OPTIMAL FLOW PARAMETERS OF LOUVERED FIN HEAT EXCHANGERS FOR AUTOMOTIVE AND AIR-CONDITIONING APPLICATIONS

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ABSTRACT

Louvered fin heat exchangers have been used extensively in automotive and air-conditioning applications. It provides additional heat transfer surface while maintaining low pressure drop compared to typical corrugated fins. The geometry of these fins is seen to be critical in determining the performance of heat exchangers. This project reports the effects of geometrical parameters on the pressure drop and heat transfer characteristics of louvered fin heat exchangers. Investigation was conducted using both experimental and simulations work. Experimental work was implemented to visualize the flow characteristics at different Reynolds number. The experiment involved the fabrication and testing of 10:1 scaled up model of multiple louvered fins installed inside a test section. Simulations were also conducted using commercial CFD code, ANSYS Fluent. Two types of domain were modeled using single and multiple stacking. In this simulation, three identified variables are louver angle, louvered pitch and fin pitch with different Reynolds number from 200 to 1000. The heat exchanger performance was analyzed in terms of pressure drop and heat transfer to determine the suitable parameters of louvered fins. Two types of Reynolds number were also used including Reynolds number based on louver pitch (Re_{LP}) and fin pitch (Re_{FP}). The results obtained from the experiment show that significant changes of flow direction occur as the Reynolds number increases from 200 to 1000. The changes occur from duct directed flow (low Reynolds number) to louver directed flow (high Reynolds number). In simulation work, the fin pitch and louver pitch shows a considerable effect on the pressure drop as well as heat transfer rate. It is observed that the increasing fin pitch will result in an increase of heat transfer rate and lower pressure drop. On the other hand, low pressure drop and low heat transfer rate are obtained when the louver pitch is increased. Overall results show that configuration 5 (L_P = 0.7 mm and F_P = 3.25 mm) at louver angle 25.5^o possess highest heat transfer coefficient and lowest pressure drop. These findings

indicate the capability of louvered fin in enhancing the performance of heat exchangers.

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LIST OF SYMBOLS AND ABBREVIATIONS

f	-	Friction factor
D, l	-	Diameter, Length
F_p	-	Fin pitch
L_p	-	Louver pitch
C_p	-	Specific heat at constant pressure
η	-	Flow efficiency
Re	-	Reynolds number
ρ	-	Density
V	-	Flow velocity
μ	-	Fluid viscosity
v	-	Kinematic viscosity
α	-	Louver angle
t	-	Louver thickness
l	-	Length
Q	-	Heat flux
h	-	Heat transfer coefficient
T_{wall}	-	Wall temperature
T_{ref}	-	Room temperature

P	-	Pressure
Eu	-	Euler number
Nu	-	Nusselt number
k	-	Thermal conductivity of fluid
St	-	Stanton number

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CHAPTER 1

INTRODUCTION

1.1. Background

Louvered fin compact heat exchangers are used extensively in several automotive applications such as radiators, oil coolers, condensers, and charge air coolers. The purpose of placing louvers on the fin is to provide additional heat transfer surface area and to interrupt the growth of the boundary layer forming along the fin surface. This new boundary layer formation provides a high heat transfer region along the fin. Under typical operating conditions of most fin–and-tube air-and-water heat exchangers, the dominating thermal resistance is on the air (external) side and can be as much as 95% of the total thermal resistance. It also stated by Kays (1984) that by achieving a better understanding of the flows in the louvered fin heat exchanger, multiple methods of reducing the thermal resistance can be developed which will ultimately lead to a reduction in space, weight, and cost of louvered fin heat exchangers.

In the long list of fins types that have been studied in compact heat exchangers, such as strip fin, offset fin, wavy fin, the louvered fin is most widely used in automotive applications. Radiator system in a vehicle is a component that has great effect on the efficiency and stability of the operation in terms of heat because its function of producing heat to the outside air. Louver is generally used to improve heat transfer area. It is also used to increase the heat transfer rate significantly. Hence to obtain excellent results, a high *Reynolds* number play a great influence on good air ventilation which will be trapped by the louvered fin in the radiator.

Louver layout is built consist of inflow and outflow. The flow will pass through each part of the outer layer of the louver, where the fin louvers are connected to one another. The louvers are essentially formed by cutting the sheet metal of the fin at intervals and rotating the strips of metal so formed out of the plane of the fin. They enhance heat transfer by providing multiple flat-plate leading edges with their associated high values of heat transfer coefficient. As such, they are similar in principle to the offset strip fin and can enhance heat transfer by a factor of 2 or 3 compared with equivalent non-louvered surfaces.

The louvers have the further advantage that the enhancement of heat transfer is gained without the disproportionate increase in flow resistance that results from the use of turbulators. The extensive use of these surfaces has tended so far to be limited very largely to the automotive industry, where they are used for radiators, heaters, evaporators, and condensers. In this study, an analysis is performed using Computational Fluid Dynamics software to get as near as the real results required. CFD is a numerical methods and algorithms to get a critical analysis of the pressure drop and heat transfer of louvered fins at different geometrical conditions. The experiment is also conducted to obtain the flow visualization inside louvered fin at different configurations.

1.2. Problem statement

There are a lot of study in designing heat exchanger that have most effectively heat transfer. At this time, the fin on the radiator system or air conditioning system the air is still using flat fins. Fins produced at this time still do not have louver where it acts as a trap air to create a boundary layer on the surface of the louver.

The study of geometry design of the louvered fins needs a high cost and time consuming because of a lot of parameters number involved in the study such as louver angle, louver pitch, louver length and fin pitch. By using simulation method, the cost and time will be reduced. This study investigates the pressure drop of the louver fin. The high pressure drop is not good for the system. It is important because higher pressure drops require more pumping power. The different result of pressure drop will be obtained by different louver angle. From this study, the effective fin geometry will be determined in order to maximize the heat transfer and minimize pressure drop.

For the experimental results, it was conducted using flow visualization to investigate the effects of geometrical parameters of louvered fin heat exchanger to the flow characteristic, pressure drop and heat transfer.

1.3. Importance of study

This study is important, because it will enlighten the effects of geometrical parameters to the pressure drop and heat transfer characteristics of a louvered heat exchanger, and finding its suitable geometrical parameters which will highly improve the performance of the louvered heat exchanger. In addition, the pressure drop will be determined by using CFD software as well. The best louver angle that have lowest pressure drop will be obtained. By that, the pressure drop of the louver fin will be reduced and the effectiveness of the device will be increased. Thus, the pumping power needed in the heat exchanger will be reduced. This study will give a good indication on the designing of the new heat exchanger that has high heat transfer performance.

