Performance Evaluation of Wavy Fins for Compact Plate and Fin Heat Exchangers

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Abstract

In the automotive industry, there have been tremendous technological advancements in the field of materials. This subsequently increased the power output from the engines without a significant increase in the size. This poses a new problem of cooling such engines. The cooling system of such engines has to cater for increased heat dissipation in the smallest possible space available. For Armoured Fighting Vehicles (AFVs), the design of cooling system becomes much more critical compared to commercial vehicles. The operating conditions of AFVs are very severe where the ambient temperature crosses 50°C. Hence for an efficient cooling system design, the heat exchangers need to be very effective even at those tough ambient conditions for the engine to perform without any failure. Most automotive vehicles use cross flow heat exchangers with compact fins with compactness ratio of greater than 1200 m^2/m^3. In the present paper, one such compact fin, a louvered fin is considered and is studied in Ansys Fluent for heat transfer and pressure drop characteristics. After validating the results from the experimental studies, a wavy fin is considered and it is studied for various parameters like wavelength and pitch. Heat transfer characteristics namely Colburn factor and heat transfer coefficient are calculated through CFD analysis and they are compared to arrive at the fin with superior heat transfer and pressure drop characteristics.

Keywords: *Wavy fin, 2D analysis, Compact Heat Exchanger, Plate and fin, Colburn factor*

1 Introduction

Plate fin heat exchangers are compact heat exchangers used in a wide variety of applications namely in automobile and aerospace industry. Typical applications are radiators, charge air coolers, refrigeration and air conditioning systems, etc. Figure 1 shows the general form of a plate fin heat exchanger and various fin configurations. In India, AFVs operate at ambient temperature higher than 50°C and also very high-powered engines of the order of 1000 hp are required to propel them. This demands a very effective design of cooling system and more importantly the heat exchangers. Almost all heat exchangers used today are made of aluminium due to its superior thermal conductivity, manufacturability and cost effectiveness. AFVs use plate fin heat exchangers where the fluid streams are separated by flat plates, between which corrugated fins are sandwiched. These plates can be arranged into variety of configurations based on the fluid stream namely parallel, counter and cross flow heat exchanger. Since the space available for heat exchangers is very less, these heat exchangers have to be very compact with a compactness ratio of 2000 m^2/m^3. In order to reduce the size of heat exchanger and make it more compact, various configurations of fin surfaces have been developed which provides superior heat transfer characteristics. Typical fin geometries are pin fin, plain fin, perforated fin, offset fin, louvered fin and wavy fin. The improvements in the performance of the heat exchangers have attracted many researchers for a long time as they are of great technical and economical importance. The most effective way to enhance the heat transfer characteristics of fins is to modify the fin pattern and geometry

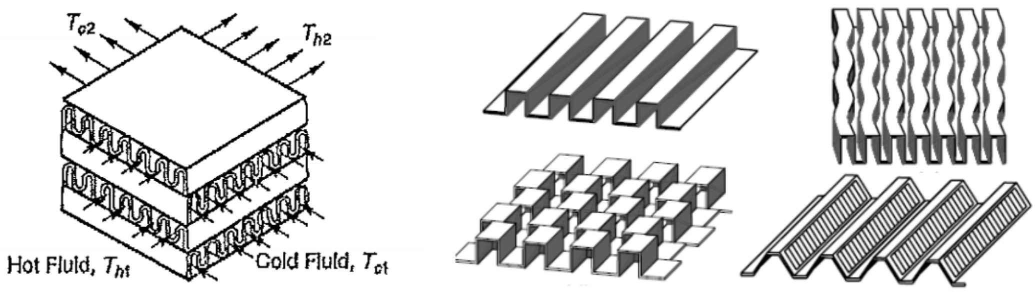

Figure 1 Plate fin heat exchanger and various fin configurations [5]

A plain fin has the least thermal performance since it just increases the heat transfer area without causing any turbulence. On the other hand, a multi-louvered fin has better heat transfer characteristics since it creates turbulence in the fluid flow. The drawback of Multilouvered fin is that it has high pressure drop and also louver gaps clogged with sand particles in desert environments which subsequently reduce its performance. But Wavy fin offers good thermal and pressure drop characteristics. In this paper such a compact wavy fin is considered and it is studied for various wavelengths and pitch.

