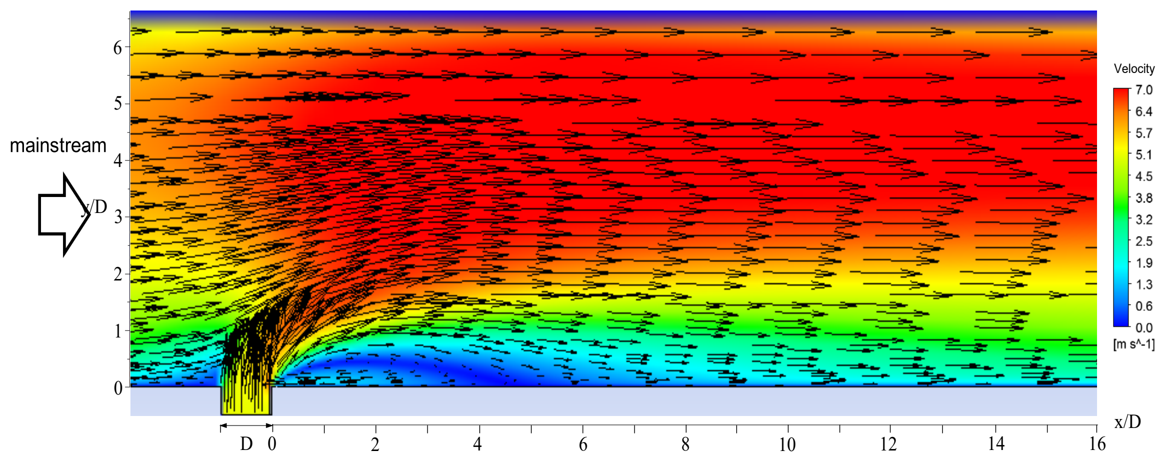

Figure. 4 The direction and velocity magnitude of mainstream behind the jet hole in the center plane of the exit

From Fig. 4, the highest velocity in center plane of jet hole increases. It is due to injection the jet stream obstructs the mainstream at lower part of channel, and then velocity at upper section of channel is increase similar to flow across fin.

To compare flow characteristic, swirling flow between a circular pin and a circular jet. For jet, a pair of rotational flow is occurred on jet stream fluid itself while rotational flow in case of circular pin is generated on mainstream fluid. Fig. 5 shows the velocity vector of mainstream on the perpendicular plane at the distances of x/D= 4, 8, 16 and 32 at the velocity ratio of 0.6 and 1.3 for the circular jet and the circular pins with mainstream velocity of 5 m/s. Figure 4a represented that when the mainstream reaches to the pin, there will be a flow around and exhibits circulation flow which presents the reverse direction into the pin. This result is from sheer force in between fluid layer when contact to the pin surface.

Fig. 6 b, for jet, shows that the strength of circulation flow after jet interacting with mainstream at low velocity ratio is also low, but the circulation pattern is the same when the mainstream interacts with the jet injecting from the surface. Mainstream is separates around the jet bundle after reaching at upstream of jet hole. This flow mechanism between jet and mainstream dominates by shear force of both fluid that presents the difference in velocity vector. Then, the counter rotating vortex pair, CRVP, due to the induction of the mainstream around the jet is generated on jet stream. Left hand and right-hand sides of CRVP rotates in opposite directions. The side where the flow approaches the surface is called the down wash, and the side where the flow moves upward is called the up-wash side. The up-wash position is located at the center of the jet hole which shows where the position of both side of CRVP contact. For strength of CRVP, it depends on the VR and the distance along downstream direction. The strength at position close to jet hole is high and gradually decrease according to downstream distance. At VR=0.6, it can be observed that the CRVP at the distance x/D=32 does not appear due to low original strength of CRVP after jet-mainstream interaction at the hole and then cannot maintain the swirl flow at far position.

From the simulation results of flow characteristics behind the jet holes and circular pins shows that CRVP are generated and flow along downstream over heat transfer surface, but characteristics are difference. The CRVP of pin study is occurred with the mainstream. But, at the meanwhile, with jet study CRVP is formed into jet stream itself.

