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Design and Analysis on Compact Fin Heat Exchangers with Perforations

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ABSTRACT:
This paper aims at optimizing the performance of plate fin heat exchangers with the help of perforations using FLUENT software. The widespread use of the heat exchangers design has ensured that there are numerous dimensional variations and shown that changes in dimensional parameters affect the performance. It is then important to understand how the geometry of compact heat exchanger can affect its performance. Therefore an investigation into the parametric effect on the global performance on types of plate fin heat exchangers (plain fin, circular and elliptical perforated fin, strip offset fin with and without perforations) are modeled and simulated at same boundary conditions (low Reynolds number). From the results, the heat transfer behaviour, Nusselt number, j and f factors are analyzed and compare all the parameters for different types of plate fin heat exchangers.

Keywords:
Strip offset fin, perforated fin, plate fin heat exchanger, Fluent, modeling, heat transfer

INTRODUCTION:
Plate fin heat exchangers are widely used in automobile, aerospace, cryogenic and chemical industries. They are characterized by high effectiveness, compactness (high surface area density), low weight and moderate cost. Although these exchangers have been extensively used around the world for several decades, the technologies related to their design and manufacture remain confined to a few companies in developed countries. Recently efforts are being made in India towards the development of small plate fin heat exchangers for cryogenic and aerospace applications.

This thesis constitutes a part of this overall effort. Its focus, however, is on the basic heat transfer and flow friction phenomena applicable to all plate fin heat exchangers, and not confined to the Indian development programme.

1.1 Plate Fin Heat Exchangers:
A plate fin heat exchanger is a form of compact heat exchanger consisting of a block of alternating layers of corrugated fins and flat separators known as parting sheets. A schematic view of such an exchanger is given in Fig. 1.1. The corrugations serve both as secondary heat transfer surface and as mechanical support against the internal pressure between layers.

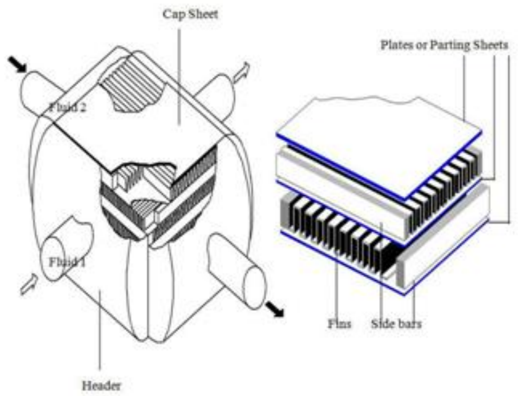

Fig 1.1: Plate fin heat exchanger

Materials
Plate fin heat exchangers can be made in a variety of materials. Aluminium is preferred in cryogenic and aerospace applications because of its low density, high thermal conductivity and high strength at low temperature. The maximum design pressure for braze aluminium plate fin heat exchangers is around 90 bar.

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At temperatures above ambient, most aluminium alloys lose mechanical strength. Stainless steels, nickel and copper alloys have been used at temperatures up to 500^0 C. The brazing material in case of aluminium exchangers is an aluminium alloy of lower melting point, while that used in stainless steel exchangers is a nickel based alloy with appropriate melting and welding characteristics.

LITERATURE SURVEY

Yinhai Zhu, Yanzhong Li [1] studied about four basic fins of the plate-fin heat exchangers, rectangular plain fin, strip offset fin, perforated fin, and wavy fin, are modeled and simulated by taking account of fin thickness, thermal entry effect, and end effect. Three-dimensional numerical simulations on the flow and heat transfer in the four fins are investigated and carried out at laminar flow regime. Validity of the modeling technique is verified by comparing computational results with both corresponding experimental data and three empirical correlations from literatures. Global average Colburn factor (j factor) and friction factor (f factor) and their local 1D stream wise average distributions along the fins are presented by introducing data reduction method. The heat transfer behaviors in both the developing and developed regions are analyzed by examining variations of the local Nusselt number along the flow direction. It is found that the thermal entry length of the four fins might be expressed in the format of $\mathbf{Le = C_1 Re^{c2} Pr D_h}$, which has the same form as the one in a circular tube.