1.4. Rationale of Study

The louvered fin on flat tube with rectangular channel (Figure 1.1) is the preferred type of compact heat exchanger for automobile applications. Correlating the friction factor for such an important geometry was done by the past researcher as shown in equations 2.18 to 2.24. However, these correlations are generalized and the percentage of deviation between these is as large as ± 15% and no consideration of the louver thickness parameter. In 2003, Zhang and Tafti [16] determined that for small louver angles there is a significant thickness ratio effect on the heat transfer and the flow efficiency, defined in section 2.3. Determining the optimum condition of the louver angle by using Chang’s correlation is unlikely to lead to the right answers. Therefore in this study the ratio of heat transfer rate to pumping power is considered to determine the optimum angle.

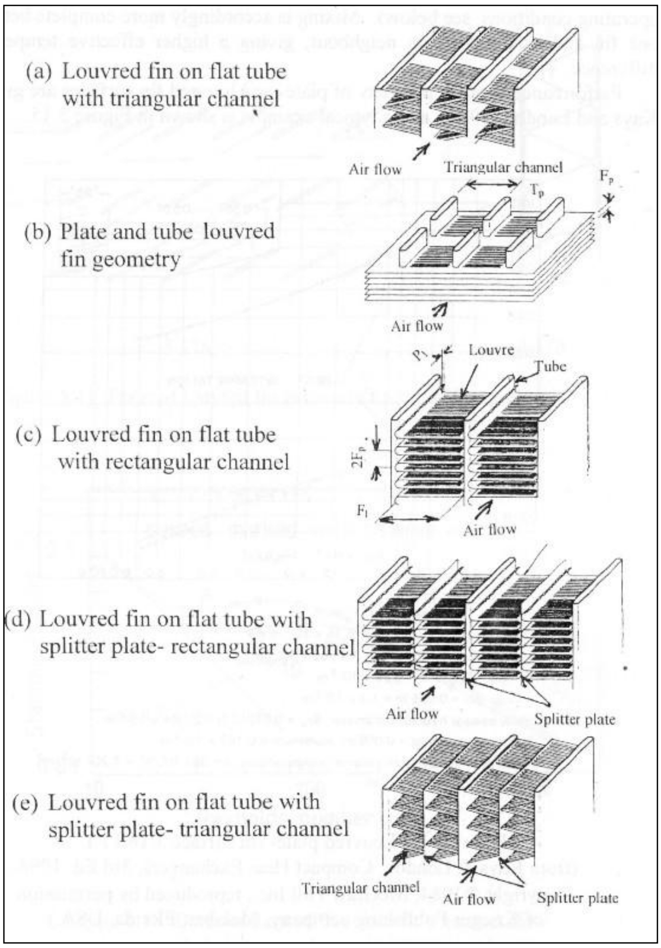

Figure 1.1: Forms of louvered fin-flat tube surface [16].

In a typical reliability test of a radiator, the air flow is conducted at 10 m/s (corresponding to a typical Reynolds number of 1000). Analogy of a real situation for such a reliability test is one where the heat load from engine becomes high when the automobile encounters a long upward slope. In such a case when the ram air velocity becomes low, the heat rejection of the radiator can no more depend on the ram air velocity, and has to depend on the fan.

Below a Reynolds number of about 300, Davenport [4] noted that an inconsistency occurred in the heat transfer due to the thickness of the boundary layer developing on the louvers. This idea was also confirmed by the results of Achaichia and Cowell [13]. A review of the past literature, in section 2.7 of this thesis, showed that the heat transfer correlation is yet to have a confirmation of which correlation has the strongest agreement. Besides, such a low Reynolds number is not in the practical range. To exclude this uncertainty, therefore, Reynolds numbers below 300 are not considered in this study.

The importance of the thermal wake on the local heat transfer coefficients along a particular louver had been studied experimentally by Kurosaki et al. [18], and numerically by Suga and Aoki [19] and Zhang and Tafti [20]. Zhang and Tafti state that neglecting thermal wake effects at low flow efficiencies can introduce errors as high as 100% in the heat transfer. To perform such a study in large scale experiment would induce even more errors when the heating on louver fins is not uniform. Therefore, to avoid such large errors, it is preferable to do this study fully by a computational method. Furthermore, errors are eliminated at validation stage. The results are validated by comparison with previous published correlations. The purpose of validation is to verify that the mesh distribution and solution procedure are suitable before the study is carried further.

1.5. Objective

This study embarks on the following objectives:

i. To model the fluid and heat flow through singular and stacked louvered fins
ii. To investigate the effects of geometrical parameters of louvers on pressure drop and heat transfer for compact cross-flow louvered fin heat exchangers
iii. To simulate the fluid flow and heat transfer through louvered fins using Computational Fluid Dynamics and obtain pressure drop and Nusselt number/ Stanton number
iv. To determine optimal flow parameters for louvered fins to be used in automotive radiators, refrigeration and air-conditioning heat exchangers

1.6. Scope of study

The scopes of this study are:

i. Simulation will be performed using ANSYS Fluent.

ii. Validation will be conducted using the experiment conducted at different angle such as 21.5°, 25.5° and 28.5° as well as different louver pitch such as 0.7 mm and 1.4 mm.

iii. The Reynolds number (based on louver pitch and maximum velocity) is 200-1000.

iv. Geometrical model will be using 3D stacks of louvered fins.

v. The air inlet temperature is 27 °C which is the room temperature.

vi. Experimental work involves flow visualization technique which is used to determine the flow characteristics inside the louver.

vii. Experiment is conducted at different fin pitch which are 8.1 mm, 11 mm dan 14 mm.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Nowadays efficient heat exchangers are required for saving energy. But there are several factors that inborn in the design limit the potential for performance improvements, such as the increasing flow resistance in the wake region at the rear part of round tube, thermal contact resistance between tubes and fins and so on. It was found that multi-louver fin and flat tube heat exchanger is one of the potential alternatives for replacing conventional finned tube heat exchangers [14].

This chapter will describe the effect of louver angle and louver pitch on pressure drop. Various studies were conducted by previous researchers to obtain the relationship between pressure drop and heat transfer to the louver fin geometry. The heat transfer efficiency is important to increase the heat exchanger performance. This chapter also includes the effects of geometry on pressure drop by using Computational Fluid Dynamics (CFD).