2. Downstream surface heat transfer

The heat transfer on the downstream surface is expressed as a dimensionless variable Nusselt number as shown in equation 1 to describe the heat transfer ability. For convection coefficient, it can be calculated the equation $h = Q/(T_s-T_f)$. Where Q is the heat flux supplied to the downstream surface of pin or jet, which is

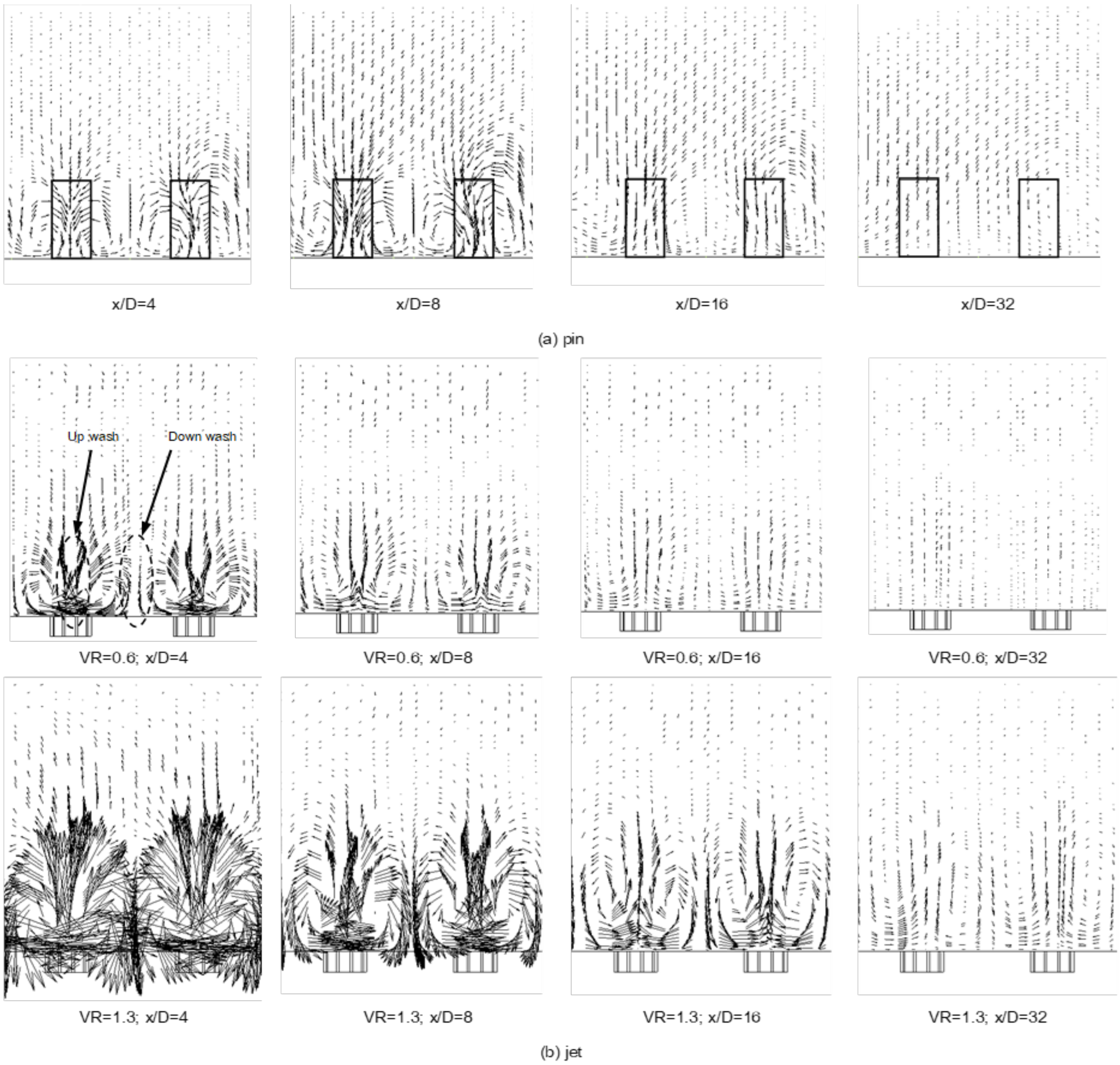

Figure 5. Velocity vectors in perpendicular plane to the mainstream flow direction at distances of x/D= 4, 8, 16 and 32 where (a) circular pins (b) circular jets.

