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Heat Transfer Enhancement of Single-Phase Internal Flows using Shape Optimization and Additively Manufactured Flow Structures

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A B S T R A C T

This paper reports heat transfer enhancement of forced internal single-phase flow enabled by additively manufactured internally finned channels. We consider internal liquid coolant flow through a tube with constant heat flux applied to the exterior surface. A genetic algorithm was developed and used to optimize the fin geometry in order to minimize total thermal resistance for laminar flow or convection thermal resistance for turbulent flow. The genetic algorithm sampled more than 500 fin geometries, evaluated thermal resistance, and selected the optimum fin geometry. We selected three designs for experimental testing: a complex fin structure suggested by the genetic algorithm; a straight fin design; and a smooth circular channel as a reference. The devices were made from aluminum silica (AlSi10Mg) using direct metal laser sintering additive manufacturing. The devices were tested using a water ethylene glycol mixture (80:20) over the hydraulic diameter based Reynolds number range of 400 – 18,000, covering both laminar and turbulent flow regimes. Finite element simulations of heat transfer and pressure drop helped to understand and interpret the measurements. Compared to the smooth pipe reference design, the total thermal resistance of the genetically optimized fin design was 77% lower for laminar flow at $Re_h = 2{,}000$ and 65% lower for turbulent flow at $Re_h = 10{,}000$. Compared to the straight fin design that is commonly used for enhancing convection heat transfer in internal flows, the total thermal resistance of the genetically optimized fin design was 55% lower for laminar flow at $Re_h = 2{,}000$ and 29% lower for turbulent flow at $Re_h = 10{,}000$. We explore the potential design space for different types of heat exchangers by investigating how total heat transfer varies with exterior heat transfer coefficient and channel wall thermal conductivity. This research shows how shape optimization and additive manufacturing can result in devices with improved internal convection heat transfer.

Introduction

Heat transfer enhancement using internal fin structures has broad applicability in heat exchangers [1–5]. Internal flow convection heat transfer enhancement often consists of extended surfaces inside the channel that increase convection coefficient and wetted surface area, or alternatively installing inserts such as twisted tapes and wire coils to promote fluid advection and mixing [6–11]. Heat transfer may also be enhanced by increasing wetted surface area between the channel and fluid [8,12,13]. For turbulent flow, heat transfer enhancement techniques typically focus on both macroscopic and microscopic approaches including enhancing surface roughness to improve fluid mixing and convective heat transfer [14–16]. The placement of extended surfaces or fins inside a channel or duct is a common heat transfer enhancement technique that can be used for both laminar and turbulent regimes of single-phase and two-phase flows [8,17,18]. This paper focuses on methods to develop internal fins that increase the convection coefficient and increase the wetted surface.

Most published research that focuses on internal fins uses simple fin shapes that may be triangular, rectangular, or trapezoidal [8,18,19]. Thermal-fluidic analysis of these simple fin shapes is relatively straightforward, and simple fin shapes are also easier to fabricate via conventional methods such as extrusion or drawing. Accordingly, most studies focus on simple fin shapes, while fewer investigations have explored more complex fin geometries even though these geometries can enhance heat transfer performance

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