2.2 Heat exchanger

A heat exchanger is a device that is used to transfer thermal energy between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact. Typical applications of heat exchanger can be found in district heat stations, refrigeration systems, air conditioning, power production and chemical processing. In most heat exchangers, heat transfer between fluids takes place through a separating wall or into and out of a wall in a transient manner. In many heat exchangers, the fluids are separated by a heat transfer surface, and ideally they do not mix or leak. Common examples of heat exchangers are shell-and tube exchangers, automobile radiators, condensers, evaporators, air pre-heaters, and cooling towers.

Louvered fin design has been extensively studied experimentally and more recently numerically with CFD codes using the finite element or finite volume method. Louver fin can increased the heat transfer in heat exchanger. Compared to plain-fin surfaces, louvered fins enhance air-side heat transfer primarily through boundary-layer. It is developed to enhancing performance of heat exchanger.

In the past few years, there were extensive studies on louvered-fin flat-tube heat exchangers experimentally and numerically. And most of them have shown that, in order to improve the overall heat exchanger performance, fin surface enhancement is critical because the air side resistance is about 80% of total thermal resistance. Therefore, an enhanced fin surface will provide opportunity for the reduction in heat exchanger size, weight, material cost, and increase in energy efficiency. It is also been proved that louver-fin heat exchangers could be more effective in thermal enhancement [1, 2, 9, 13].

Likewise, L.Tian et al. [5] have conducted research on fin-and-tube heat exchanger as in Figure 2.1. They also found that to improve the overall performance of fin and tube heat exchanger in order to meet the demand of high efficiency and low cost, the use of enhanced fin surface is the most effective way to do that. It is found that the thermal resistance of gas is inherently higher than that of liquid by a factor of 5 to 10, the dominant thermal resistance of fin-and-tube heat exchanger is usually on the gas side (usually air side), which may account for 85% or more of the total thermal resistance [3-5, 13].

Moreover, fins employed on the gas side can increase the heat exchanger surface area and strengthen the flow disturbance. Many researchers stated that longitudinal vortex generators (LVGs) are widely applied in various heat exchangers to increase the heat transfer coefficient with only small increase in pressure drop penalty [5].

On the other hand, Qi *et al.* [6] studied the factors that affect the heat transfer and flow friction characteristics of a heat exchanger with corrugated louvered fins using Taguchi method. The results show flow depth, ratio of fin pitch and fin thickness and number of the louvers are the main factors that influence significantly the performance of the heat exchanger.

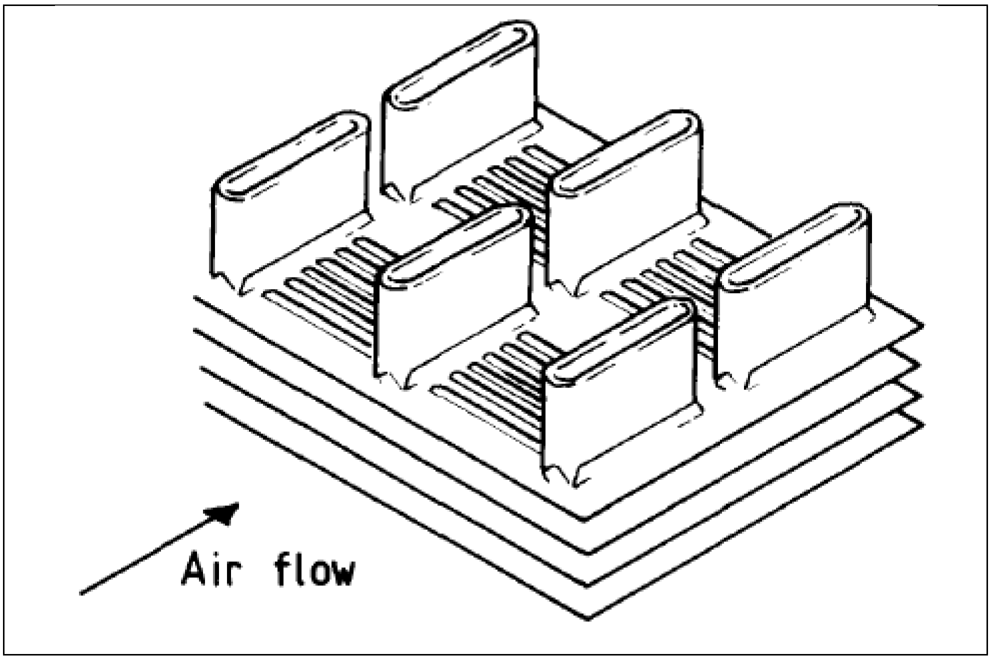

Figure 2.1: Flat-sided tube and louvered plate fin heat transfer surface [1]

2.3. Louvered fin

Nowadays, louvered fins are widely used in compact heat exchangers. The louvers act to interrupt the airflow and create a series of thin boundary layers that have lower thermal resistance. For a compact heat exchanger, the resistance on the air-side is the dominant thermal resistance, and the louvered fins have the advantage of reducing the large thermal resistance. Louvered fin can increase the heat transfer in heat exchanger. Compared to plain-fin surfaces, louvered fins enhance air-side heat transfer primarily through boundary-layer. Figure 2.2 describes the geometrical definitions of common heat exchanger.

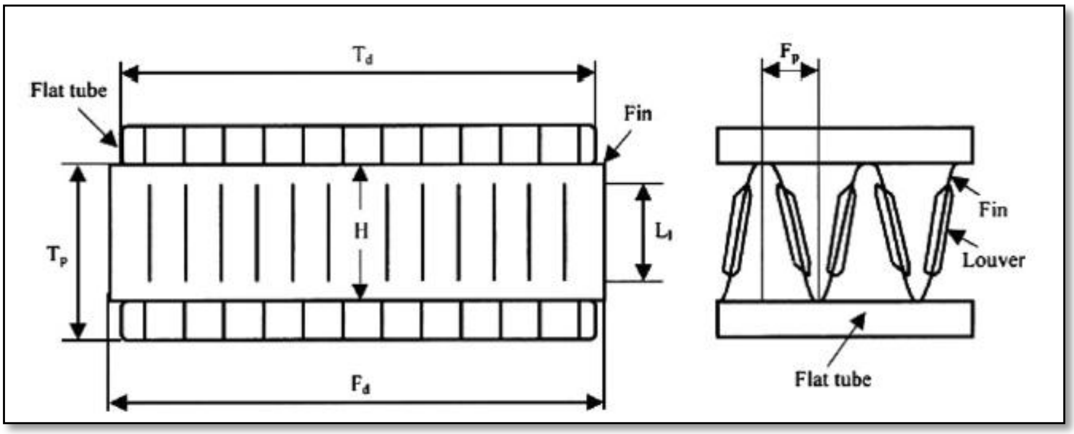

Figure 2.2: Geometrical definitions of a heat exchanger with louvered fin (Qi , 2007)

The first reliable published data on louvered fin surfaces was in 1950 by Kays & London. They performed an experimental study on heat transfer characteristics of different louvered fin arrays and reported a decrease in heat transfer coefficient at low air velocities with increasing fin pitch. They also found that the heat transfer coefficient initially increased with louver angle reaching a maximum value at an angle of 28–30° after which it decreased.

