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NUMERICAL ANALYSIS ON PERFORMANCE EVALUATION OF A FLAT PLATE LOUVERED FIN HEAT EXCHANGER

SUHAS B. GOPALAKRISHNA[1], RAJESH RAVI[2], CHIDANAND K. MANGRULKAR[1], KIRAN KUMAR UMASHANKAR[1], SHIVAPRASAD K. VIJAYALAKSHMI[3, *]

[1]Department of Mechanical Engineering, B.M.S College of Engineering
Bull Temple Road, Bengaluru, 560019, Karnataka, India
[2]School of Aerospace and Automotive Engineering, Université Internationale de Rabat
Technopolis Rabat-Shore Rocade Rabat-Salé, Rabat, 11103, Morocco
[3]Department of Engineering, Durham University, Durham, DH13LE, United Kingdom
*Corresponding Author: spkvnitk@gmail.com

Abstract

Over the years, heat exchangers have shown themselves to be the most efficient solution to the required heat recovery capabilities. The louvered fin heat exchanger could be employed in almost all sectors of heating and cooling applications. As it is well known that plate fin heat exchangers in radiators have limited heat transfer efficiency, louver fin heat exchangers demonstrated an enhancement in the heat transfer within the same operating conditions. From the literature, it is very critical to use louvered fin exchangers with slightly higher louvered angles for a lower value of the Reynolds number. In this regard, an analysis is carried out in order to determine the optimal louver angle for a fin heat exchanger at three different louver angles and air Reynolds number. Primarily, a theoretical analysis is executed by using MATLAB tool to find out the Colburn *j*-factor and *f* factor at different louver angle and the Reynolds number. The theoretical values are then compared with the values obtained from numerical simulation carried out by ANSYS FLUENT. The analysis results show that the heat transfer rate in a louvered fin heat exchanger is substantially higher at lower Reynolds numbers. The study also confirms that the louver angle of 23-degree exhibits greater heat transfer among the other louver angles. At higher Reynolds number and higher louvered angles greater than 23-degree, over all heat transfer performance decreased due to reduction in *j* factor.

Keywords: Colburn j- factor, Friction factor, Heat exchanger, Heat transfer, Louvered angles.

1. Introduction

A heat exchanger is device often used to transfer thermal energy at varying temperatures, when in thermal contact between two or more fluids and between solid surface and a stream [1, 2]. Their primary purpose is to provide either cooling and/or heating services to the application. In most cases, secondary/finishing structures added onto a primary surface of heat exchanger. The principal purpose of secondary surfaces is to improve the heat transfer efficiency of the heat exchanger, while considering the allowable pressure drop range [3, 4]. The secondary surfaces are called as fins and prominently used are rectangular or triangular plain, wavy, offset strip, perforated, and louvered types. Commercially, these fin surfaces are used in the air-conditioning, heating, power plants, automotive, and food industries. Recently, the nanofluids have been used in heat exchanger by the various researchers to obtain enhanced heat transfer in free, forced, and mixed convection [5-7].

The several studies performed by Rajesh et al. to find the variation heat transfer coefficient and optimised design for finned type heat exchanger, at varying air velocities and flow rates. It was noted that the overall heat transfer efficiency of finned tube heat exchanger was greater than the tube heat exchanger without fins. The simulation results provided the finest configuration to enhances heat recovery from the diesel engine exhaust gas [8, 9].

The experimental and numerical analysis has been carried out by Choudhary et al. [10] on heat transfer in a tube type heat exchanger. In this study, the variation in the heat transfer coefficient was tested for finned and finless heat exchanger, at varying air velocities and flow rates. It was noted that the overall heat transfer efficiency of the finned tube heat exchanger was greater than the tube heat exchanger without fins.

Kang and Jun [11] conducted the analysis to assess the heat transfer performance of a heat exchanger utilised in a fuel cell. The measurement domain chosen in this study to simulate a realistic system environment was a pair of fins, placed in a free airflow region. The airflow chosen was assumed to be of the three-dimensional variety, have a laminar flow, and be in a stable state with no natural convection and heat conductivity in the fin. The multi-tube prototype heat exchanger used in this analysis has showed a large reduction of the air-side heat transfer rate matched to the expected heat transfer rate. Due to reduced heat transfer efficiency, the thermal output of the fin and flat tube heat exchanger is deprived.