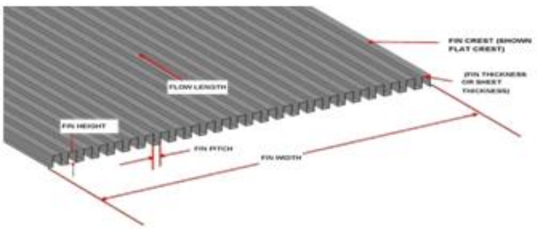

Fig 3.1: Plain fin Heat Exchanger

ANALYSIS ON PLAIN FIN HEAT EXCHANGER

3.1 Plain Fin Surfaces

The plain rectangular fin is the simplest among the plate fin surfaces.

Heat exchanger surfaces with plain fins consist essentially of continuous passages of rectangular or trapezoidal cross section. Improvement of performance is caused primarily by the significant increase of secondary surface area. The average heat transfer coefficient also increases to some extent due to the developing flow over the entrance region. The heat transfer performance of a plain fin surface is generally poorer than that of more complex geometries such as the offset strip and the wavy fin surfaces at the same Reynolds number. But, because of its superior flow friction characteristics, a plain fin surface requires a smaller frontal area compared to other geometries for the same mass flow and heat transfer rates and pressure drop constraints. The required flow length, however, is higher for the same performance, leading to a greater overall volume.

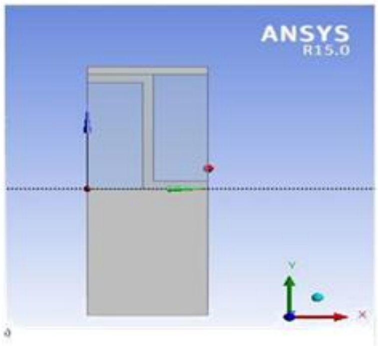

Fig 3.3: Plain fin model

Plain Fin Model:

The plate fin heat exchangers have periodic arrays of fins. Due to existence of periodicity, the symmetric model of computational domain is considered for the analysis i.e., half the fin is modeled in Ansys workbench as shown in figures below.

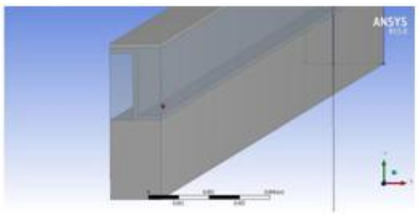

Fig 3.4: Plain fin model (front view)

Boundary Conditions

Table 3.2 Boundary Conditions for plain fin

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Reynolds number	285
Fluid inlet velocity *(V)*	0.075 (m/s)
Working fluid	Water
Fluid Inlet temperature	333 (Kelvin)
Density	983 Kg/m^3
Input heat flux to fin surface	30,000 W/m^2
Viscosity (μ)	0.00047 Pa s
Thermal conductivity of water (k)	0.655 W/m K
Thermal conductivity of aluminum (k)	206 W/m K
Specific heat (Cp)	4180 J/Kg K

Boundary conditions mentioned in the Table 3.2, are considered for the present analysis. These values are taken from Yinhai Zhu and Yanzhong Li [1] for validation purpose and also for analysis of other cases of present study.

Contour Outputs:

The plain fin heat exchanger which is modeled in Ansys workbench is mesh refined and solved in Ansys Fluent by applying the boundary conditions as shown in table 3.2. In the Ansys Fluent setup, Laminar-model is taken as the present study is based on Laminar flow conditions. Plain fin model is simulated and the contours of the plain fin heat exchanger are plotted as shown below.

