Chapter 1

Introduction

1.1 Fins for heat transfer enhancement

The performance of a heat exchanger having cylindrical primary surface can be augmented by the use of annular fins. By increasing the effective heat transfer area, fins increase the rate of heat dissipation from the primary surface to the surroundings [2, 13, 14, 34, 47]. However, the attachment of fins requires additional design, material and fabrication, and thus raises the production costs. Hence, effort has been put in recent years for size and shape optimization of annular fins for effective utilization of fin material [11, 27, 28, 55, 72, 77]. Designers have to identify a fin configuration that maximizes the heat dissipation rate and minimizes the fin volume or weight. The simplest shape of an annular fin is of rectangular cross-section. However, the cross-sectional area of a rectangular annular fin being constant, fin material is not used effectively for conducting heat near its tip, which raises the issues of optimum fin profile of variable thickness (shape optimization) and fin with step change in thickness (size optimization) [44]. Keeping in mind the requirement of higher heat transfer rate and lower production cost, designers strive to optimize the geometry of fins, so that a higher heat transfer rate can be achieved for a given fin volume, or a smaller fin volume can be obtained for a specified heat duty. However, practical applicability of fins with complicated profiles (shape optimization) is limited because of the involved complex fabrication processes. In a parallel effort, accordingly, optimization of dimensions (size optimization) of fins is also attempted where the profile shape is pre-specified. Therefore, modification of the geometry of a rectangular profile fin, in view of reducing the fabrication complexity as well as efficient utilization of fin material for heat transfer process, has immense scope [39]. A fin with step change in thickness, which is a modification of the uniform thickness annular fin, not only involves a simple fabrication process, but also dissipates heat making effective utilization of the fin material to certain extend.

Fins are used in places where generated heat needs to be dissipated, such as heat exchangers, semi-conductors, electronic components, etc. Even if the design criteria of fin differ from application to application, the primary concerns are the maximization of the rate of heat transfer and minimization of the total volume of the fins. Thus, the optimization of a fin based on these two requirements is highly desirable. Many studies are dedicated to analyze heat transfer from fins, considering either steady state heat transfer in the radial direction of the fins [26, 44, 46, 66, 67], or transient response to heat transfer [16, 57, 58, 68, 90]. Based upon the orientation, they are known as either longitudinal fins [6, 20, 33, 81] or annular fins [4, 7, 54, 65]. In a cylindrical primary surface, annular fins are the main tools for the augmentation of heat transfer.

1.2 Thermal stress induced in fins

Thermal stress is induced along the length of a fin due to change in temperature gradient. The developed thermal stress is usually responsible for various types of mechanical failures, such as creep, crack propagation, and fatigue, which shorten the life of a fin. Hence, the design of a fin profile demands a systematic thermal stress analysis for better life expectancy and performance of the fin [60–63].

The temperature gradient along the length of a fin develops thermal stress. Since a very thin fin induces a high thermal resistance, a poor conductive heat transfer rate causes a higher temperature gradient in the fin radial direction leading to the development of excessive thermal stress. On the other hand, an increase in heat transfer surface area of a fin causes a higher heat transfer rate from the fin surface, thus inducing a higher temperature gradient throughout the fin. In other words, a higher thermal stress is associated either with a low heat transfer rate when a steeper temperature gradient is caused by a higher thermal resistance to conduction, or with a higher heat transfer rate when the steeper temperature gradient is caused by a high heat transfer from the surface. In any case, the development of thermal stress is undesirable as it can cause many mechanical failures, such as crack propagation, creep, and fatigue. Hence, a systematic analysis of the thermal stress in fins is essential so as to increase the life expectancy as well as to maintain the performance of the fins. However, numerical analysis of thermal stress in annular fins involves complex mathematical formulations along with non-linearity of the problem, thus limiting the study on thermal stress analysis in annular fins to a small number [1, 9, 17, 19, 49, 93].