The louvered fins being favoured as efficient heat transfer devices due to its size, light weight and better output. The louvers act like astounds, thus reduces velocity of air being used as a cooling medium. Owing to a reduced air velocity, air stays in contact with the tubes for longer time and enhances the heat transfer from the hot fluid through the tubes. The first reliable data about louvered fin surfaces was published by Kays and London in 1950 [12]. Later, researchers conducted studies that further solidified the existing knowledge at the time, as to how the geometrical parameters affected the heat transfer characteristics [13-19].

Beamer and Cowell [20] proposed a heat exchanger with a varying louver angle design. These studies concluded that the change in design reaped better heat rejection rates, which helped compensate for the increase in the pressure drop. The pressure drop and heat transfer characteristics in various louvered fin geometries used in commercial louvered fin and round tube heat exchangers were studied by the research group headed by Okbaz et al. [21]. Later, Zuoqin et al. [22] investigated the thermal hydraulic behaviour of louver fin by performing numerical simulation and were validated by numerical and experimental data from reported article.

Yaningsih et al. [23] conducted experimentations to find out the effect of slant angle of louvered strip and the thermal performance of concentric tube heat exchanger. The outcomes determined that the addition of louvered strip provides higher heat transfer rate and enhanced thermal performance for a given Reynolds number. Menni et al. [24] studied the fluid structure interaction air flow around flat and arc-shaped baffles in shell-and-tube heat exchangers.

Menni et al. [25] also analysed the baffle orientation and geometry effects on turbulent heat transfer of an incompressible fluid flow inside a rectangular channel. Tran and Wang [26] conducted numerical simulation and experiment on louvered fin heat exchanger in a radiator and found that thermal performance of the radiator improved at higher louvered angle. As found in the results, it is very critical to use louvered fin exchangers with slightly higher louvered angles for a lower value of the Reynolds number. This enhancement in heat transfer can be very advantageous in large scale industries as the initial investment and output requirements are high. However, there are limited numerical studies on heat exchanger with louvered fins at various louvered angles with different Reynolds number.

In this article, a flow simulation is carried out on louvered fins 3D model at different louver angles and Reynolds number of air. The present application can be found in cooling of coolant in the radiator by using this type of heat exchanger. The analysis has been conducted with respect to the fin tube heat exchanger used by Kim and Bullard [27] for their experimental investigation. The airflow temperature is set at 294 K and the temperatures of the fluid inlet at 324 K. The analytical results obtained at three different louver angles are compared with the experimental results of Kim and Bullard investigation and, thus optimum angle is determined based on the maximum heat transfer rate. The CFD simulation is carried out by considering a set of standard conditions at optimum louvered angle and obtained results are then compared with the experimental and numerical values.

2. Methodology

In order to investigate the heat transfer performance of louvered fin tube heat exchanger, an appropriate MATLAB code is first developed, relevant to the problem statement. The obtained results are then validated in relation to results of referred literature [27] and present simulation results. A 3D model of the setup, as shown in Fig. 1, is made in CAD software. The dimension of the heat exchanger is provided in Table 1. Using ANSYS's Fluid Fluent software, simulations are carried out for the model. The meshed model of louvered fins is shown in Fig. 2.

Multiple trials were undertaken with relevant boundary conditions. The optimum values of the louver angle and pitch of the louvers for the heat transfer is to be determined from numerical simulation. This is followed up by a setting up of the solver and the solution is computed. The results established on louvered fin angle are examined and compared. Necessary changes are made to the design and the analysis is repeated until required results are achieved.

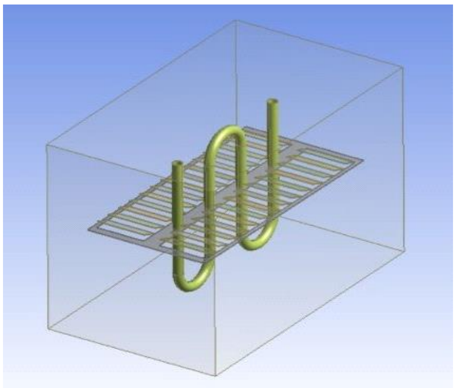


Fig. 1. 3D model of the louvered fin heat exchanger.

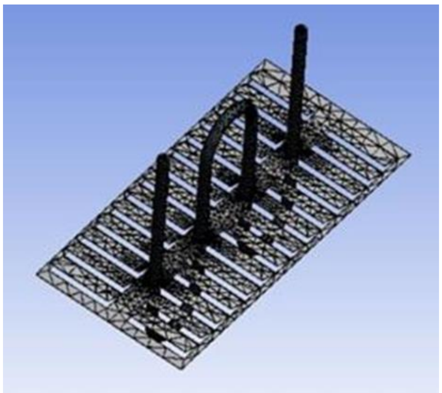


Fig. 2. Meshed model of louvered fins.