Chang and Wang (1997) investigation on louvered fin heat exchanger is mainly concentrated on numerous full scale experiments. Overall air side heat transfer coefficient and pressure drops determination have been performed and generalized correlations had been established. Webb and Trauger (1991) used visualization techniques to investigate the relationship between the flow alignment and the geometrical parameters of the louver angle, louver pitch and fin pitch. They found that the degree of flow alignment at a given Reynolds number is increased as the fin-to-louver pitch ratio is reduced.

Jang (2001) numerically investigated three-dimensional convex louvered finned-tube heat exchangers. In the study, the effects of different geometrical parameters, including convex louver angles (h = 15.5°, 20.0°, 24.0°), louver pitch (Lp = 0.953 mm, 1.588 mm) and fin pitch (8 fins/in., 10 fins/in., 15 fins/in.) were investigated in detail for the Reynolds number ranging from 100 to 1100. It was shown that, for equal louver pitch, both the average Nusselt number and pressure drop coefficient are increased as the louver angle is increased, while for equal louver angles, they are decreased as the louver pitch is increased. Figure 2.2 illustrates the cross section of louvered fin heat exchanger.

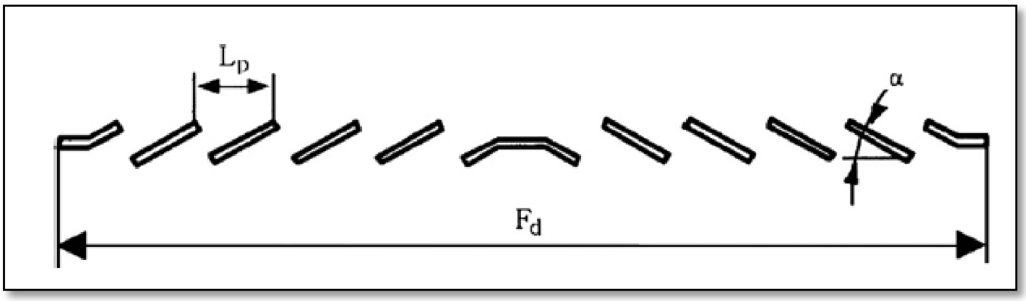

Figure 2.3: Cross section of louvered fin (Qi, 2007)

T'Joen (2009) conducted a study about the flow within an interrupted fin design, the inclined louvered fin. They investigated experimentally through visualization. The inclined louvered fin is a hybrid of the offset strip fin and standard louvered fin, aimed at improved performance at low Reynolds numbers for compact heat exchangers. The flow behavior was studied in six geometrically different configurations over a range of Reynolds numbers and quantified using the concept of fin angle alignment factor. The transition from steady laminar to unsteady flow was studied in detail. The fin geometry had a very large impact on the transitional flow behavior, especially on vortex shedding. They focused solely on the characteristics of the flow passing through the interrupted element, aimed at determining possible future uses of this fin type. Figure 2.4 shows the inclined louvered fin that used in this study.

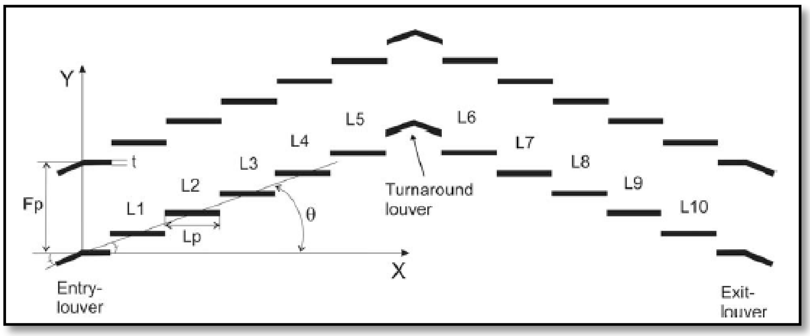

Figure 2.4: Inclined louvered fin array and relevant geometric parameters (T'Joen, 2009)

From the study they found that the flow through inclined louvered fins became unsteady at very low Reynolds numbers (200–300). The initial instabilities occurred in the wake of the turnaround and exit-louver. A larger fin angle resulted in a much earlier transition to unsteady flow as larger recirculation cells were formed which became unstable at lower Re. Compared to offset strip fins and louvered fins, the transition in inclined louvered fins is triggered by the angled plates and not by the accumulation of perturbations. As the onset of unsteady flow is geometrically driven and already appears at low Re, this further emphasizes possible applications in low Re flows, as unsteady flow increase the heat transfer rate with a moderate rise.

2.4. Flow behavior in louvered fins

The heat transfer performance of the louvered-fin geometry is directly influenced by flow behavior. This behavior may consist of boundary layer development and other features such as vortices, separation, and wakes. The presence of such features is dictated by the flow rate and geometric parameters such as fin pitch, louver pitch, and louver angle. In order to understand the influence of flow on heat transfer, it was first necessary to quantify the flow behavior [21].

Louvered-fin geometries as shown in Figure 2.5 have been a popular technique to augment fin heat transfer in compact heat exchangers. Studies have proved that louvers provide benefits in terms of increased cooling capacity, but the flow mechanisms responsible for louver performance are still not completely understood.

Several theories to explain louvered-fin flow behavior have been proposed. Some investigators contend that louvers simply serve as flow tabulators, disturbing the airflow path and thereby increasing fluid mixing. Others believe louvers align the airflow in the louver direction creating a series of miniature flat plates with heat transfer typical of flat plate boundary layers [1]. The complexity of the flow and the difficulty in constructing a large array of test samples has limited louvered-fin flow modeling efforts [15].