1.3 Fin array

Most of the works on annular fins were concerned with the optimization of a single fin isolated from the surrounding. However, application of a single fin for heat dissipation is rarely found in practice. Instead, a number of fins in a row, known as a fin array, is generally used for augmenting heat transfer [14, 25, 73, 76, 87]. In that case, optimization of a fin profile in combination with fin inter-spacing becomes essential for efficiently dissipating heat from a fin array. Still, only a limited number of works in that direction have been reported in literature. Many of the optimization processes are carried out considering fins of constant thickness or constant inter-spacing [41, 43, 45]. However, an appreciable saving in the fin material can be achieved by modifying the fin profile and fin inter-spacing of a fin array.

1.4 Multi-objective optimization in fin Design

Though the maximization of heat dissipation from fins and fin arrays are a primary requirement, there exist some other objectives to be satisfied, thus leading the fin and fin array design to be a multi-objective optimization problem for optimizing all such conflicting objective functions simultaneously. The multi-objective optimization process gives a set of trade-off solutions, where an optimized solution satisfies all the objectives with a certain level of acceptance without being influenced by any other solution. However, scrutinizing the present literature, it is observed that no work designing an annular step fins and annular fins subjected to induced thermal stress as a multi-objective optimization has been reported so far.

1.5 Aim of the thesis

It is clear that an efficient fin and fin array configurations can be attained by optimization of the various design related parameters. This thesis aims to enhanced the performance of six types of different annular fin arrangements. The heat dissipation from the fin tip is also taken into account. To make the fin and fin array design cost as well as thermally efficient, all the six fin arrangements are formulated as multi-objective optimization problems for optimizing simultaneously different combinations of six objective functions, which are maximization of heat transfer rate, minimization of fin volume, minimization of induced thermal stress, maximization of fin efficiency (surface efficiency in fin arrays), maximization of fin effectiveness (augmentation factor in fin arrays), and minimization of heat transfer surface area. The fact that modifying the fin geometry as well as fin inter spacing can actually increase the heat transfer and its performance related factor and at the same time reduce the thermal stress induced thus making optimization a practical reality. However, to the best knowledge of the authors, no work on annular step fin and its array and continuously varying thickness annular fin and fin array subjected to induced thermal stress under multi-objective optimization has been reported in the specialized literature. Hence, the present work is taken up to fill up such a gap in literature.

The main objective of the present study is to put forward the trade-off optimal scenarios based on various conflicting objective functions along with the level of influence of different design variables on the objective functions, so that designers can enjoy the freedom to choose favorably solutions as per their requirements depending upon the availability and practicability of information and resources. Another objective of the present study is to present a comparative analysis of the trade-off optimal scenarios of various fin profiles and fin array configurations in terms of some conflicting objective functions, so as to facilitate a designer to arrive at a suitable fin and fin array configurations and a corresponding compromise solution.

1.6 Outline of the thesis

Chapter 1 gives the prologue of the project and illustrates the overall objective of the project along with its importance and significance. It also describes the fundamentals on which the work is founded, i.e. importance of fin as a heat dissipation agent, significance of design optimization to enhance its performance etc.

Chapter 2 reviews the research works already done in the area of the problem undertaken in this thesis. This review includes the present research status of annular fin and its array and optimization in this area.

In chapter 3, the problem related to isolated fin attempted in the thesis is represented theoretically and diagrammatically. The chapter also presents the mathematical formulation of the problem for calculating different variables to be determined and the formulation of the multi-objective optimization problem which comprises of the objective functions evaluation as well as the constraints handled in the formulation. Further, this chapter gives the outcome of the work done related to isolated annular fin. It shows the results of the optimization problem taking into account the practical applications. Both the results and observations of multi-objective optimization are presented with the help of various plots.

Chapter 4 handles the formulation, optimization and results and discussions of annular fin array in the same fashion as that of isolated fin in chapter 3.

Chapter 5 sums up all the points derived from this work and give the views obtained. This chapter also states the further scope of research in this area.