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Research Article

The Effect of Inlet Baffle on the Skin Friction Coefficient and Turbulence Intensity in an Air-Cooled Channel

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Abstract

This study addresses the impact of an inlet baffle mounted opposite a hot surface on the properties of turbulence and flow resistance in an air-cooled channel. This study focuses on analyzing the variation in the skin friction coefficient and air turbulence intensity along the hot surface. The influence of an inclined baffle angle α = 15−60° and relative baffle length L_n = 0.625−0.875 under the Reynolds number spectrum Re = 4000−16000 was considered. Results indicated that turbulence intensity increased when the Reynolds number increased, the baffle length increased, or the inclined baffle angle decreased. The skin friction coefficient increased when the Reynolds number decreased, the baffle length increased, or the inclined baffle angle decreased. The maximum heat transfer rate occurs at α = 15°, L_n = 0.875, and Re = 16000, and vice versa at α = 60°, L_n = 0.625, and Re = 4000. In comparing the lowest and highest heat transfer configurations, the skin friction coefficient decreased by 77.9 %, and turbulence intensity decreased by 97 %. This means that heat transfer can be increased at the cost of higher pump power. The results of this study contribute to a more comprehensive understanding of the effect of an inlet baffle on fluid chaotic motion and flow resistance, as well as the mechanism that leads to the variation in heat transfer ability and pressure loss in the channel under the impact of the inlet baffle.

Keywords: *Air-cooled channel; baffle; numerical simulation; skin friction coefficient; turbulence intensity.*

1. Introduction

Enhancing heat transfer in thermal equipment is important in improving efficiency, reducing equipment size, and minimizing the impact on climate change. Therefore, many strategies have been used to increase the heat transfer rate, such as by adding baffles, adding fins, creating ribs, using nanofluid, adding an insertion, and creating dimples [1-3]. The research results have provided potential solutions for practical applications. In many fluids, air is the fluid commonly used in cooling applications. Besides advantages such as availability and simplicity in use, the disadvantage of air is its low heat transfer ability. Therefore, increasing the heat transfer rate towards the air side is a main strategy for improving cooling efficiency. The use of baffles to change flow structure is one of the methods many researchers have pointed out as having the potential to improve heat transfer rate. Yilmaz [4] experimentally studied heat transfer and pressure loss in an air-cooled channel with an inlet baffle. Results showed that the heat transfer and friction factor were 1.39−2.43 and 28.26−94.45 times higher, respectively, than with a smooth channel. Menni et al. [5] analyzed channels with multi-baffles. The results showed that heat transfer and friction factor were 3.623−5.008 and 10.829−25.412 times higher, respectively, than with the smooth channel. Ameur [6] studied air-cooled channels using an inclined baffle. Results indicated that the straight baffle yields a wider vortex than the inclined baffle. Promvonge et al. [7] examined a channel with an arc-shaped baffle. They reported that heat transfer was enhanced, but pressure loss increased significantly. Luan et al. [8] analyzed multi-objective optimization in an air-cooled channel. They concluded that thermohydraulic performance increased with a decreasing Reynolds number, increasing baffle angle, and increasing clearance ratio. Saha et al. [9] studied channels with variable baffle positions. They reported that a turbulent airflow structure greatly affects heat transfer and pressure loss. Salhi et al. [10] investigated channels with partially inclined baffles. Results indicated that increasing the height and number of baffles enhanced heat transfer. Menni et al. [11] tested channels with S-shaped baffles. They commented that the use of baffles enhances heat transfer. Boonloi et al. [12] studied channels with V-shaped baffles. They reported that using a V-baffle increased heat transfer by 1.04−15.55 times, and friction factor increased by 1.71−112.08 times, compared to a smooth channel. Many studies that have used baffles to enhance heat transfer in air channels can be found in the literature [13]. The literature review reveals that using baffles in air-cooled channels has been a topic of interest to many authors. The results of the studies have provided valuable reports on thermohydraulic properties in channels.