Literature survey shows that CFD simulation has been used to find the heat transfer characteristics of various fin geometries numerically by various researchers. Vladimir Glazar et. al [2] have studied the effect of fin pitch on heat transfer performance for wavy fin through the CFD analysis and arrived at the optimum fin pitch for the given inlet air velocity. Christophe T'Joen et. al [3] studied the flow behaviour within an inclined louvered fin experimentally through visualization and numerically through Computational Fluid Dynamics (CFD) simulation. Zhimin Wan et. al [4] have studied the effect of Reynolds number on micro square pin fin array through 2D CFD analysis. Similarly, the methodology of the analysis has been benchmarked in various studies across the world.

A compact fin is considered from the text book "Compact Heat Exchangers" by William Kays and A.L. London [1] and it is studied through CFD and validated with experimental results. After validating the simulation methodology, a wavy fin is considered and its heat transfer characteristics are studied for the parameters i.e., wavelength and pitch. For the given fin, Colburn factor and pressure drop are calculated for all the cases of varying pitch and wavelength and they are compared. Finally, for the given length, the best combination of fin pitch and wavelength is arrived at.

Nomenclature

a	amplitude of fin (*mm*)	h	heat transfer coefficient (W/m^2K)
L	wavelength of fin (*mm*)	k	Thermal conductivity (W/mK)
p	fin pitch (*mm*)	Re	Reynolds number
u	velocity (m/s)	Nu	Nusselt number
ρ	density (kg/m^3)	Pr	Prandtl number
μ	dynamic viscosity (Ns/m^2)	St	Stanton number
h_d	Hydraulic diameter (m)	j	Colburn factor

2 CFD Simulation for Performance Evaluation

CFD simulation has attracted many researchers in analyzing the flow behaviour, heat transfer performance and pressure drop characteristics numerically and has been validated by comparing it with experimental data. An extensive study on heat transfer and pressure drop characteristics of various types of fins was done by William Kays and A.L. London and the experimental results have been presented in [1]. In order to validate the 2D CFD simulation, a compact louvered aluminium fin was considered from [1] as shown in Figure 2. The thickness of the fin considered was 0.153 mm [1]. More details of geometry like fin pitch, louver length, etc., are available in [1]

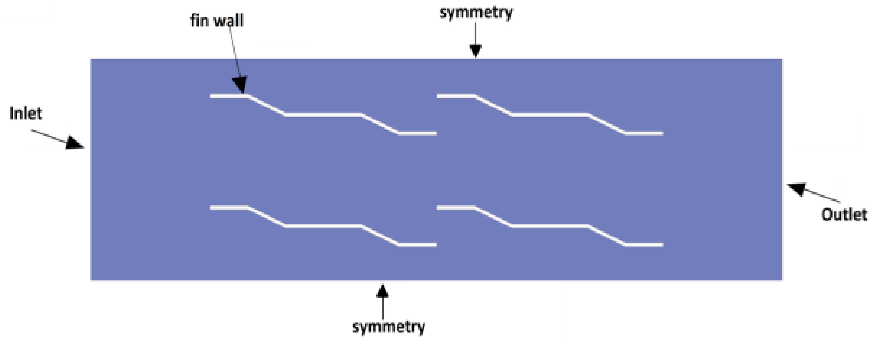

Figure 2 Louvered fin geometry with boundary conditions

A surface model of the geometry was made in CREO and then it was imported to Ansys for meshing.

3 Grid Independence Study

Grid independence test was carried out using five different mesh sizes namely 0.3, 0.25, 0.2, 0.1, 0.05 mm. Among the mesh sizes tested, the variation between 0.1 mm and 0.05 mm was less and hence it was proposed to proceed further analysis with a maximum mesh size of 0.1 mm.