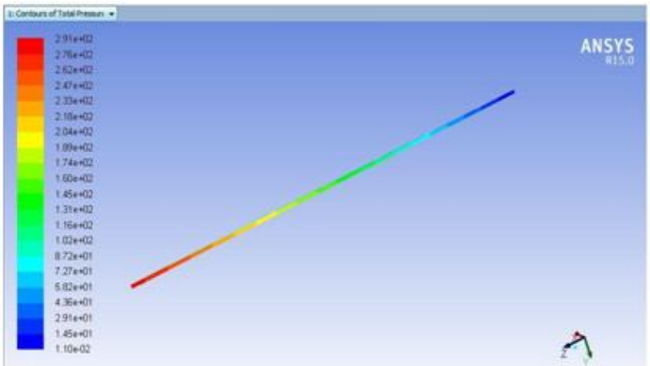

Fig 3.6: Pressures Contour for Plain Fin

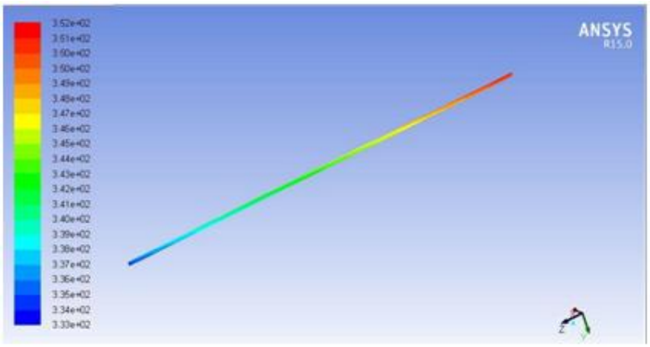

Fig 3.7: Temperature Contour for Plain Fin

ANALYSIS ON PERFORATED FIN HEAT EXCHANGER

4.1 Perforated fin Surfaces

Perforated fins are made by punching a pattern of spaced holes in the fin material before it is folded to form the flow channels. The channels may be triangular or rectangular in shape with either round or rectangular perforations. While this geometry, with boundary layer interruptions, is a definite improvement over plain fins, its performance is generally poorer than that of a good offset strip fin, since the material removed in creating the perforations is thrown out as scrap. Perforated fins are now used only in limited number of applications such as turbulator in oil coolers.

Perforated Fin Geometry

Perforations models are circular and elliptical shapes. Elliptical perforations are again divided into four ratios, and the performance is evaluated in both the circular perforated and elliptical perforations. By making holes in the straight fin, it leads to increase the thermal performance of the perforated fin.

Table 4.1 Perforated fin geometry

Fin type	Fin thickness, *t* (mm)	Fin height *h* (mm)	Fin spacing distance, *s* (mm)	Fin array length, L (mm)	Fin Hole Diameter (mm)
Perforated Fin	0.152	2.26	1.52	306	0.8

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4.4 Boundary Conditions

To simulate both the circular and elliptical perforated fins, the inputs and boundary conditions are shown in the table 4.2, by using these inputs and boundary conditions, both the circular and elliptical perforated fin models are simulated.

Table 4.2: Boundary Conditions of Perforated Fins

Reynolds number	285
Fluid inlet velocity (v)	0.0735 (m/s)
Working fluid	Water
Fluid Inlet temperature	333 (Kelvin)
Density	983 Kg/m^3
Input heat flux to fin surface	30,000 W/m^2
Viscosity (μ)	0.00047 Pa s
Thermal conductivity of water (k)	0.655 W/m K
Thermal conductivity of aluminum (k)	206 W/m K
Specific heat (Cp)	4180 J/Kg K

Contour Outputs

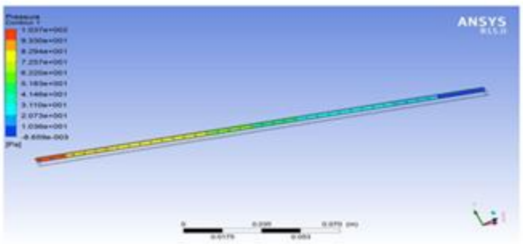

Fig 4.5: Pressures Contour for Circular Perforated Fin

From Fig 4.5, it is observed that, the fluid flow along the fin surface, fluid pressure is reducing towards the end of the fin.