Flow structure greatly affects heat transfer and pressure loss in the channel. Flow turbulence is closely related to the

Reynolds number and channel geometry. Therefore, the study on the flow and heat transfer properties is necessary for orienting the geometric shape change suitable for practical applications. Some authors have analyzed and evaluated this in previous studies [14, 15]. The researchers of [4, 8] discussed the impact of the inlet baffle on the overall heat transfer and pressure loss values in air-cooled channels. However, the chaotic motion and flow resistance properties along the hot surface have not been analyzed. Thus, this study extends the analysis of turbulence intensity and skin friction coefficient along the hot surface to elucidate the impact of the inlet baffle on fluid chaotic motion and flow resistance, to clarify the mechanism leading to the variation in heat transfer ability and pressure loss in the channel. Overall, the obtained results provide a comprehensive view of the impact of inlet baffles on flow characteristics along the hot surface, providing valuable insights for both theoretical understanding and practical applications when considering the use of an inlet baffle in an air channel.

2. Analytical Method

Figure 1 shows the computed domain with a 320 mm test section length, 80 mm channel height, 600 mm entrance section length, 300 mm exit section length, and 160 mm channel width. Geometric parameters are referenced from the research of Yilmaz [4]. Inside the channel was a baffle with an inclined angle $\alpha = 15-60^o$ and relative length $L_n = 0.625-0.875$ ($L_n = a/H$). The inlet air temperature was 300 K, and the heat flux supplied to the hot surface was 1000 W/m^2. Air leaving from the exit section was set up as equal to atmospheric pressure. The upper wall was set up with the adiabatic boundary condition. The no-slip condition was set up for the solid walls.

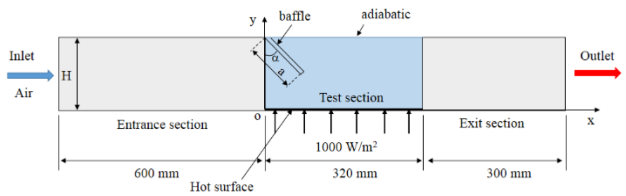


Figure 1. Computed domain.

Figure 2 shows the meshing in the computed domain with a hexahedral mesh and the creation of a five-layer mesh reinforcement. The thickness of the first layer ensures that the near-wall element spacing is approximately equal to unity. Four mesh levels were used for grid-independent tests (see Figure 3). From the results obtained, the mesh size corresponding to 169525 elements was chosen. It reduces the simulation time but still ensures the accuracy of the results.

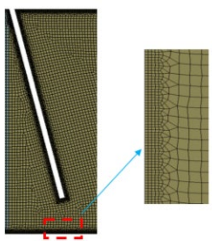


Figure 2. Mesh in the computational domain.

The difference in air temperature between the outlet and the inlet of the test section is small. To simplify the solution approach, we assume incompressible flow, steady-state heat transfer, ignore the effect of gravity, and negligible radiation heat transfer. We also assume that the air physical parameters are constant and referenced at 300 K [8]: ρ = 1.117 kg/m^3, c_p = 1007 J/kg.K, k_a = 0.0262 W/m.K, μ = 1.857×10^{-5} kg/m.s. The standard k−ε turbulence model was used in the present work based on previous work [8], and its equations can also be found in the literature [16]. In this work, the residual for the equations of continuity, momentum, energy, k, and ε was 10^{-6}. The SIMPLE algorithm was used to deal with the problem of velocity and pressure coupling. Figure 4 shows the validation results based on data from the reports of Yilmaz [4]; high agreement is observed. Therefore, the simulation settings are suitable, and the results are analyzed and discussed in the next section.

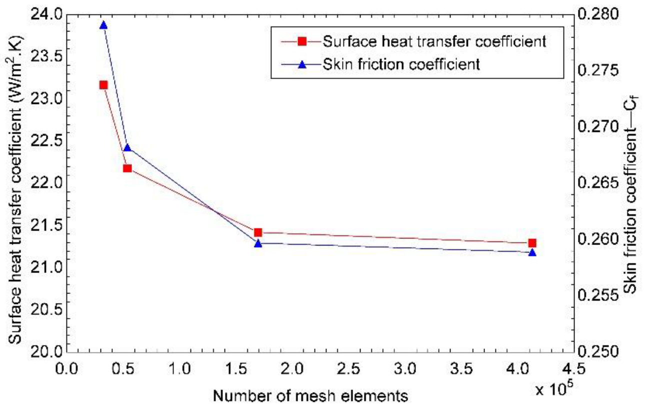


Figure 3. Grid independence test.