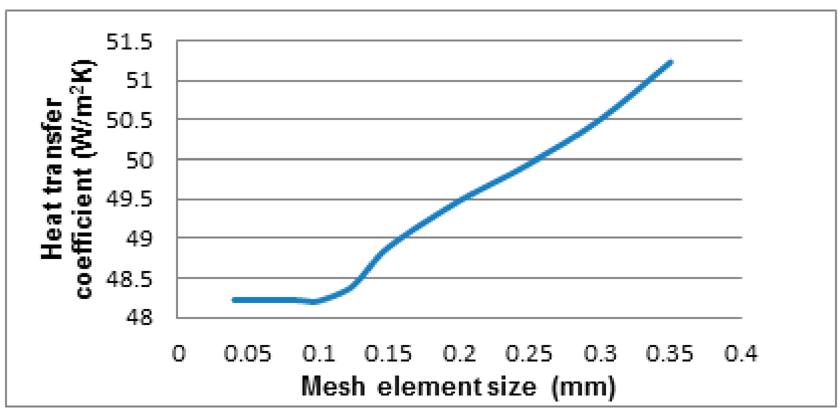

Figure 3 Grid Independence Study

Quad mesh with a maximum size of 0.1mm was generated with inflation of 5 layers at the fin wall to effectively capture the effects of boundary layer. The 2D surface model was discretized into 38766 elements with 40551 nodes. Meshed model is shown in the Figure 3.

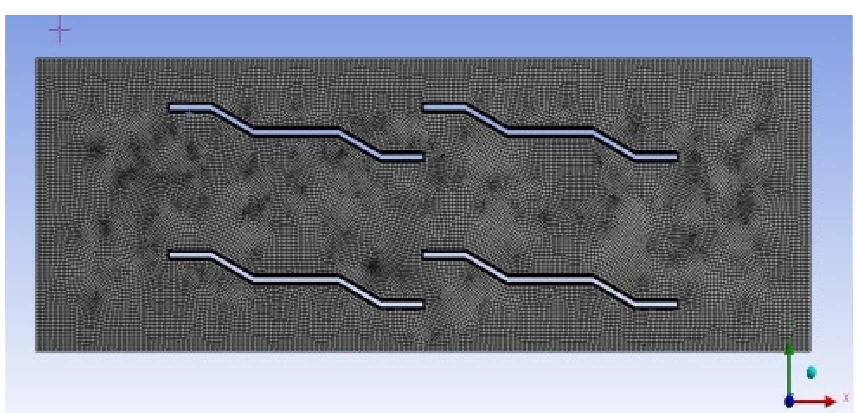

Figure 4 Meshed model

4 Boundary Conditions

The following boundary conditions have been applied on the CFD model for analysis

Fluid medium	Air
Inlet	Velocity inlet
Outlet	Pressure outlet at atmospheric pressure
Wall	Stationary wall with constant temperature

Symmetry boundary condition was used at the top and bottom edges of the 2D fluid domain. The simulation was performed in the commercial heat transfer and fluid flow solver FLUENT. k-ω SST turbulence model was used since it is the best model to capture wall effects. SIMPLEC algorithm was used to solve the problem. This fin was analyzed for various inlet velocities corresponding to the Reynolds number range of 500 to 10000 and the heat transfer coefficient was calculated for each of the cases. Figure 4 shows the temperature distribution of air around the fins. The velocity vector plot in Figure 6 shows that near the louver opening, there is very high velocity resulting in the excessive turbulence generation which further enhances the thermal performance. The Colburn factor was calculated and plotted for the Reynolds number range. Similarly, pressure drop was calculated for each of the cases and plotted. The Colburn factor was calculated from the following relations:

$$\text{Reynolds Number,} \quad Re = \frac{\rho.u.d_h}{\mu} \tag{1}$$

where ρ is density of the fluid medium in kg/m^3 , u is the velocity of the fluid medium in m/s, d_h is the hydraulic diameter of the fin in m, μ is the dynamic viscosity of the fluid medium in $N.s/m^2$

$$\text{Prandtl Number,} \quad Pr = \frac{\mu.c_p}{k} \tag{2}$$

where μ is the dynamic viscosity of the fluid medium in $N.s/m^2$, c_p is the specific heat of the fluid medium in J/kgK and k is the thermal conductivity of the fluid medium in W/mK

$$\text{Nusselt Number,} \quad Nu = \frac{h.d_h}{k} \tag{3}$$

where h is the convective heat transfer coefficient in W/m^2K, d_h is the hydraulic diameter of fin in m, k is the thermal conductivity of the fluid medium in W/mK

$$\text{Stanton Number,} \quad St = \frac{Re}{Nu.Pr} \tag{4}$$

$$\text{Colburn factor,} \quad j = St.\,Pr^{2/3} \tag{5}$$

The temperature and velocity profile are shown below.