The base plate dimensions for mesh generation are tabulated in Table 1.

Table 1. Base plate dimension for mesh generation.

Parameter	Value
Length	200 mm
Breadth	150 mm
Mesh details are Growth rate	1.2
Nodes	171287
Defeature size	0.1194
Elements	556401
Smoothing	medium

In the present work, the correlations Eqs. (1) and (2) have been used in order to calculate the values of the Colburn j and friction f factors respectively for validation [20].

$$j = Re_{L_p}^{-0.487}\left(\frac{L_p}{90}\right)^{0.257}\left(\frac{F_p}{L_p}\right)^{-0.13}\left(\frac{F_h}{L_p}\right)^{-0.29}\left(\frac{F_d}{L_p}\right)^{-0.235}\left(\frac{L_h}{L_p}\right)^{0.68}\left(\frac{T_p}{L_p}\right)^{-0.279} \tag{1}$$

$$f = Re_{L_p}^{-0.781}\left(\frac{L_a}{90}\right)^{0.444}\left(\frac{F_p}{L_p}\right)^{-1.682}\left(\frac{F_h}{L_p}\right)^{-1.22}\left(\frac{F_d}{L_p}\right)^{0.818}\left(\frac{L_h}{L_p}\right)^{1.97} \tag{2}$$

The value of Reynolds number is varied between 100 and 450. All other values are kept constant, except the value of louver angle. Table 2 provides the geometric parameters and its values of louvered fin.

Table 2. Geometric parameters of louvered fins.

Parameter	Value
Louver pitch	1.7 mm
Fin pitch	1.4 mm
Fin height	8.15 mm
Flow depth	20 mm
Louver height	6.4 mm
Tube pitch	10.15 mm

ANSYS FLUENT 19.0, is used to study the pressure drop and temperature variation with respect to Colburn *j*-factor. The semi-implicit method for pressure linked equations algorithm is adopted in the present analysis. Before the commencement of the simulation, the dimensionless distance *y*+ is limited to the value less than 5 known as enhanced wall treatment. The parameter *y*+ function is a vital non-dimensional variable in the turbulence model, which is based on the length from the wall of the louvers to the boundary layer of the very first node. Enhanced wall treatment with, k−ε model is adopted to solve for kinetic energy and dissipation as given in equation (3) and (4) respectively.

Rate of change of turbulent kinetic energy with respect to time + Transport of turbulent kinetic energy by means of advection = Transport of turbulent kinetic energy by means of diffusion + Rate of production of turbulent kinetic energy - Rate of destruction of turbulent kinetic energy (3)

Rate of change of dissipation turbulent kinetic energy with respect to time + Transport of dissipation of turbulent kinetic energy by means of advection = Transport of dissipation of turbulent kinetic energy by means of diffusion + Rate of production of turbulent kinetic energy dissipation - Rate of destruction of turbulent kinetic energy dissipation (4)

Kinetic energy and dissipation are used to determine the turbulence viscosity as shown in Eq. (5).

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

where $C_\mu = 0.09$

Turbulence viscosity is essential to obtain the values of velocity, pressure and temperature distribution through momentum and energy equations. The conservation equations are energy equation, continuity equation, enhanced wall treated k−ε equations, and momentum equations. The normalized residual errors to satisfy convergence criteria are found to be less than 10^{-3}, 10^{-6}, 10^{-3} and 10^{-3}, respectively. It is observed that during the grid independence study, the number of elements beyond 556401 showed no significant variation in the results.

3. Results and Discussions

The pre-processing program ANSYS FLUENT is used for implementation of an analysis of louvered fin heat exchanger. From the properties of the fluid at operating temperatures, the temperature and velocity distribution of louvered fin heat exchanger coolant and air are determined. Figure 3 shows the variation of temperature distribution of fluid passing through the louvered fins at Reynolds number of 100. It can be seen that, the fluid temperature varied in the range of 318.15 K to 314.15 K. This confirms that the average temperature drop of 10K is observed with respect to the initial temperature of 324 K. The higher values of temperature drop could have been observed with multiple flat plate type of heat exchanger. It is expected to decrease in temperature at the outlet. But the red colour is observed in small patches at the outlet, indicating that the temperature is 318 K. The reason may be attributed due to the fluid at the outlet may be re heated due to presence of hot air.

Figure 4 shows the variation of air along the length of the cold fluid flow at high Reynolds number of 450. The air separated from the surface of the fins of the tube and louvers causing secondary vortex flow. The secondary vortex flow led to a keen drop in flow velocity and a significant deprivation in heat transfer rate.