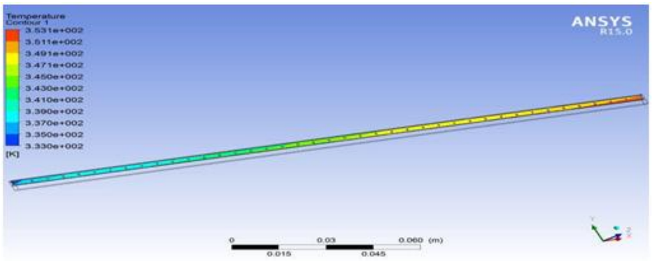

Fig 4.6: Temperature Contour for Circular Perforated Fin

From Fig 4.6, it is observed that, the fluid flow along the fin surface, fluid temperature raises towards the end of the fin.

4.6 Results

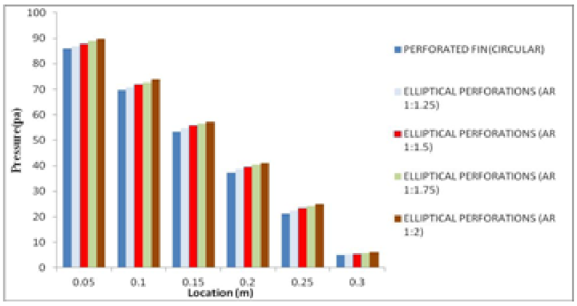

Fig 4.7: pressure distribution for circular and elliptical perforated fins along the flow direction.

The fig 4.7 shows the pressure distribution for circular and elliptical perforated fins along the flow direction, and it is observed that comparatively pressures produced in circular perforated fin is lower than elliptical perforated fins, and the pressure produces in elliptical perforations aspect ratio (1:2) is more compared to other perforated fins.

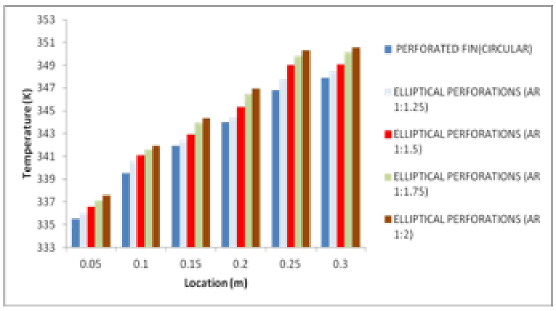

Fig 4.8: Temperature distribution for circular and elliptical perforated fins along the flow direction.

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The fig 4.8 shows the temperature distribution for circular and elliptical perforated fins along the flow direction, and it is observed that comparatively temperature produced in circular perforated fin is lower than elliptical perforated fins, and the temperature produces in elliptical perforations aspect ratio (1:2) is more compared to other perforated fins.

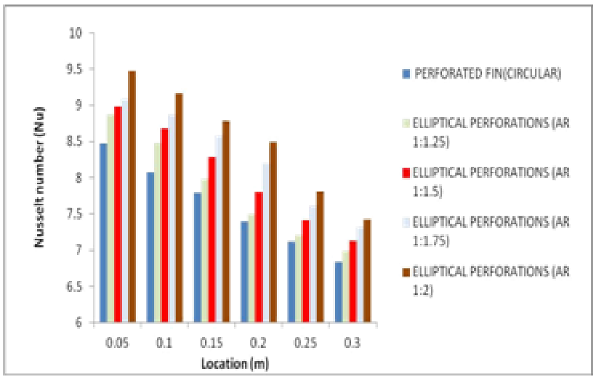

Fig 4.9: Local Nusselt number distribution for circular and elliptical perforated fins along the flow direction

The fig 4.9 shows the local Nusselt number distribution for circular and elliptical perforated fins along the flow direction, and it is observed that comparatively Nusselt number produced in circular perforated fin is lower than elliptical perforated fins, and the Nusselt number in elliptical perforations aspect ratio (1:2) is more compared to other perforated fins.