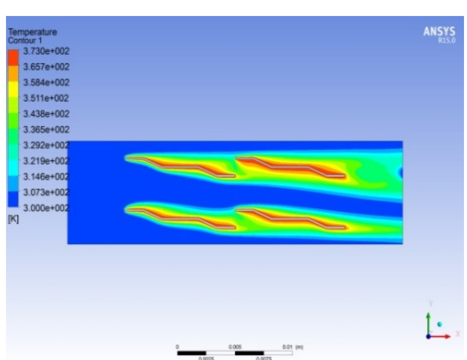

Figure 5 Temperature contour of louvered fin

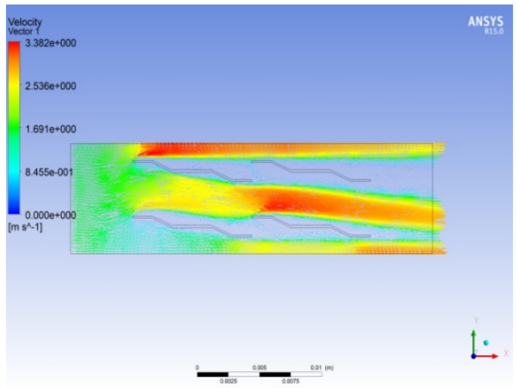

Figure 6 Velocity vectors of louvered fin

The results obtained from CFD simulation matched with the experimental results as shown in the plot below. Thus the methodology is validated.The comparison of j factor from experiment with CFD results for the louvered fin is shown below

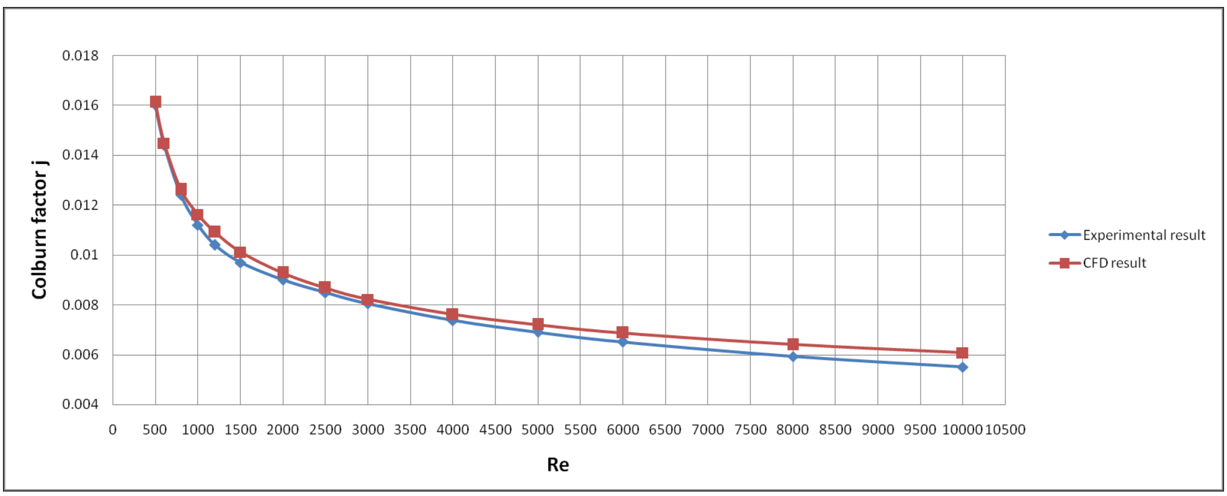

Figure 7 Comparison of experimental results with CFD

The validation study proved that 2D CFD simulation can be used effectively to predict the heat transfer performance.