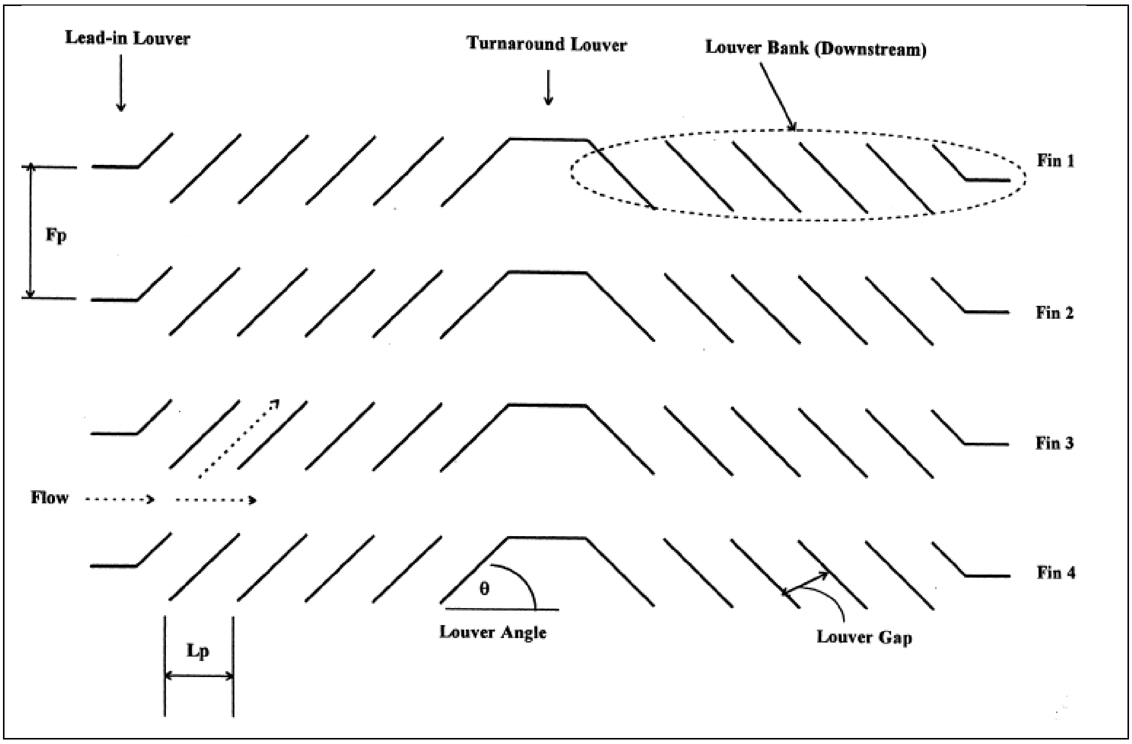

Figure 2.5: Section through typical louvered-fin showing key geometrical parameters [15].

Beauvais [1] used flow visualization on large scale models and showed that louvers act to realign the air flow in a direction parallel to their own planes. Davenport [1] has gone further than that and demonstrated that the degree of alignment with the louvers was a function of Reynolds number. At low Reynolds number values, realignment would be slight, but at high Reynolds number it was almost complete. Moreover, at low Reynolds number as a result of low air velocities the developing boundary layer on the louvers become sufficiently thick to effectively block off the gaps between louvers. The flow then passes largely straight through the louver array down the gap between fins, increasing the heat transfer rate as illustrated in Figure 2.6. But at the same time, as the flow path is extended the frictional pressure drop increases. However, in standard louvered fins, the change in flow behavior is due to the flow following the path of least resistance in other word, the path corresponding to the lowest overall pressure drop [1, 4, 7, 8, 9].

Davenport and Cowell [7] have come out with the same results they revealed that the flow pattern could be characterized in terms of duct directed or louver directed flows, depending on the Reynolds number. Cowell [1] used the Reynolds number based on louver pitch Lp rather than on the hydraulic diameter, and this reference length Lp is now widely used in louver fin investigations. The flow within the louver array is governed by laminar boundary layer growth and renewal. At low Reynolds number, the boundary layers are so thick that the gaps between adjacent louvers are blocked and flow is duct directed, in the direction of the fin. At higher Reynolds number, the boundary layers are thinner and the flow is almost aligned with the louvers as shown in Figure 2.6. The intermediate Reynolds number at which the flow becomes louver directed is still a challenging question [1, 7, 8, 11].

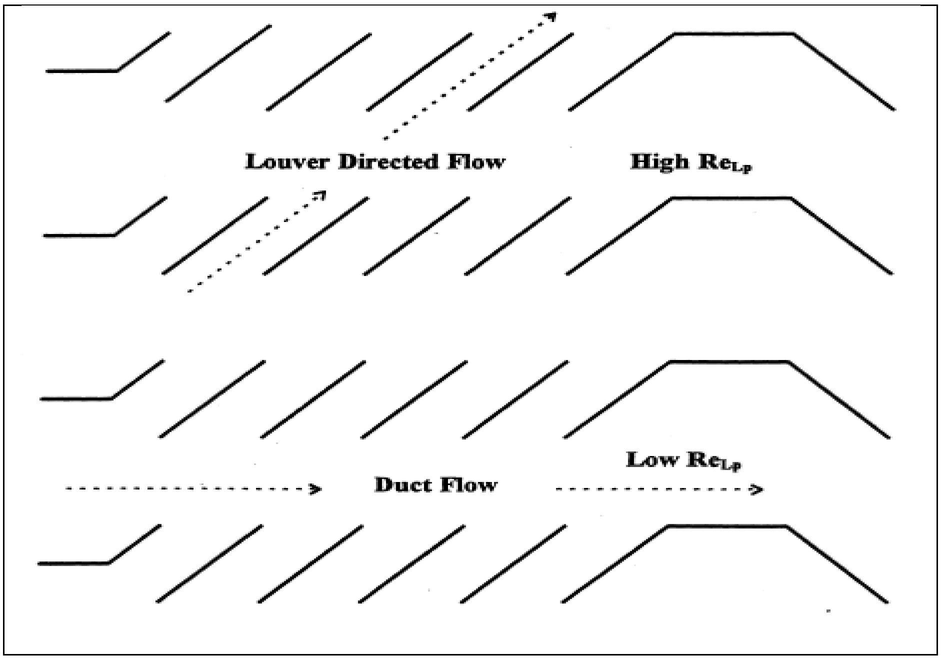

Figure 2.6: Section through louver array indicating possible flow directions [15].