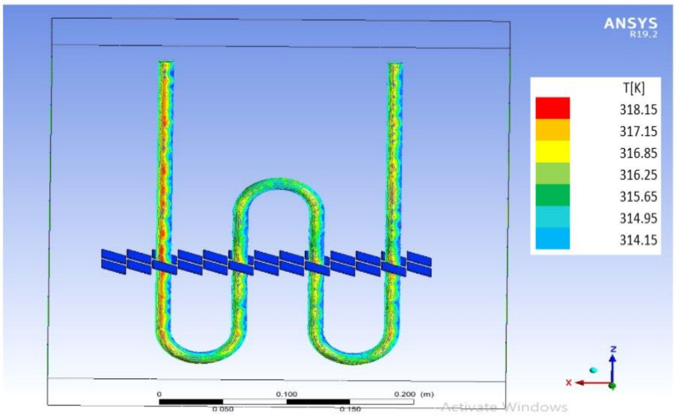


Fig. 3. Temperature distribution of fluid.

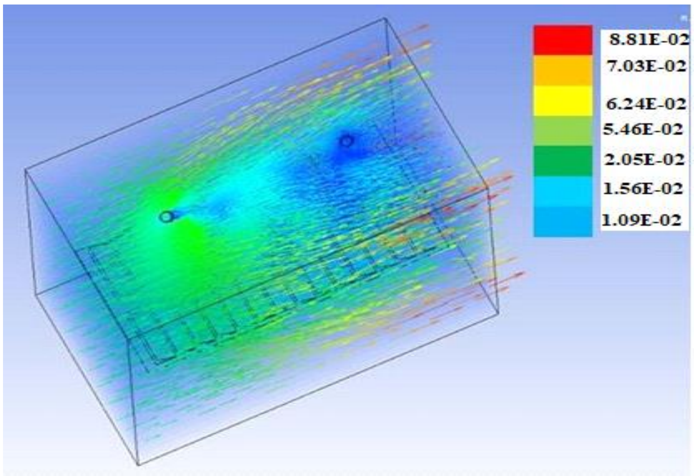
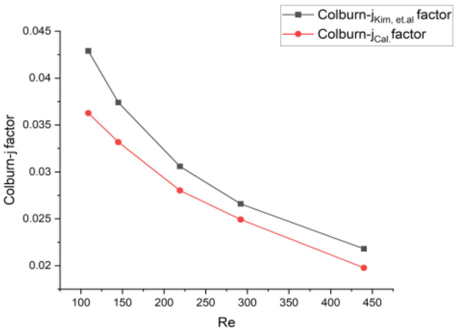
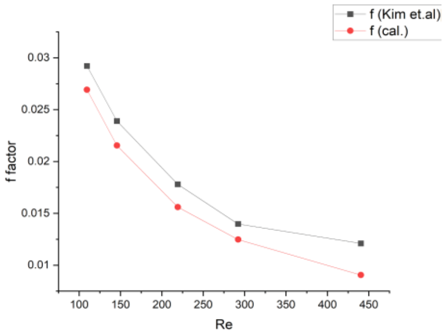


Fig. 4. Velocity variations of air (m/s) along the length.

Figures 5, 6 and 7 depict the variation *j* and *f* factors with various Reynolds number at 19, 21 and 23-degree louver angle respectively. The plot compares the Colburn *j*-factor and friction factor of numerical calculations and the experimental values of Kim and Bullard investigation [27]. From the plot, it can be seen that as the Reynolds number is increased, there is an accompanying decrease in the *j* factor and *f* factor values. Upon comparison, at 19 and 21-degree louver angle, the Colburn *j*-factor values of numerical analysis are greater than the experimental values. This variation may be due to the presence of various external factors and functionalities. In comparison of numerical and experimental data, a maximum value of *j*-factor of 0.045 is obtained at louver angle of 23 degree and Reynolds number of 100 for numerical analysis. It can also be concluded that Colburn *j*-factor is higher than friction factor which reduces the entropy generation points and thus improves significant enhancement in heat transfer.