5 Analysis of Wavy Fin

Wavy fin was then considered and analyzed similarly for various geometrical parameters namely wavelength and fin pitch with constant amplitude of 1.5 mm. Four different wavelengths of 5, 6, 7, 8 mm were considered with amplitude of 1.5mm. Pitch was then varied for 6 cases and studied for heat transfer and pressure drop characteristics. The cases studied are

Case 1: wavelength = 5mm, pitch = 1.5mm
Case 2: wavelength = 6mm, pitch = 1.5mm
Case 3: wavelength = 7mm, pitch = 1.5mm
Case 4: wavelength = 8mm, pitch = 1.5mm
Case 1a: wavelength = 5mm, pitch = 1mm
Case 1b: wavelength = 5mm, pitch =1.1 mm
Case 1c: wavelength = 5mm, pitch =1.2 mm
Case 1d: wavelength = 5mm, pitch =1.3 mm
Case 1e: wavelength = 5mm, pitch =1.4 mm
Case 1f: wavelength = 5mm, pitch =1.5 mm

Then the fin with higher *j* factor was selected and studied for six different fin pitches. A study has also been made for fin with wavelength of 6 mm for different pitches. *j* factor is lesser in all the cases compared to 5 mm wavelength. Figure 8 gives the understanding of the geometry details of wavy fin considered.

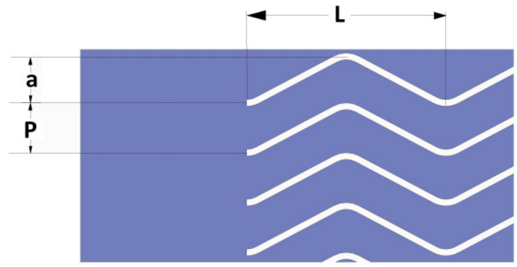

Figure 8 Schematic of wavy fin

Each case was solved separately in Ansys Fluent with the same boundary conditions and solution methodology as followed for the louvered fin analysis. The temperature profile and velocity vectors for one particular case is elucidated in the below Figure 9 and Figure 10 respectively

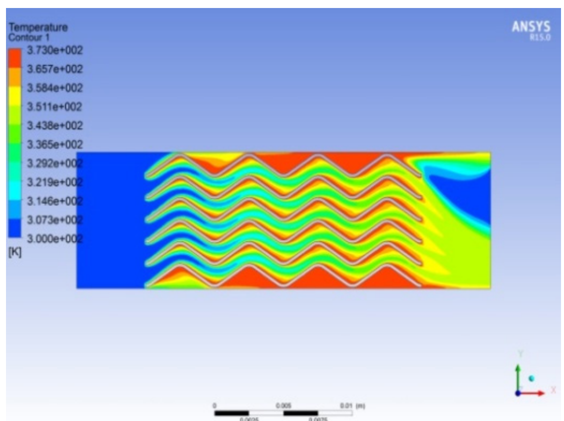

Figure 9 Temperature contour of wavy fin

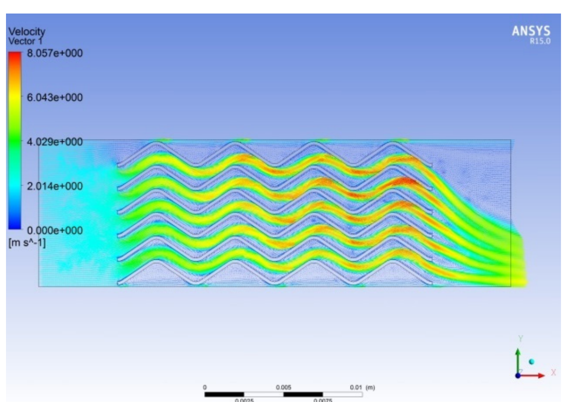

Figure 10 Velocity vectors of wavy fin

6 Results

For all of the cases discussed above, the Colburn factor was calculated according to the procedure shown in the validation study. Colburn factor and pressure drop is plotted for Reynolds number varying from 500 to 10000. The comparison is shown below Figures 11, 12,13 and 14.