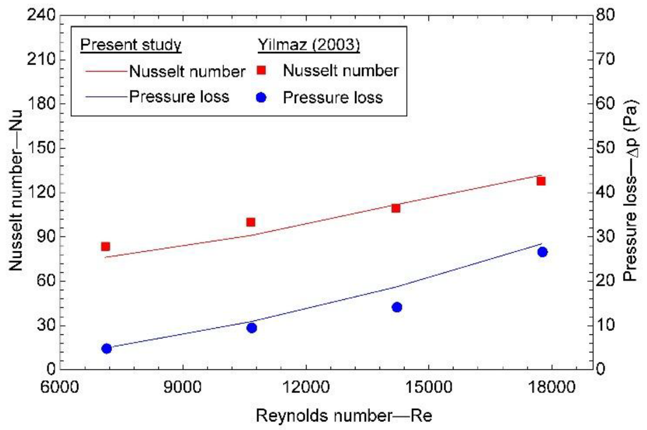


Figure 4. Validation based on the experiment of Yilmaz [4].

Under the above assumptions, the governing equations are as follows [8]:

The continuity equation:

$$\frac{\partial\left(\rho u_j\right)}{\partial x_j} = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial\left(\rho u_i u_j\right)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left[\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

The energy equation:

$$\frac{\partial}{\partial x_j}\left(u_j \rho T\right)=\frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{\mathrm{Pr}}+\frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_j}\right] \tag{3}$$

The hydraulic diameter was calculated using the following formula [17, 18]:

$$D_h=\frac{4(HW)}{2(H+W)} \tag{4}$$

The Reynolds number was determined using the following formula [17, 18]:

$$\mathrm{Re}=\frac{u\rho D_h}{\mu} \tag{5}$$

The turbulence intensity was computed using the formula [19]:

$$I_t=\frac{1}{u_m}\sqrt{\frac{2}{3}k} \tag{6}$$

The skin friction coefficient was expressed as follows [19, 20]:

$$C_f=\frac{\tau_w}{\frac{1}{2}\rho u^2} \tag{7}$$

The ratio of the average temperature of the hot surface with inlet air temperature was expressed as follows:

$$T_R=\frac{T_w}{T_i} \tag{8}$$

3. Results and Discussion

3.1 Effect of the Reynolds number and Baffle on the Skin Friction Coefficient and Turbulence Intensity

Figure 5a shows the effect of the Reynolds number on C_f along the hot surface in the case with $\alpha = 30^o$ and $L_n = 0.75$. It can be seen that C_f decreased when the Re increased. The reason for this may be that the increase in the wall shear stress was lower than the increase in the square of reference velocity (inlet velocity) when the Re increased, resulting in a decrease in the C_f. The highest C_f was found at points $X_d = 0.133$ for Re = 4000, $X_d = 0.129$ for Re = 8000, $X_d = 0.138$ for Re = 12000, and $X_d = 0.145$ for Re = 16000. These are locations with high differences in velocity gradient. At Re = 4000, the average C_f increased by 13.1 %, 19.9 %, and 22.9 % compared to the cases of Re = 8000, Re = 12000, and Re = 16000, respectively. The decrease in C_f with increasing Re is consistent with the trend of the decreasing friction factor with increasing Re, as previously reported [4]. Figure 5b shows the influence of the Reynolds number on the turbulence intensity of flow along the hot surface. It can be seen that increasing the Re significantly increased the I_t. This is because at high Re, inertial forces dominate, resulting in increased turbulence and strong energy transfer in the flow. Therefore, increasing Re is the reason for the increase in heat transfer between the hot surface and the airflow. At Re = 16000, the average turbulence intensity is 1.4 times, 2.3 times, and 4.9 times higher than at Re = 12000, Re = 8000, and Re = 4000, respectively.