Sunden and Svantesson [16] have proven an important point, they showed that all the louvered surfaces are more efficient than the corresponding smooth surface, and the standard louver fin geometry reveals higher Stanton number than other inclined louver geometries.

Although other studies on louvered fins have been made, they are mostly based on the assumption that the louver angle is uniform and constant. Hsieh and Jang [8] proposed successively increasing or decreasing the louver angle of adjacent louvers and carried out a 3-D numerical analysis on heat and fluid flow. Their results indicated that varying the louver angles applied in heat exchangers could effectively enhance their heat transfer performance.

C. T'Joen et al. [4] have conducted studies on inclined louvered fins, and they found out that interrupted surfaces/louvered fins can provide performance improvement compare to continuous fins. They went further to explain that, interrupted surfaces restart the thermal boundary layer, and because the resulting average thermal boundary layer thickness is smaller for several short plates than for one long plate, the average convective heat transfer coefficient is higher for interrupted surfaces. Moreover, interrupted surfaces can cause vortex shedding above critical Reynolds number and the resulting mixing and flow unsteadiness result in an increase in heat transfer.

DeJong and Jacobi [10] also have studied the flow behavior in detail and reported that the transition between the two flow profiles occurs rather sudden around Reynolds number of 200. They also mentioned that the change in flow behavior is due to the flow following the path of least resistance- the path corresponding to the lowest overall pressure drop. The degree of the flow deflection is usually quantified using the concept flow efficiency.

2.5. Flow efficiency (*η*)

Flow efficiency is used to describe the percentage of the fluid flowing along the louver direction. 100% efficiency represents ideal louver-directed flow while 0% represents complete duct-directed flow. Two kinds of definition of flow efficiency have been used in the past studies. In experimental dye injection studies flow efficiency is defined as the ratio of actual transverse distance (N) traveled by the dye to the ideal distance (D) if the flow were aligned with the louvers. In numerical simulation, flow efficiency is defined as ratio of mean flow angle (β_{mean}) to louver angle (α) [4, 14].

$$\eta_{\exp} = \frac{N}{D} \tag{2.1}$$

$$\eta = \frac{\beta_{mean}}{\alpha} \tag{2.2}$$

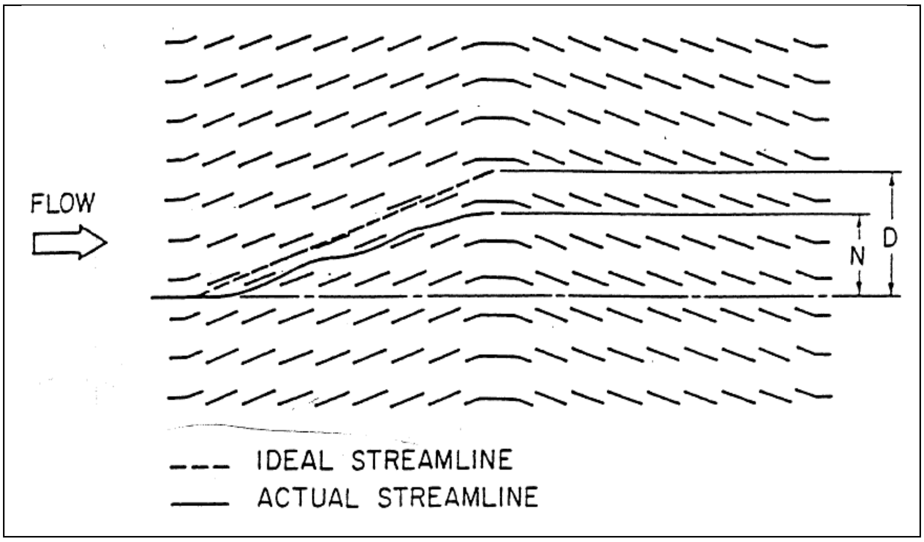

Figure 2.7: Flow efficiency as defined by Webb and Trauger [15]

Flow efficiency has a strong effect on the heat transfer capacity in multi-louvered fins. Flow efficiency is a function of Reynolds number and geometrical parameters, fin pitch ratio and louver angle at low and intermediate Reynolds number. Flow efficiency increases with increase of Reynolds number and louver angle, and decreases with fin pitch ratio. As Reynolds number increases, flow undergoes a transition from duct directed flow (low efficiency) to louver directed flow (high efficiency). There exists a critical Reynolds number beyond which the flow efficiency is independent of Reynolds number [17].

Zhang and Tafti [10] determined a correlation for the flow efficiency of louvered fins. Results show that η is strongly dependent on geometrical parameters, especially at low Reynolds numbers. Flow increases with Re and louver angle while decreasing with fin pitch and thickness ration.

The study of flow efficiency is important and convenient to determine the optimum heat transfer in the design of the compact heat exchanger.

2.6. Pressure drop

Studies have shown that, it is not enough to have a heat exchanger with high heat transfer performance; we have take pressure drop as well into consideration in order to obtain optimal performance balancing efficient heat transfer with reasonable pressure drops. Because higher pressure drops require more pumping power and this is not very much needed.

Jang and Tsai [8] presented studies using a numerical optimization technique in the geometrical optimization of louvered fins and found that, pressure drops are affected significantly by Reynolds numbers and louver angles. As the louver angle is increased, there is a greater pressure-drop penalty due to drag associated with duct-directed flow, and the path of least resistance becomes louver-directed. These results reveal that the optimal louver angles with specific louver pitches can be applied in heat exchangers, which would effectively enhance their heat transfer performance.

Huisseune and Jaeger [3] also explained that the interrupted fin design prevents the formation of thick boundary layers and encourages flow destabilization. But the major drawback is that the associated pressure drop is significant. In contrast to interrupted fin patterns plain fins with vortex generators enhance the heat transfer rate with relatively low penalty of the pressure drop.

Leu [18] also reported that, for a fixed louver length and louver angle, results of various axis ratio indicated that both the heat transfer performance and pressure drops decrease with increase of axis ratio. And also for a fixed geometrical parameters, both the heat transfer performance and pressure drops increase with decrease of louver pitch. Moreover, the pressure drops increase consistently with louver angle. Both heat transfer performance and friction increase with louver length. Surprisingly, the rate of increase of heat transfer performance is about the same as the increase of pressure drop.