137.6 W/m^2. T_s is the surface temperature, and T_f is the temperature of mainstream, which is 300 K. For the K_f, it is equal to 0.02558 W/m K, which considers at film temperature of air at 301 K.

Fig. 6 shows the temperature distribution on the surface at VR=1.0. The highest heat transfer, at the position of x/D=5, showing the lowest temperature area, is shifted away from rib region near the fin to compare with low VR. This area relates to mainstream reattach flow position, resulting in enhancing heat transfer.

From Fig. 7, the Nusselt number on the surface in the case of cross fin at the downstream position near the fin is relatively low due to the back flow effect and low flow velocity. Far from this position, the Nusselt number increases with the highest value at x/D=14. This result corresponds to where the mainstream behind the fin presents reattach flow

phenomena of mainstream fluid passing the fin. After reaching the highest value, heat transfer on the surface starts to decrease progressively.

In the case of the slot jet, at region close to the jet hole with the lowest VR, the Nusselt number is very high. But it will decrease very quickly as well. This is due to low momentum of jet stream is immediately bended and flow attaching to the surface form retarding force by mainstream which presents much higher momentum. Then, heat transfer of area adjacent to the jet hole is promoted. But in the case of high VR, the downstream heat transfer close to jet hole is reduced when the CRVP is presented which is similar to the case of cross fin.

When comparing the heat transfer between the cross fin and the slot jet, it is found that heat transfer using slot jets can create CRVP and shows better heat transfer rate near the jet holes, but cross fin exhibits better heat transfer for far distance instead.

Fig. 8, two local surface Nusselt number, line of the jet hole center or pin and center of between jet holes or pins, in the case of circular pins and circular jets is represented.

In the case of pins, for near pin position, it is found that the Nusselt number on the line pin center has better heat transfer rate than the line of center of between pins. To consider the flow behavior, low heat transfer at pin center reasons from reverse flow behavior. For away position, heat transfer in this line becomes higher due to the mainstream that flow around pin combine at the pin center and creates swirling flow over surface.

In the case of a circular jet, the heat transfer between the center of the jet holes and the center between the jet holes is also different. For near jet hole position with low VR, Nusselt number on the line the center between the jet holes higher than jet hole center line is observed. But heat transfer dramatically decreases for away position due to rapidly engulf of jet stream by mainstream.

