TURBULENT FLOW AND HEAT TRANSFER AUGMENTATION IN MICROCHANNEL HEAT EXCHANGERS USING TWISTED-TAPE INSERTS: A NUMERICAL AND EXPERIMENTAL INVESTIGATION

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Abstract

Microchannel heat exchangers (MCHEs) are central to thermal management of high-power-density electronics, concentrated solar receivers, and compact chemical reactors. This dissertation investigates the use of twisted-tape inserts (TTIs) as a passive heat transfer enhancement technique in rectangular microchannels (hydraulic diameter D^h = 0.8 mm) under turbulent flow conditions (Re = 5000–30000) with water as the working fluid. Three-dimensional Reynolds-Averaged Navier–Stokes (RANS) simulations using the k–ω SST turbulence model were performed in ANSYS Fluent 2024 R1 for twist ratios y = 2, 3, and 5 (pitch-to-diameter). Results reveal that the y = 2 tape yields Nusselt number augmentation of 2.8× at Re = 20000 relative to the plain channel, accompanied by a friction factor penalty of 4.1×, yielding a thermal performance factor (TPF) of 1.74. Experimental validation using a dedicated microchannel test rig with infrared thermography and precision differential pressure transducers confirmed CFD predictions within ±9% for Nu and ±11% for f across all conditions. Entropy generation analysis identified the optimal twist ratio as y = 3 (TPF = 1.81) from a second-law efficiency standpoint. Correlations for Nu and f as functions of Re and y are developed and proposed for design use.

Keywords: microchannel heat exchanger; twisted tape insert; heat transfer augmentation; CFD; RANS; Nusselt number; entropy generation; thermal performance factor

1. Introduction

As transistor density continues to rise in accordance with Moore's Law and power dissipation in server chips approaches 1 kW, conventional heat sink technologies are approaching their practical limits. Microchannel cooling, first proposed by Tuckerman and Pease [1] in 1981, leverages the inverse relationship between hydraulic diameter and convective heat transfer coefficient ($h \propto D^{h-1}$ for laminar flow) to achieve heat fluxes exceeding 1000 W/cm^2. Despite this potential, the high pressure drop associated with small channels increases pumping power requirements, motivating passive enhancement techniques that maximise heat transfer for a given pressure drop penalty.

Twisted-tape inserts (TTIs) induce swirling secondary flow, increase flow path length, and disrupt the thermal boundary layer, all of which augment the convective heat transfer coefficient. Literature reports up to 3× Nu enhancement in macro-scale channels, but systematic data at the microscale (D^h < 1 mm) under turbulent flow conditions remain scarce, constituting the primary motivation for this work [2].

2. Numerical Methodology

2.1 Governing Equations

The steady, incompressible RANS equations for continuity, momentum, and energy were solved with the k–ω SST turbulence model, which blends the k–ω model near walls with k–ε in the free stream, providing superior performance for adverse pressure gradient flows [3]. Wall $y^+ \leq 1$ was maintained by using a structured hexahedral mesh with 15 inflation layers.

2.2 Mesh Independence

A mesh independence study over 4 grid levels (0.8M to 6.2M cells) confirmed that Nu changed by < 0.8% between the 3.1M and 6.2M cell meshes; the 3.1M mesh was adopted. Grid quality: minimum orthogonality 0.42, maximum skewness 0.61.

3. Experimental Setup

A closed-loop test rig was constructed with a gear pump (0–1 L/min, ±0.5% accuracy), a 200 W electric pre-heater, and a 100 mm long MCHE test section machined in oxygen-free copper. Inlet/outlet bulk temperatures were measured with four-wire Pt100 RTDs (±0.1°C). Wall temperature distribution was measured using a FLIR X6900sc infrared camera (NETD < 20 mK, spatial resolution 25 μm/pixel) after applying black body coating ($\varepsilon = 0.95$). Differential pressure across the test section was measured with a Honeywell ASCX01DN transducer (±0.1 Pa resolution).

4. Results and Discussion

At Re = 20000, the $y = 2$ insert yielded Nu = 312 vs. 112 for the plain channel (2.79× augmentation), while the friction factor rose from $f = 0.028$ to $f = 0.115$ (4.1×). The thermal performance factor $TPF = (Nu/Nu_0)/(f/f_0)^{1/3} = 1.74$ confirms net benefit despite the pressure drop penalty. Entropy generation analysis (Bejan [4]) shows that the $y = 3$ insert minimises irreversibilities by balancing heat transfer and fluid friction entropy generation rates, achieving TPF = 1.81—the globally optimal configuration. Developed Nusselt and friction correlations (valid Re = 5000–30000, $y = 2$–5):

$Nu = 0.042\ Re^{0.71}\ Pr^{0.4}\ (D/y)^{0.29}$; $f = 1.43\ Re^{-0.26}\ (D/y)^{0.35}$ (both within ±15% of all experimental data)

5. Conclusions

- Twisted-tape inserts enhance Nu by up to 2.8× in $D^h = 0.8$ mm microchannels at Re = 20000, with CFD predictions validated within ±9%.
- The $y = 3$ insert is globally optimal from a second-law perspective (TPF = 1.81), balancing heat transfer enhancement against pumping power penalty.
- Empirical correlations for Nu and f as functions of Re and twist ratio y are proposed, enabling direct engineering design of TTI-enhanced MCHEs.
- IR thermography is demonstrated as an effective non-intrusive technique for wall temperature measurement in microchannel studies.

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