Moreover, Bullard [14] has mentioned that the effect of louver angle on heat transfer is different according to flow depth, fin spacing and Reynolds number, but the effect of fin spacing is relatively small. Pressure drops increase with louver angle and flow depth and decrease with increasing fin pitch. The effect of fin spacing on the pressure drop decreases with louver angle. The f correlation indicates that the flow depth is one of the important parameters, which affects the pressure drop significantly.

Although many studies on louver fin have been reported, they are based on the assumption that the louver angle is uniform. Beamer and Cowell [16] proposed an invention with varying louver angle design. With this design, the airflow is turned through the leading set and turned back through the trailing set in a successive and incremental fashion. They claimed the benefits in heat rejection rates would compensate for the increase in pressure drop.

$$\Delta P = P1 - P2 = f\ \frac{l}{D}\frac{\rho V^2}{2}\ \text{(Kpa)} \tag{2.3}$$

Where:

f = friction factor

l = length of pipe

D = diameter

ρ = density of fluid

V = average velocity

2.7. Heat transfer

Heat transfer as an energy transfer process affects every facet of our everyday lives, ranging from the generation of power (electricity), to cooking, preserving food (refrigeration) and providing a suitable indoor climate (HVAC – air conditioning). Because of the huge variety in the nature of the processes involving heat transfer, heat exchangers can take on many different forms. Regardless of their form, the heat exchangers are very important to the overall efficiency of the energy transfer process, and to the cost and size of the system. A very typical application is the exchange of heat between a liquid and a gas, mostly air (e.g. air conditioning, space heating, and energy recovery from flue gas streams) [10].

In many compact heat exchanger applications, interrupted-fin surfaces are used to enhance the air-side heat transfer performance. Interrupted surfaces restart the thermal boundary layers and since the average boundary-layer thickness is smaller for short plates than for long plates, the average heat transfer coefficient is higher for an interrupted surface than for a continuous surface. Furthermore, above some critical Reynolds number, interrupted surfaces can cause vortex shedding which may enhance heat transfer [11].

Aoki *et al.* [14] performed an experimental study on heat transfer characteristics of different louver fin arrays and reported a decrease in heat transfer coefficient at low air velocities with increasing fin pitch. They also found that the heat transfer coefficient initially increases with louver angle reaching a maximum value at an angle of 28°–30° after which it decreases [14, 19].

Romero-Méndez *et al.* [10] used flow visualizations to show that a large reduction of the fin spacing can result in excessive laminarisation of the flow. Any turbulent or vortical motion such as the horseshoe vortex is then quickly dissipated by mechanical blockage and skin friction. So there exists a law of diminishing returns for adding fin surface area. Below a certain fin pitch (spacing between two fins) the increase in surface area will in fact reduce local heat transfer coefficients, causing a need for even more surface area.

In addition, adding more fin surface area will also result in a large increase in pressure drop and material costs. To further enhance the heat transfer performance (i.e. the ability to transfer more heat in a given volume) of fin-and-tube heat exchangers, the convective heat transfer coefficient has to be increased. This can only be done through flow manipulation, as the heat transfer resistance is the result of the surface temperature distribution, which is closely coupled with the velocity field through the thermal boundary layer [10].

Rugh *et al.* [14] investigated heat transfer coefficients and friction losses for high-density louvered fin and flat-tube heat exchangers (2000 fins/m) and proposed j and f correlations. They reported a louvered fin heat exchanger produced a 25% increase in heat transfer and a 110% increase in pressure drop relative to a plain fin.

2.8. Reynolds number

Inside a heat exchanger, the fluid flow is either turbulent or laminar. Turbulent flow produces better heat transfer, because it mixes the fluid. Laminar-flow heat transfer relies entirely on the thermal conductivity of the fluid to transfer heat from inside a stream to a heat exchanger wall. An exchanger's fluid flow can be determined from its Reynolds number:

$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{V L}{v} \qquad (2.4)$$

Where:
Re = Reynolds number
$\rho =$ Density
V = flow velocity
L = length
μ = fluid viscosity
v = kinematic viscosity

The units cancel each other, making the Reynolds number dimensionless. If the Reynolds number is less than 2,000, the fluid flow will be laminar. If the Reynolds number is greater than 6,000, the fluid flow will be fully turbulent. The transition region between laminar and turbulent flow produces rapidly increasing thermal performance as the Reynolds number increases. The type of flow determines how much pressure a fluid loses as it moves through a heat exchanger. This is important because higher pressure drops require more pumping power. Laminar flow produces the smallest loss, which increases linearly with flow velocity.

Springer and Thole (1998) studied the detailed flow field in which measurements were made in the entry region of several louvered fin geometries whereby the louver angle, ratio of fin pitch to louver pitch and the Reynolds number were all varied. The result show that the as the Reynolds number increased, longer development lengths were required and higher average flow angles occurred as compared with a lower Reynolds number case. Time-resolved velocity measurements indicated some flow periodicity behind the fully developed louver for a range of Reynolds numbers. Figure 2.8 illustrates the flow direction and fins configurations of heat exchanger.

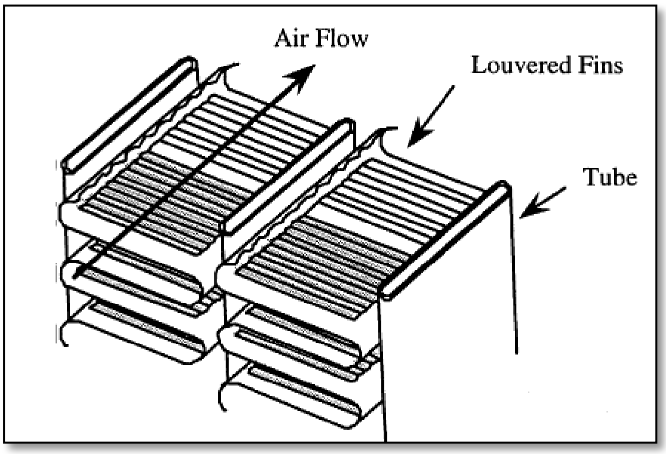

Figure 2.8: Schematic of louvered fin (Springer and Thole, 1999)

Davenport (1983) and Cowell (1995) performed the smoke traces or dye injection techniques. They revealed that the flow pattern could be characterized in terms of duct directed or louver directed flows, depending on the Reynolds number. Cowell used the Reynolds number based on louver pitch L_p rather than on the hydraulic diameter, and this reference length L_p is now widely used in louvered fin investigations. The flow within the louver array is governed by laminar boundary layer growth and renewal. At low Reynolds number, the boundary layers are so thick that the gap between adjacent louvers is blocked and flow is duct directed, in the direction of the fin. At higher Reynolds number, the boundary layers are thinner and the flow is almost aligned with the louvers. The intermediate Reynolds number at which the flow becomes louver directed is still a challenging question. Parameter sensitivity including fin pitch, louver pitch and angle, tube pitch, fin thickness has been extensively performed.