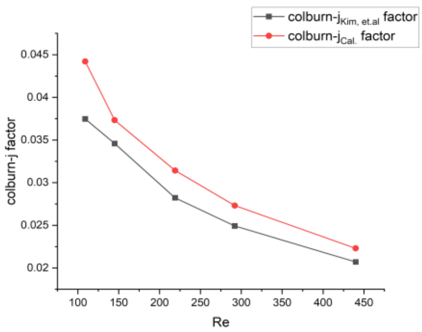


(a) *j* factor

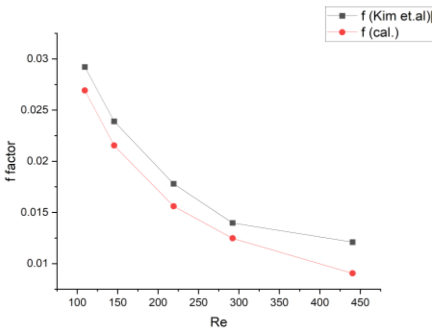


(b) *f* factor

Fig. 5. Variation of *j* and *f* factor with Re at louver angle of 19 degrees.

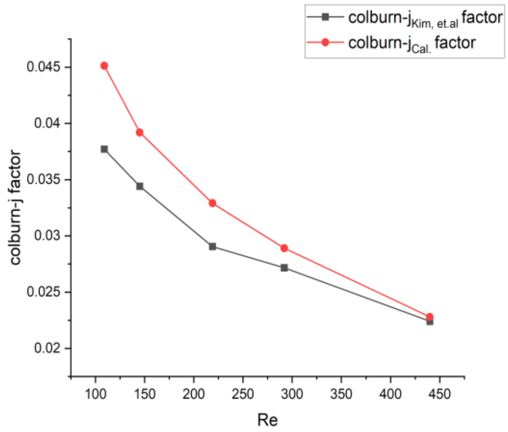


(a) *j* factor

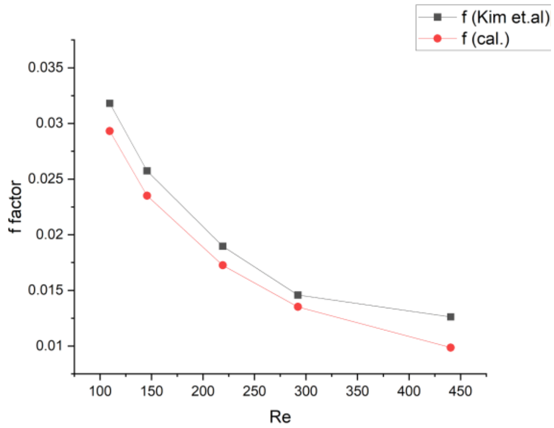


(b) *f* factor

Fig. 6. Variation of *j* and *f* factor with Re at louver angle of 21 degrees.



(a) *j* factor

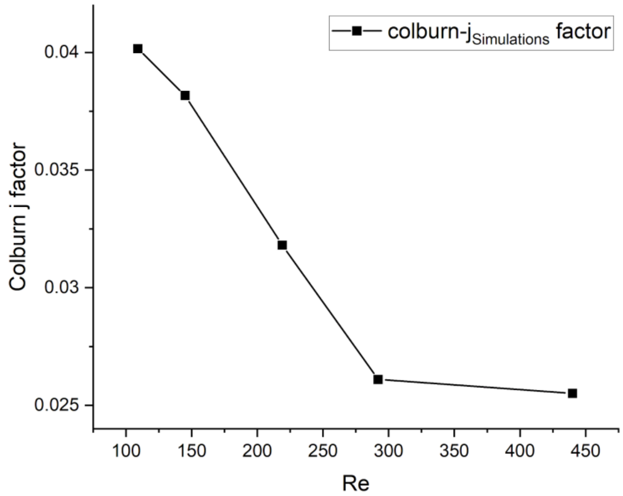


(b) *f* factor

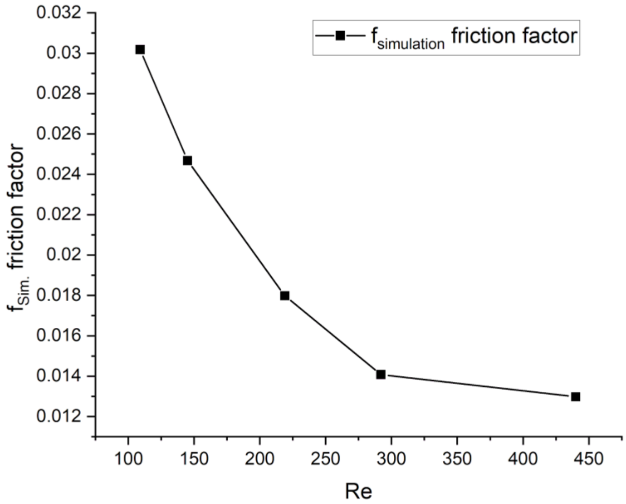
Fig. 7. Variation of *j* and *f* factor with Re at louver angle of 23 degrees.