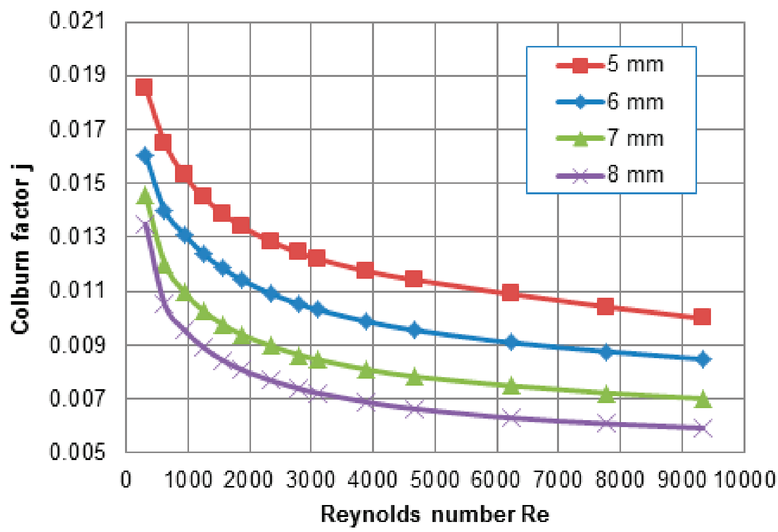

Figure 11 Colburn factor for various wavelength

Figure 11 shows that for lesser wavelength, the heat transfer characteristics are better. But the pressure drop also increases as the wavelength decreases. It is observed that the fin with wavelength of 5 mm has the best heat transfer characteristics. In the velocity contour (Figure 9), it is observed that the local velocities near the wavy surface is high implying the enhanced turbulence and thus making it better in heat transfer characteristics. This, in turn, effectively breaks the boundary layer compared to 8mm wavelength fin. But when the pressure drop is compared, the same fin has the highest pressure drop. The fin with highest wavelength i.e. 8 mm has the least pressure drop since the flow is smooth in the fin of 8 mm wavelength compared to fin of 5 mm wavelength as seen in Figure 12. From 6 mm wavelength to 5 mm wavelength, the pressure drop is almost twice whereas the improvement in heat transfer characteristics is much lesser than twice. This shows that further reduction in wavelength will lead to higher pressure drop. Hence, 5 mm wavelength is considered for further study.

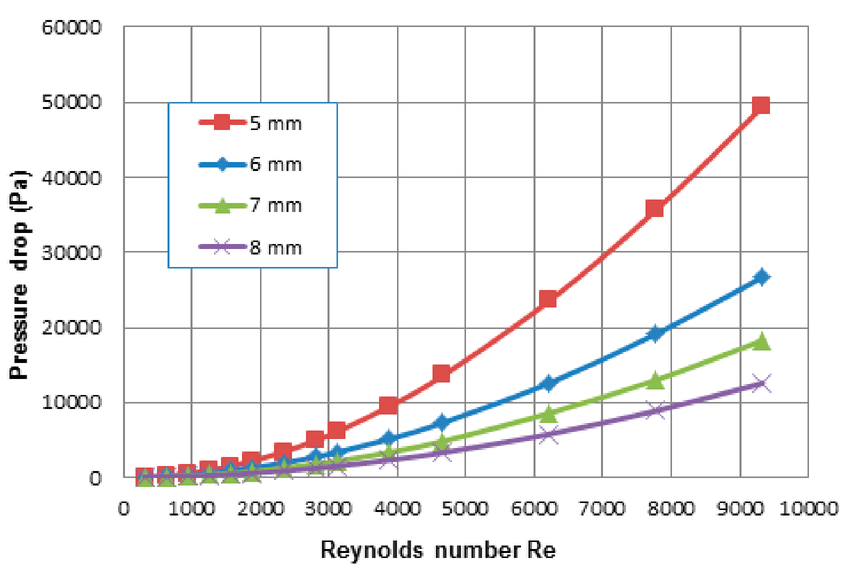

Figure 12 Pressure drop for various wavelength

From the above study, it is observed that the fin with 5 mm wavelength has better heat transfer characteristics than that of the other wavelengths. Hence the same geometry was considered for studying the effect of fin pitch on heat transfer and pressure drop characteristics. Six pitches were considered as discussed above and the characteristics are plotted as shown in Figures 13 and 14.