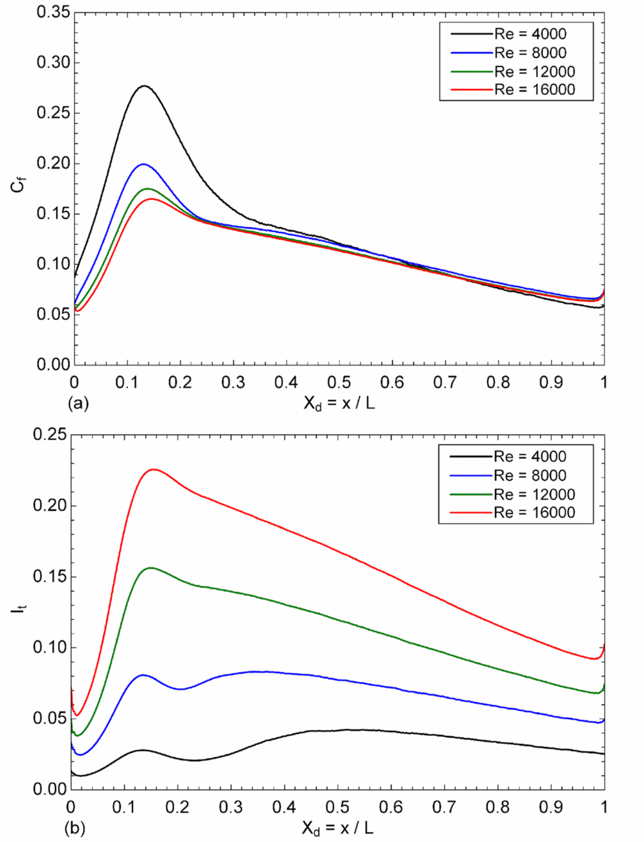
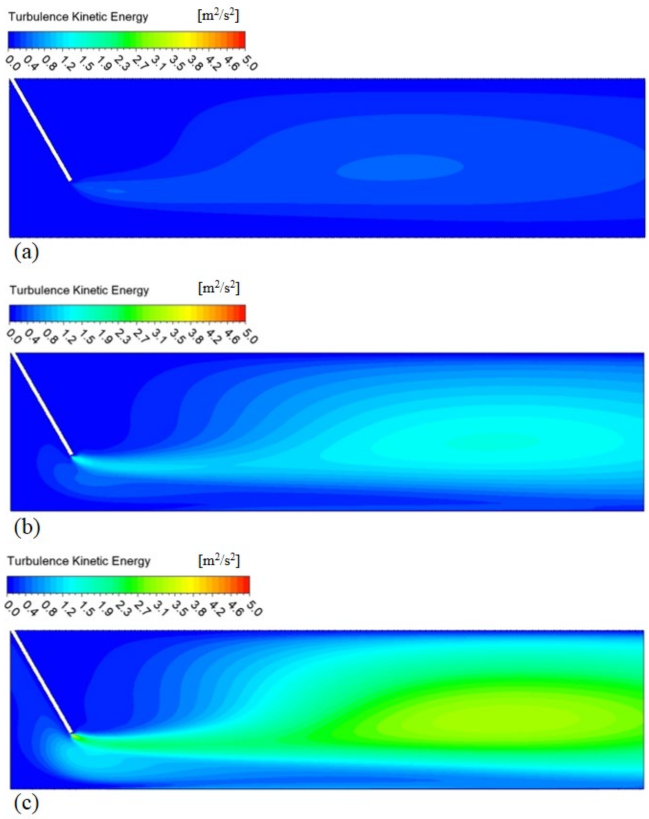


Figure 5. Effects of Reynolds number: (a) local skin friction coefficient; (b) local turbulence intensity.

Figure 6(a−d) show the turbulent kinetic energy contour in the cases under analysis. Higher turbulent kinetic energy was observed at high Reynolds number. This demonstrates that increasing the Reynolds number increases the turbulence intensity in the domain and along the hot surface, which agrees with the previous analysis.



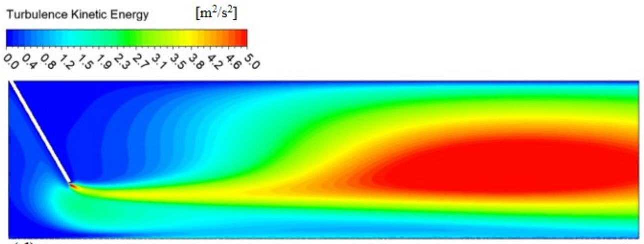


Figure 6. Turbulent kinetic energy contour with different Reynolds numbers: (a) Re = 4000; (b) Re = 8000; (c) Re = 12000; (d) Re = 16000.

Figure 7a shows the influence of baffle length on C_f along the hot surface in the case with $\alpha = 30^o$ and Re = 8000. The results show that increasing the L_n increased the C_f. This is because the air velocity after passing through the baffle suddenly increases, increasing the air-layer velocity gradient along the hot surface, leading to an increase in wall shear stress, or an increase in C_f. The longer the baffle, the higher the C_f. This means that increasing the baffle length increased the pressure loss, which is consistent with the report in the literature [4]. The average C_f at $L_n = 0.625$ decreased by 44.2 % and 72.5 % compared to the cases of $L_n = 0.75$ and $L_n = 0.875$, respectively. Figure 7b shows the effect of baffle length on turbulence intensity along the hot surface. It can be observed that the turbulence intensity increased with increased baffle length. Increasing the baffle length increases the air velocity after passing the baffle, leading to increased turbulence and increased mixing. This increases the rate of energy transfer in the flow. Therefore, increasing the baffle length increases the heat transfer in the channel. The turbulence intensity of the shortest baffle decreased up to 69 % compared to the longest baffle.