Figure 8(a) shows the variation of *j* factor with the Reynolds number and Fig. 8(b) shows the variation of *f* factor with Reynolds number which are obtained from simulation results at optimised 23degree louver angle. This variation represents the change of Colburn *j*-factor as the Reynolds number is increased at 23°. It is seen that the *j* and *f* factor significantly decreased as the Reynolds number increased from 100 to 450. The air flowing around the tube could emerge stronger turbulence intensity than that flowing through the louver fin, which led to better heat transfer and higher pressure drop at low Reynolds number [27].

Figures 9(a) and 9(b) depict the comparison of *j* factor and *f* factor values of experimental, numerical and simulation analysis. At all louver angle, the value of *j* factor and *f* factor varies inversely with the Reynolds number. This is because, at higher Reynolds number, inertia force is higher which causes air to flow at relatively higher velocity, thus reducing the skin friction coefficient. This causes reduction in friction factor. Colbourn *j* factor is the dimensionless number giving the ratio of Nusselt number to the product of Reynolds number and Prandtl number. It shows the significance of heat transfer due to dimension of the heat exchanger to the velocity of flow through the heat exchanger. Therefore, at higher velocity, the *j* factor decreases. The average deviation of 8.34% of Colburn *j*-factor and 5.36% deviation of friction factor of the simulation results in comparison with that of numerical analysis. Average deviation for *j* factor and *f* factor is obtained by substituting the parameters provided in Table 2 in the equation (3) and (4) respectively. The value of *j*-factor and *f* factor is found maximum at Reynolds number of 100 in all the investigation findings. This implies that heat transfer coefficient and heat transfer rate is higher at 23-degree louver angle as it varies inversely with the *j* factor. The louvered angle greater than 23 degree caused resistance to the flow of air thus decreasing the heat transfer [28-30]. At higher Reynolds number, due to decrease in *j* factor, over all heat transfer performance is reduced.

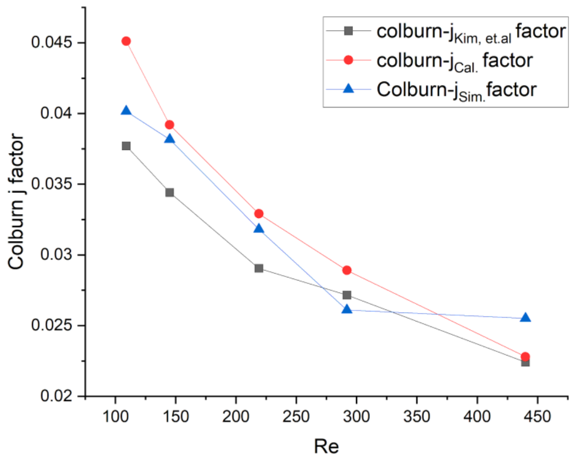


(a) *j* factor

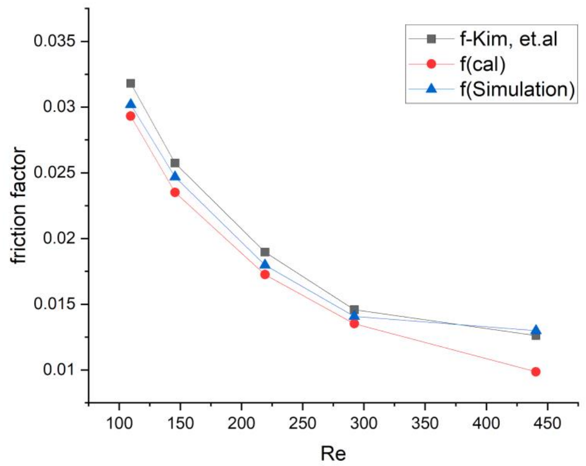


(b) *f* factor

Fig. 8. Variation of *j* and *f* factors with Reynolds number at louver angle of 23 degree.



(a) *j* factor



(b) *f* factor

Fig. 9. Comparison of *j* and *f* factor with Re at louver angle of 23 degree.

4. Conclusions

Variation of heat transfer with respect of Colburn *j*-factor and pressure drop with respect of friction factor is studied for flat plate type louvered fin heat exchanger. The outcomes of numerical simulation which is carried out by using CFD analysis provides useful data to the designers to arrive at the optimal Reynolds number and louver angle for enhancing performance of louvered fin and tube type heat exchanger eliminating expensive and prolonged experimentations. The following conclusions are made upon completion of the study, and subsequent examination of the results.