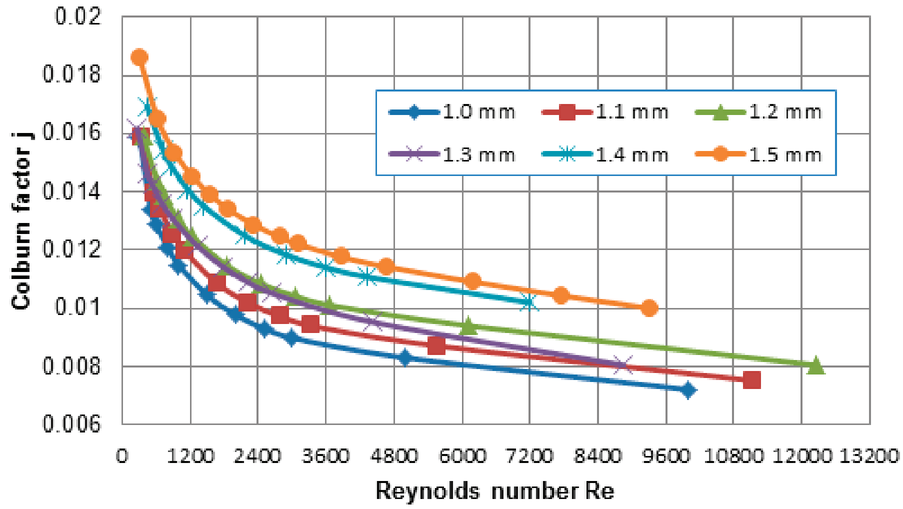

Figure 13 Colburn factor for various pitches

It is seen that as the fin pitch increases, Colburn factor also increases (Figure 13). Fin with high pitch i.e.1.5 mm has very good heat transfer characteristics. This fin also has the least pressure drop which is desired for any fin. But if the fin pitch decreases (for a denser fin), heat transfer will be higher. This is because of higher overall heat transfer area than that of the fin with higher pitch (lesser dense fin).

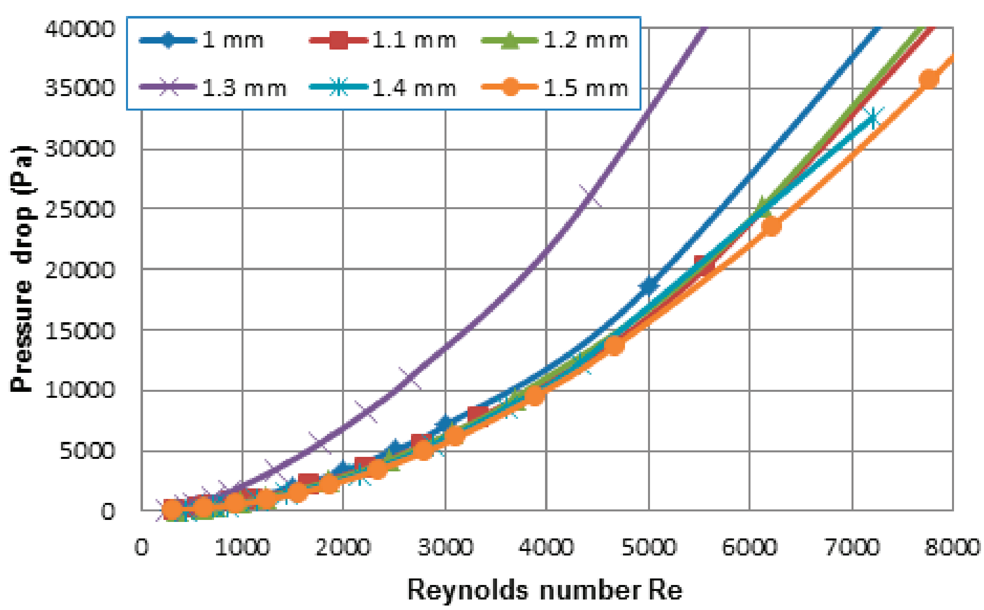

Figure 14 Pressure drop for various pitches

It is seen from the graph that 1.5 mm pitch (lesser dense fin) has the least pressure drop when compared with other fin pitches.

Conclusion

A comprehensive study was carried out for understanding the effect of heat transfer and pressure drop characteristics with variation in wavelength and pitch of a wavy fin. The CFD simulation methodology followed was validated by analyzing a compact louvered fin and comparing the simulation results with experimental results. From the comparison plots, it is observed that the Colburn factor increases with decrease in wavelength of the fin and also increases with increase in pitch.

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