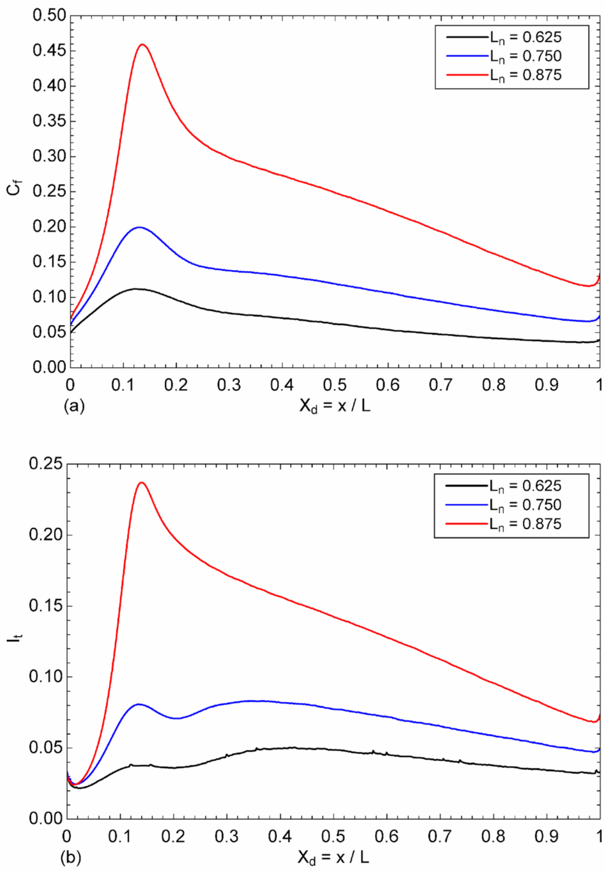


Figure 7. Effects of baffle length: (a) local skin friction coefficient; (b) local turbulence intensity.

Figure 8(a–c) show the turbulence kinetic energy contour of the case under analysis. High turbulent kinetic energy levels were observed for high L_n. This result demonstrates that increasing L_n increases the turbulence intensity in the domain and along the hot surface, which is consistent with the previous discussion on the effect of L_n. From the analysis results, it can be seen that an increased baffle length increased the skin friction coefficient and increased turbulence intensity along the hot surface. This clearly explains the motivation for increases in heat transfer and pressure loss in the channel when increasing baffle length.

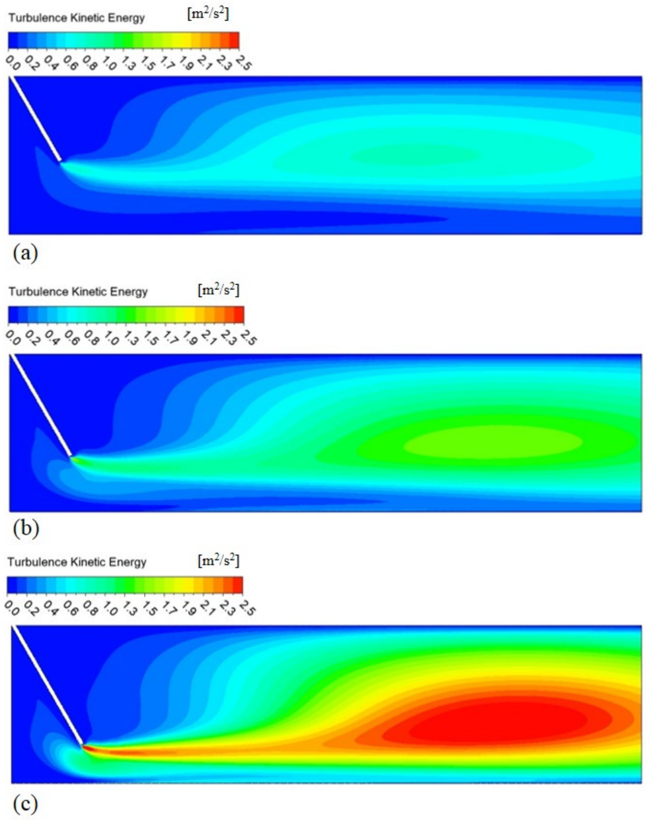


Figure 8. Turbulent kinetic energy contour with variations in L_n: (a) $L_n = 0.625$; (b) $L_n = 0.75$; (c) $L_n = 0.875$.