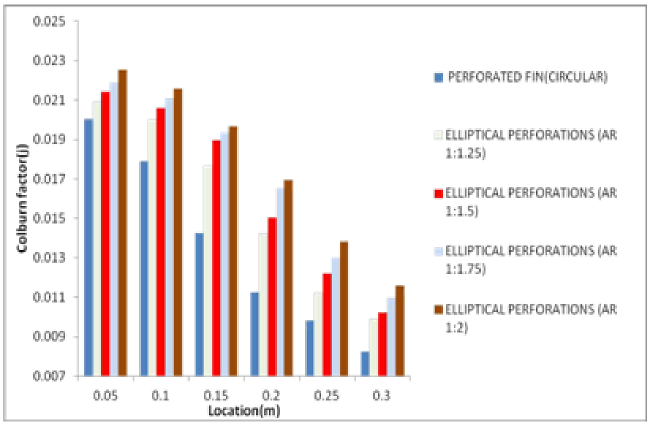

Fig 4.10: Local Colburn factor distribution for circular and elliptical perforated fins along the flow direction.

RESULTS AND DISCUSSION

Global average j and f factors

The global average j and f factors of the fins are calculated by Equation 1*a*, 1b; the plain fin has the lowest *j* in tested Reynolds number due to the heat transfer in other three flow-interrupted fins enhanced by thermal boundary layer interruption with offset strip fins, holes. Results show that *j* factors of the strip offset is high, and the strip offset fin with elliptical perforations has the highest *j* factor at Re 285 and it has the greatest pressure loss especially at large values of Re. Local heat transfer and pressure behaviors. Further insights into the heat transfer behaviors in the fins are carried out by examining variations of the local stream wise average *j* factors along the flow direction, as presented. In all cases, heat transfer is enhanced at both the fin entrance and exit due to the thermal entry effect and end effect. As Re increases, the thermal entry effect enhances but the end effect becomes weak. The fluid is blocked by leading surfaces and separated by tailing surfaces, resulting in *j* factor increases at these locations. As we know from results in previous two-dimensional models, the flow in the strip offset fin is not periodic in two strip fin lengths but four strip fin lengths, obviously because the fin thickness in the *Y*-direction is considered in the present simulation and the results are compared in four cases as shown below.

- CASE 1 : Plain fin vs. circular perforated
- CASE 2: Circular perforated fin vs. Elliptical perforated fin
- CASE 3: Plain fin vs. Strip offset fin
- CASE 4: Strip offset fin vs. strip offset fin with perforations

All these four cases have been studied and analyzed for the following parameters given below:

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6.2 Parameters studied

a) Pressure contour

b) Temperature contour

c) Colburn factor

d) Friction factor

e) Nusselt number

f) Weight

6.3 Pressures Comparison for Plate Fin Heat Exchangers

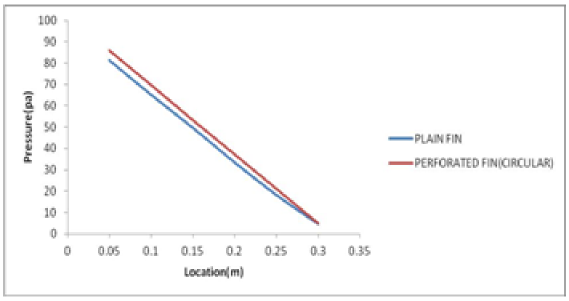

Fig 6.1: Comparison of pressure distribution for plain fin and circular perforated fin along the direction of flow