Investigation by Thomas Perrotin (2004) showed that the velocity and thermal fields at different Reynolds number have different result. They found that at low velocity (Re_{Lp}= 78.6), the boundary layers over the louvers are very thick. The air flow between the louvers is blocked by these boundary layers. At higher Reynolds numbers, the boundary layers around the louvers are thinner and the flow is nearly aligned with the louvers. The air flow is calculated in the array where the flow is nearly fully developed. In fact, the number of louvers of the considered fin geometry is not sufficient to have fully developed conditions, but the fully developed flow is nearly obtained for the last louver of the first half of the fin. It also shows that the flow efficiency is very sensitive to the fin pitch, the louver pitch and louver angle.

Through a two-dimensional finite-difference analysis, Achaichia and Cowell (1988) illustrated that increasing the Reynolds number results in a transition of the flow from duct-directed to more louver-directed. This is an example of boundary layer driven flows. At low Reynolds numbers the thick boundary layers block the passage between the louvers, forcing the flow to go straight through. As the Reynolds number increases, the boundary layers become thinner and the passage opens up, aligning the flow with the louvers and thus increasing the heat transfer rate. The degree to which the flow follows the louvers is called the flow efficiency. The flow efficiency is strongly dependent on the geometry, especially at low Reynolds numbers. Overall, the Reynolds number gives the large effect to the heat exchanger, especially in the pressure drop and heat transfer rate.

CHAPTER 3

METHODOLOGY

3.1. Introduction

Methodology is a method or process, or facts that involve an array of measures of work that should be in a scientific study. It can also be interpreted as a documentation of production and as a guideline to make an analysis or design process. However, a good understanding of the research scope and boundary may guide a comprehensive and concise methodology. Therefore, the experiment is carried out in systematic procedures whereas leading to attain an optimum result. Before embarking the test of the research, the test parameters and variables must be reviewed and determined from previous related research. This chapter presents the details of the experimental apparatus including flow measurement in a blower, experimental procedure for pressure drop and heat transfer measurements and its pertinent variables.

This chapter also described about the process was involved in ANSYS Fluent. Basically, ANSYS Fluent involved three main stages that have to be considered which include pre-processing, solving and post- processing. The main purposes in ANSYS Fluent is to focus on the modeling and simulation to predict the louvered fin heat exchanger's performance from the perspective of pressure drop and heat transfer rate with various configurations.

Figure 3.1 show the procedure and steps in form of flowchart regarding this process of simulation as well as the experimental process. This approach is used to achieve the objective or criteria in determine whether a procedure is can be continue or not.

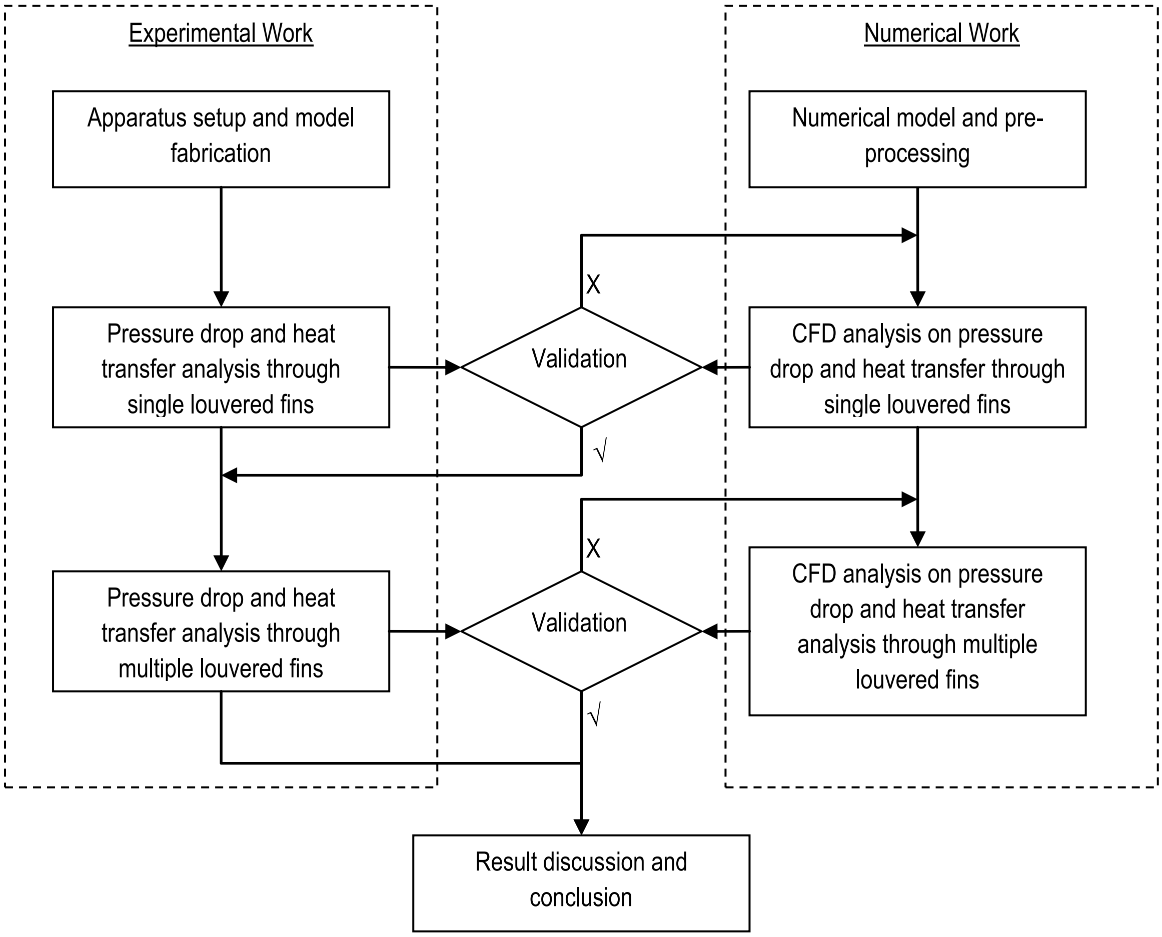

Figure 3.1: Flow chart for methodology

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