Figure 9a shows the effect of the inclined baffle angle on the C_f along the hot surface in the case with $L_n = 0.75$ and Re = 8000. The results indicate that a decreased inclined baffle angle results in an increased C_f. This can be explained by the fact that decreasing α leads to a decrease in the free flow cross-section, increasing the flow velocity after exiting the minimum gap between the baffle and the hot surface. This increase in velocity increases the air-layer velocity gradient along the hot plate, or in other words, it increases the wall shear stress and C_f. This means that decreasing α increased the pressure loss. The average C_f of the case with $\alpha = 60^o$ decreased by up to 88.2 % compared to the case with $\alpha = 15^o$. The effect of the inclined baffle angle on turbulence intensity is shown in Figure 9b: a decreased inclined baffle angle results in increased turbulence intensity. This is due to the increase in velocity gradient as α decreases. The increase in I_t explains the increase in heat transfer between the airflow and the hot surface. The average turbulence intensity at $\alpha = 60^o$ decreased by 84.5 %, compared to that at $\alpha = 15^o$.

Figure 10(a–d) show the turbulence kinetic energy contour for the cases under analysis. The results indicate that a decreased inclined baffle angle increases turbulent kinetic energy in the domain. Overall, the turbulence intensity along the hot surface increased, which is consistent with the previous analysis.

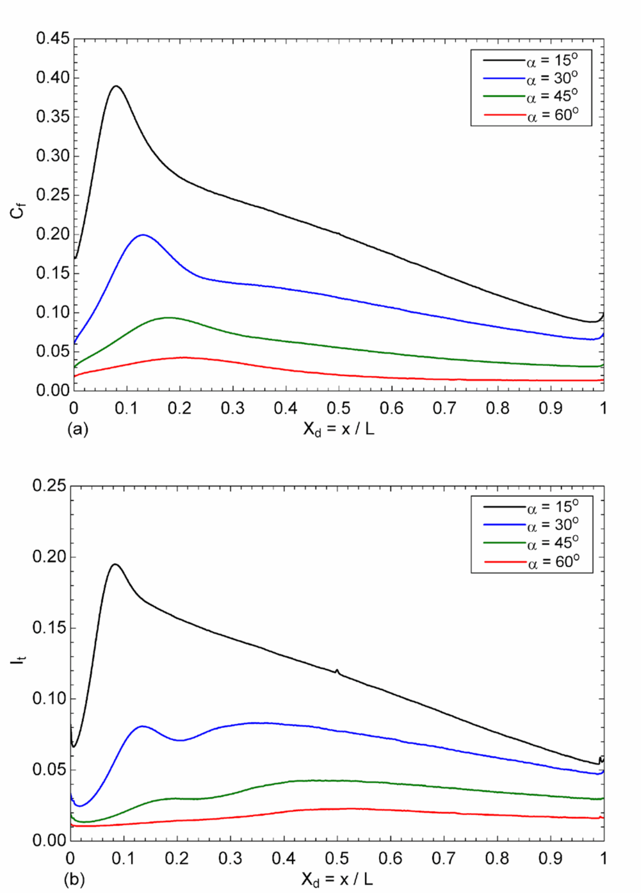
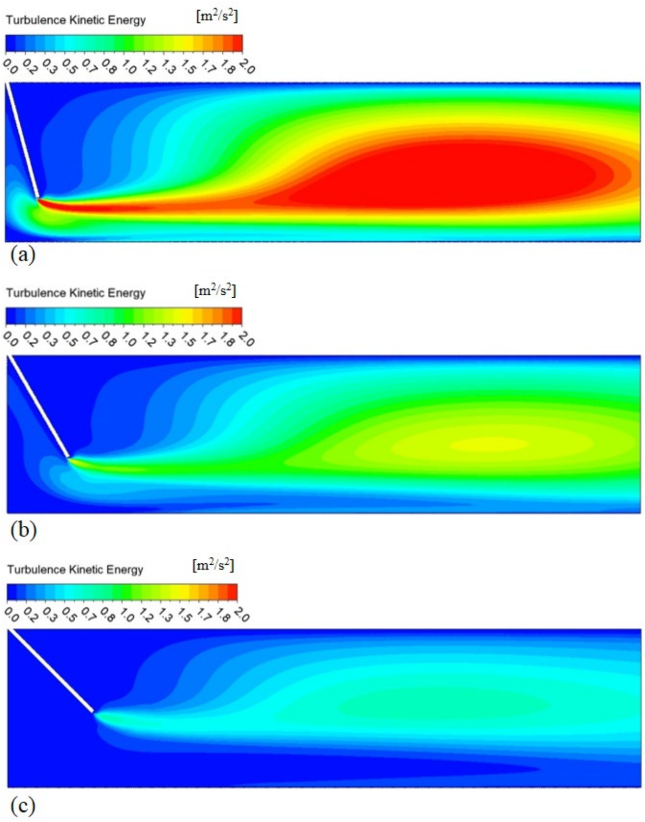