- The results concluded that the heat transfer rate in a louvered fin heat exchanger is significantly higher at louver angle of 23 degrees and Reynolds number of 100.

- The louvered angle greater than 23 degree caused resistance to the flow of air thus decreasing the heat transfer. At higher Reynolds number, due to decrease in *j* factor, over all heat transfer performance is reduced.
- The value of *j* factor through empirical correlations is found to be marginally higher while the value of *f* factor found to be lower than that of Kim and Bullard correlation.
- The average deviation of 8.34% is observed for the numerical values of Colburn *j* factor and 5.36% of average deviation for the simulation analysis of friction factor when compared with that of that of Kim and Bullard correlation.

The heat transfer performance of the louvered fin heat exchanger can be evaluated by using Nano fluids and binary mixtures for the future work.

Nomenclatures

C_p	Specific heat, J/kg.K
F_d	Fin depth, mm
F_h	Fin height, mm
F_p	Fin pitch, mm
L	Flow length, mm
L_h	Louver height, mm
L_p	Louver pitch, mm
h	Heat transfer coefficient, W/m.K
k	Turbulent kinetic energy
Nu	Nusselt number
P_{in}	Inlet pressure, Pa
P_{out}	Outlet pressure, Pa
Pr	Prandtl number
Re	Reynolds number
T	Temperature, K
T_{in}	Fluid inlet temperature, K
T_s	Surface temperature, K
u	Fluid velocity, m/s
U_{in}	Frontal inlet fluid velocity, m/s
$y+$	non-dimensional distance from the wall
Greek Symbols	
ρ	Density, kg/m.
C_μ	Data fitting for turbulent flows
ε	Dissipation of turbulent kinetic energy

References

1. Ravi, R.; Senthilkumar, P.; and Mohanraj, K. (2018). Design of heat exchanger for exhaust heat recovery of a single cylinder compression ignition engine. *Journal of Engineering Science and Technology* (*JESTEC*), 13(7), 2153-2165.
2. Ravi, R.; Pachamuthu, S.; and Kasinathan, P. (2020). Computational and experimental investigation on effective utilization of waste heat from diesel engine exhaust using a fin protracted heat exchanger. *Energy*, 200, 117489.

3. Menni, Y.; Azzi, A.; Chamkha, A.J.; and Harmand, S. (2019). Effect of wall-mounted V-baffle position in a turbulent flow through a channel: Analysis of best configuration for optimal heat transfer. *International Journal of Numerical Methods for Heat & Fluid Flow*, 29(10), 3908-3937.
4. Erbay L.B.; Ugurlubilek N.; Altun O.; and Dogan B. (2017). Numerical investigation of the air-side thermal hydraulic performance of a louvered-fin and flat-tube heat exchanger at low Reynolds numbers. *Heat Transfer Engineering*, 38 (6), 627-640.
5. Menni, Y; Chamkha, A.J.; and Azzi, A. (2019). Nano fluid transport in porous media: A review. *Special Topics & Reviews in Porous Media: An International Journal*, 10(1), 49-64.
6. Menni, Y; Chamkha, A.J; and Azzi, A. (2019). Nano fluid flow in complex geometries - A review. *Journal of Nanofluids*, 8(5), 893-916.
7. Menni, Y; Chamkha, A. J; Kaid, N.; Ameur, H.; Bensafi, M.; Sahel, D.; and Lorenzini, G. (2020). Advances of heat transfer in porous media - A review. *Special Topics & Reviews in Porous Media: An International Journal*, 11(1), 1-18.
8. Ravi, R.; and Pachamuthu, S. (2020). Experimental investigation on innovatory waste heat recovery system impacts on DIESEL engine exhaust emissions. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1-24.
9. Ravi, R.; Pachamuthu, S.; Shivaprasad, K.V.; Kasinathan, P.; Anandan, S.S.; and Sundarababu, J. (2021). CFD analysis of innovative protracted finned counter flow heat exchanger for diesel engine exhaust waste heat recovery. *AIP Conference Proceedings*, 2316(1), 030024-1-11.
10. Chaudhari, J.M.; Subhedar, D.; and Patel, N. (2014). Experimental investigation of finned tube heat exchanger. *International Journal of Innovative Research in Advanced Engineering*, 1(5), 2349-2163.
11. Kang, H.-C.; and Jun, G.W. (2011). Heat transfer and flow resistance characteristics of louver fin geometry for automobile applications. *Journal of Heat Transfer*, 133(10), 101802-1-6.
12. Kays W.M.; and London A.L. (1950). Heat transfer and flow friction characteristics of some compact heat exchanger surfaces - Part I: Test system and procedure. *Transactions of the ASME*, 72, 1075-1085.
13. Davenport, C.J. (1983). Correlations for heat transfer and flow friction characteristics of louvered fin. *AIChE Symposium Series*, 79(225), 19-27.
14. Kim, N.-H.; Kim, D.-Y.; Cho, Y.-M.; and Byun, H.-W. (2009). Air-side heat transfer and pressure drop characteristics of louver-finned aluminium heat exchangers at different inclination angles. *Journal of Thermal Science and Technology*, 4(3), 350-361.
15. Kim, N.-H.; and Cho, H. (2018). Airside heat transfer and pressure drop of louver-finned parallel flow heat exchanger having a drainage channel. *Journal of Thermal Science and Technology*, 13(1), JTST0018-JTST0018.
16. Sadeghianjahromi, A.; Kheradmand, S.; and Nemati, H. (2018). Developed correlations for heat transfer and flow friction characteristics of louvered finned tube heat exchangers. *International Journal of Thermal Sciences*, 129, 135-144.