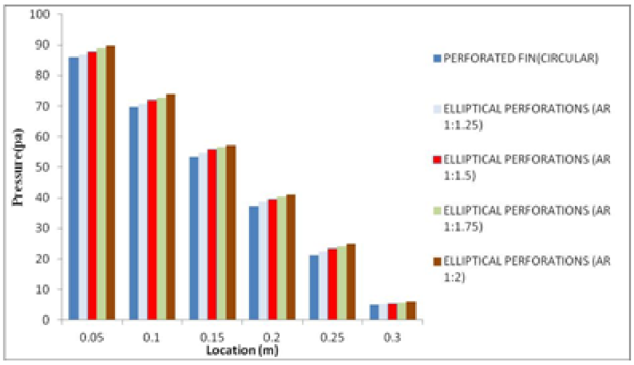

Fig 6.2: Comparison of pressure distribution for circular perforation and elliptical perforated fin along the direction of flow

6.8 Comparison of Weights for Plate Fin Heat Exchange

Table 6.1: Comparisons of Weight for Plain Fin and Circular Perforated Fin

Plain fin (grams)	Perforated fin (grams)	% Reduction in weight
5.452279	4.17007	23.51693668

Table 6.2: Comparisons of Weight for Circular and Elliptical Perforated Fins

Perforated fin(circular) (grams)	Elliptical perforated fin AR(1:2) (grams)	% Reduction in weight
4.17007	4.153273	0.102799

Table 6.3: Comparisons of Weight for Plain Fin and Strip Offset Fin

Plain Fin (grams)	Strip Offset Fin (grams)	% Reduction In Weight
5.452279	3.5733098	34.4620882

Table 6.4: Comparisons of Weight for Strip Offset fin with and without Perforations

Strip Offset Fin (grams)	Strip Offset Fin With Elliptical Perforations (grams)	% Reduction In Weight
3.5733098	3.5567239	0.4641607

From the above tables, it is observed that strip offset fin has less weight, and the strip offset fin with elliptical perforations are more advantageous in weight.

7.1 Conclusions:

Heat transfer and friction factor in complete three-dimensional geometries of the plain fin, strip offset fin with and without perforations, circular and elliptical perforated fins, are carefully investigated, in which the fin thickness, spacing, length, thermal entry effect, boundary conditions are taken into account in this work. CFD simulations are carried out for the basic fins of plate fin heat exchangers at Reynolds number 285.

The validity of the plain fin simulation model is verified by comparing the computed results of the plain fin with the corresponding experimental data Ref [1]. Good agreement has been obtained between the computations and the experiments results. Furthermore, simulations for calculation of the local Nusselt numbers, *j* factor, and *f* factor is presented, based on which, the heat transfer and pressure drop characteristics in the fins are obtained and analyzed in detail. Influences of the offset fins with perforations in the strip fin, and circular and elliptical holes in the perforated fin, on the pressure drop, heat transfer, Nu, j factor, and f factor are investigated and the results are compared for different PFHE.

a) Perforated fins have more heat transfer and friction than plain fin.

b) Elliptical perforations fins have more heat transfer and friction factor than circular perforations.

c) Offset fin have more heat transfer and friction factor than plain fin.

d) Offset fin with elliptical perforations have more heat transfer and friction factor comparatively.

From the above results, I conclude that, strip offset fin with elliptical perforations have more area in contact with the fluid passing along the fin surface, so it helps to increase the amount of heat transfer from the fin to the fluid. Because of the offsets present in the strip fins, along the fluid flow direction, these offsets obstruct the fluid flow in the fin, and it tends to increase the pressure produced in the strip fins and finally it produces the high friction factor comparatively.

7.2 Future Scope

With physical constraints on time and resources, we have not been able to address to some aspects of the problem which have a strong symbiotic relationship with the material covered in this project. Among the most obvious topics are:

1. Plain fins of non-rectangular geometry – triangular, trapezoidal and comparable shapes
2. Herringbone fins
3. Other fin types such as louver fins. The louver fin, particularly, can offer substantial computational challenges.

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