Figure 9. Effects of inclined baffle angle: (a) local skin friction coefficient; (b) local turbulence intensity.



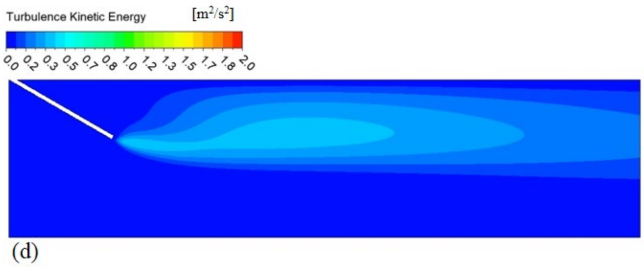
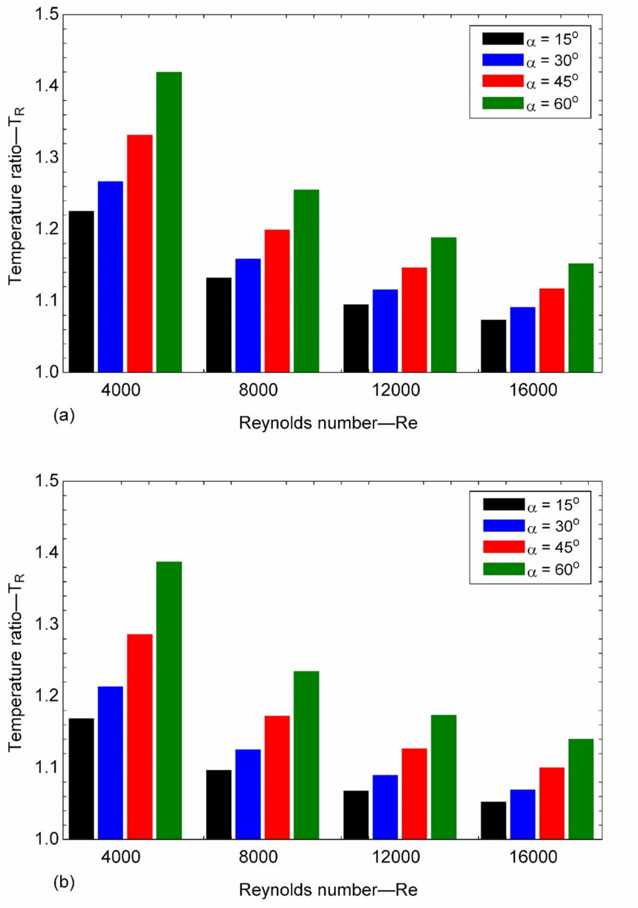


Figure 10. Turbulent kinetic energy contour with variations in α: (a) α = 15º; (b) α = 30º; (c) α = 45º; (d) α = 60º.

3.2 Effect of Baffle Use and Reynolds Number on Average Temperature of Hot Surface

Figure 11(a−c) show the ratio of the average temperature of the hot surface with the inlet air temperature. The results show that the configuration of α = 15º, L_n = 0.875, and Re = 16000 yielded the highest heat transfer. This result is consistent with the analysis of the influence of baffle use and Reynolds number on turbulence intensity. The smallest heat transfer case corresponds to α = 60º, L_n = 0.625, and Re = 4000. The C_f and I_t of the lowest heat transfer case were reduced by 77.9 % and 97 % compared to the best. This means that parameters that yield the highest heat transfer require more energy for pump power due to the large increase in flow resistance. Therefore, depending on the purpose, there is a suitable design orientation. If the purpose is to attain the highest heat transfer, the best case noted above should be considered, accepting the increased energy consumption cost. The thermohydraulic performance criteria should be considered if the goal is to obtain a balanced solution, as mentioned in previous studies [4, 8].