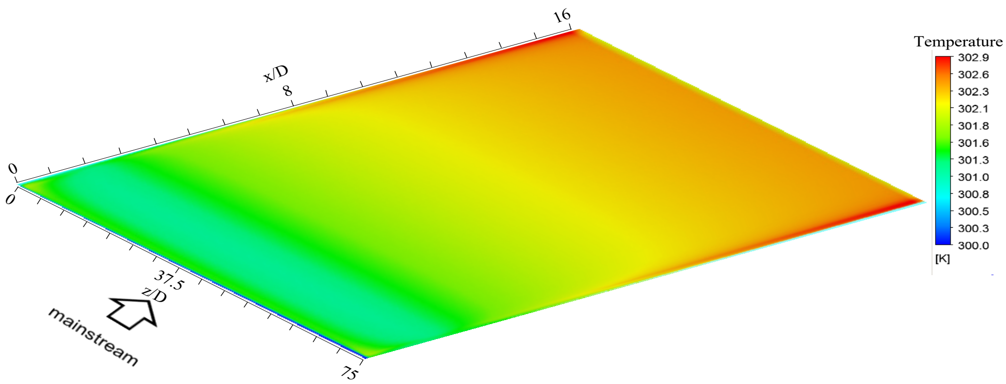

Figure 6. Downstream surface temperature distribution at VR=1.0

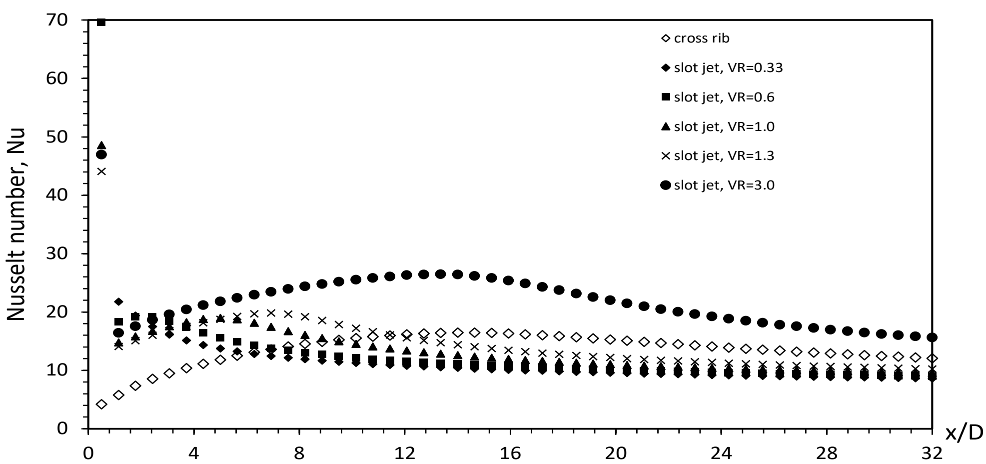

Figure 7. Nusselt number for cross rib and slot-jet

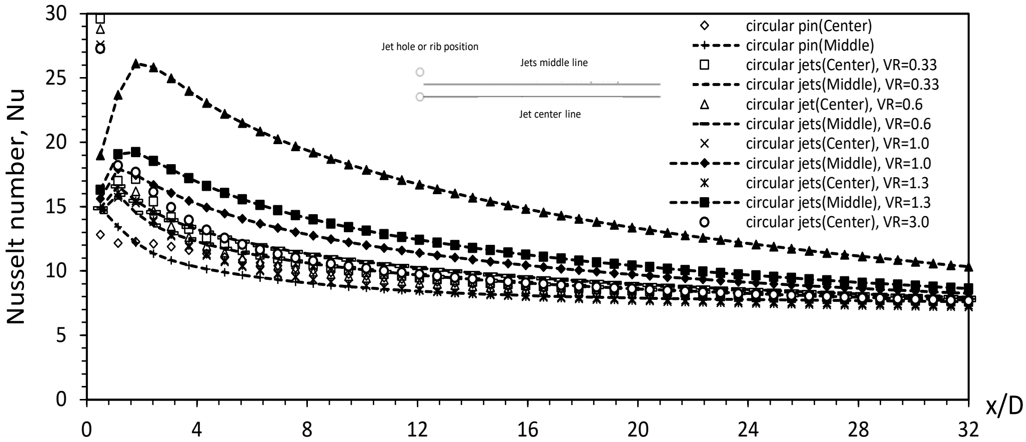

Figure 8. Local Nusselt number for circular pin and a circular jet

The heat transfer at the line center between the jet holes is attractive due to display much higher than the jet hole center line for all VR especially for lager magnitude. Higher VRs even show much difference in heat transfer between 2 lines. To consider flow characteristics that occur on 2 lines, it was found that area around jet centerline relates to the downwash position, which the swilling flow direction point into surface, and area around line of center between jet centerline corresponds to upwash position. This result can conclude that heat transfer of area under downwash position is increased and meanwhile area under upwash position is decreased.

Conclusions

Simulation results of flow and heat transfer characteristics under influence of 4 types of turbulators; 1. cross fin, 2. a row of circular pins, 3. slot jet, and 4. a row of circular jets can be concluded as follows:

Swirling flows established from cross fin and slot jet are similar. Mainstream after passing cross fin and slot jet will impinge the surface, resulting to enhance the heat transfer of downstream surface, and some of mainstream flows backward, creating low heat transfer area behind the cross fin or slot jet region.

For circular pin, heat transfer on the area between pins is higher than that centerline regions of pin. This is due to passing flow of mainstream generates swirling flow, calling counter rotating vortex pairs, CRVP, which the CRVP flows into the surface direction, calling downwash flow, at the area between the pins.

For circular jet, injecting jet perpendicular mainstream flow direction can generate CRVP on jet stream bundle itself. The generated CRVP plays an important role in heat transfer characteristics of downstream surface. The region of jet hole center line that corresponded to downwash position, shows higher heat transfer than that area around between jet hole center line, which relates to upwash flow position.

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