17. Menni, Y.; Azzi, A.; and Chamkha, A.J. (2019). Computational thermal analysis of turbulent forced-convection flow in an air channel with a flat rectangular fin and downstream v-shaped baffle, *Heat Transfer Research*, 50(18), 1781-1818.
18. Webb, R.L.; and Trauger, P. (1991). Flow structure in the louvered fin heat exchanger geometry. *Experimental Thermal and Fluid Science*, 4(2), 205-217.
19. Webb, R.L.; and Jung, S.-H. (1992). Air side performance of enhanced brazed aluminum heat exchangers. *ASHRAE Transactions*, 98(2), 391-401.
20. Beamer, H.E.; and Cowell, T.A. (1998). Heat exchanger cooling fin with varying louver angle. *United States Patent* 5730214.
21. Okbaz, A.; Pınarbaşı, A.; Olcay, A.B.; and Aksoy, M.H. (2018). An experimental, computational and flow visualization study on the air-side thermal and hydraulic performance of louvered fin and round tube heat exchangers. *International Journal of Heat and Mass Transfer*, 121, 153-169.
22. Zuoqin, Q.; Qiang, W.; Cheng, J.; and Jun, D. (2018). Simulation investigation on inlet velocity profile and configuration parameters of louver fin. *Applied Thermal Engineering*, 138, 173-182.
23. Yaningsih, I.; Wijayanta, A.T.; Miyazaki, M.; and Koyama, S. (2018). Thermal hydraulic characteristics of turbulent single-phase flow in an enhanced tube using louvered strip insert with various slant angles. *International Journal of Thermal Sciences*, 134, 355-362.
24. Menni Y.; Chamkha A.J.; Azzi A.; Zidani C.; and Benyoucef B. (2019). Study of air flow around flat and arc-shaped baffles in shell-and-tube heat exchangers. *Mathematical Modelling of Engineering Problems*, 6(1), 77-84.
25. Menni, Y.; Chamkha, A.; Zidani, C.; and Benyoucef. B. (2020). Baffle orientation and geometry effects on turbulent heat transfer of a constant property incompressible fluid flow inside a rectangular channel. *International Journal of Numerical Methods for Heat and Fluid Flow*, 30(6), 3027-3052.
26. Tran, N.; and Wang, C.-C. (2020). Optimization of the airside thermal performance of mini-channel-flat-tube radiators by using composite straight-and-louvered fins. *International Journal of Heat and Mass Transfer,* 160, 120-163.
27. Kim, M.-H.; and Bullard, C.W. (2002). Air-side thermal hydraulic performance of multi-louvered fin aluminum heat exchangers. *International Journal of Refrigeration*, 25(3), 390-400.
28. Shinde, P.; and Lin, C.-X. (2016). A heat transfer and friction factor correlation for low air-side Reynolds number applications of compact heat exchangers. *Science and Technology for Built Environment*, 23(1), 192-210.
29. Ravi, R.; and Pachamuthu, S. (2018). Design and development of innovative protracted-finned counter flow heat exchanger for an engine WHR and its impact on exhaust emissions. *Energies*, 11(10) 2717.
30. Menni, Y.; Chamkha, A.J.; Azzi, A.; and Zidani, C. (2019). Numerical analysis of fluid flow and heat transfer characteristics of a new kind of vortex generators by comparison with those of traditional vortex generators. *International Journal of Fluid Mechanics Research*, 47(1), 23-42.