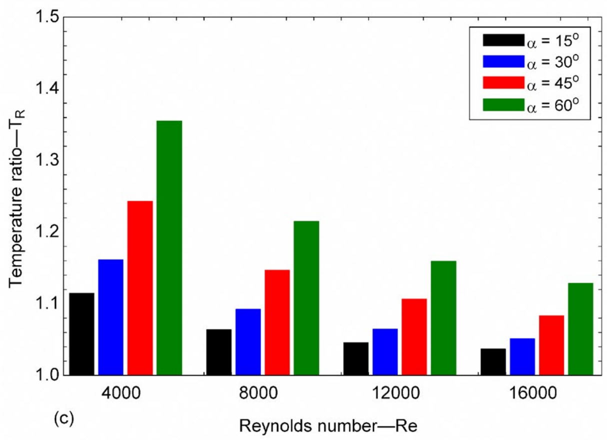


Figure 11. The ratio of the average temperature of the hot surface with inlet air temperature: (a) L_n = 0.625; (b) L_n = 0.75; (c) L_n = 0.875.

4. Conclusions

The present work focuses on analyzing the effects of the inlet baffle and Reynolds number on the skin friction coefficient and turbulence intensity along the hot surface in an air-cooled channel. The influence of the inclined baffle angle, baffle length, and Reynolds number was considered. The main results of this study are the following:

- The skin friction coefficient along the hot surface increased when the Reynolds number decreased, the baffle length increased, or the inclined baffle angle decreased.

- The turbulence intensity along the hot surface increased when the Reynolds number increased, the baffle length increased, or the inclined baffle angle decreased.

- The heat transfer rate increased when the Reynolds number increased, the baffle length increased, or the inclined baffle angle decreased. The highest heat transfer rate occurs at α = 15°, L_n = 0.875, and Re = 16000, and the smallest heat transfer rate occurs at α = 60°, L_n = 0.625, and Re = 4000.

- The smallest heat transfer case has a 77.9 % reduction in the C_f and a 97 % reduction in the I_t compared to the highest heat transfer case. This means that increased heat transfer is achieved at the cost of requiring higher pump power.

- The present study examined the turbulence and flow resistance along the hot surface under the inlet baffle effect. The results show the potential use of an inlet baffle in hot surface cooling and clarify the mechanism leading to the variation in heat transfer ability and pressure loss in the channel. Future research needs to be extended to consider using multiple baffles, plastic baffles, and inlet baffles for cooling photovoltaic panels or cooling battery packs.

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Conflict of Interest

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

Credit Author Statement

Luan Nguyen Thanh: Conceptualization, Methodology, Software, Investigation, Visualization, Formal analysis, Writing- Reviewing and Editing. **Minh Phu Nguyen:** Data curation, Writing- Reviewing and Editing. **Minh Ha Nguyen:** Investigation, Visualization, Writing- Original draft. **Hong Son Nguyen Le:** Formal analysis, Visualization. **Nam Hoai Lai:** Software, Formal analysis.

Nomenclature

a	Baffle length [m]
c_p	Specific heat of air [$J/kg.K$]
C_f	Skin friction coefficient [−]
D_h	Hydraulic diameter [m]
H	Channel height [m]
I_t	Turbulence intensity [−]
k	Turbulent kinetic energy [m^2/s^2]
k_a	Thermal conductivity of air [$W/m.K$]
L	Channel length (test section) [m]
L_n	Relative baffle length [−]
Nu	Nusselt number [−]
u	Inlet velocity [m/s]
u_m	Mean velocity [m/s]
p	Pressure [N/m^2]
Pr	Prandtl number [−]
Pr_t	Turbulent Prandtl number [−]
Re	Reynolds number [−]
T	Temperature [K]
W	Channel width [m]
X_d	Dimensionless horizontal coordinate

Greek symbols

α	Inclined baffle angle [^{o}]
ρ	Density of air [kg/m^3]
ε	Turbulent dissipation rate [m^2/s^3]
τ_w	Wall shear stress [$kg/m.s^2$]
μ	Dynamic viscosity [$kg/m.s$]
μ_t	Eddy viscosity [$kg/m.s$]

Subscripts

i	Inlet
R	Ratio
w	Wall

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