ABSTRACT

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| Title ofDissertation: | Experimental and computational analysis of aN EXTREME ENVIRONMENT heat exchanger co-designed for manufacturability and thermal-HYDRauLIC performance |
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|  | Zhengda Yao, Doctor of Philosophy, 2025 |
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Supercritical CO2 (sCO2) has recently attracted considerable attention due to its inherent properties, such as high density and volumetric heat capacity, making it an energy-dense and efficient heat transfer medium for various applications, including power generation systems, aerospace and electronics cooling. Heat exchangers (HXs) operating in extreme conditions must adhere to strict size, weight, and power consumption (SWaP) criteria to ensure efficient thermal systems. Leveraging sCO2 offers the potential to develop high-performance, cost-effective, and compact metal heat exchangers.

Beyond the fluid selection, advanced HX design plays a crucial role in improving thermal performance. In this study, a multi-pass microchannel heat exchanger design (MPMHX) with small fins (0.18 mm width) and microchannels (0.75 mm width) was adopted to achieve high compactness (surface area density = 989 m2/m3). To successfully fabricate this complicated structure, additive manufacturing (AM) was utilized with a development of AM guidance (printing configurations and powder removal process). The multi-pass design concept was applied to fabricate a long microchannel (173 mm) inside a limited printer volume. An elevated relative roughness factor (9.6%) was observed after the manufacturing process and it was incorporated into an AM-based microchannel prediction model to assess its impact on HX performance. The prediction results were validated by experiment, which indicated that the measured roughness increased the pressure loss by 172% while simultaneously enhancing thermal performance by 31%. Compared to other compact HX concepts in the literature, the MPMHX exhibited the highest experimentally demonstrated compactness (Q/V = 45.4 MW/m³, Q/V/dT = 0.34 MW/m³/°C) with a low pumping power of 11.75 W.

To further optimize the MPMHX, a genetic algorithm optimization was implemented by changing number and dimensions of microchannels. This optimization led to a 18.6% reduction in thermal resistance, albeit with an 85.7% increase in pumping power. Additionally, topology optimization (TO) was performed using a simplified pseudo-3D model. The optimizer successfully enhanced a heat sink’s thermal performance by 16.5%, at the cost of an 88.5% increase in pumping power. Comparatively, parametric optimization demonstrated superior performance, leading to 47% and 97% thermal performance improvements for the MPMHX operating at 150°C and 600°C, respectively.

This study presents a highly compact sCO₂ heat exchanger, leveraging additive manufacturing and advanced optimization techniques to enhance HX performance. The findings provide valuable theoretical/experimental insights that can drive the advancement of high-performance HXs for power generation, extreme environments, and high-efficiency applications.

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| Experimental and computational analysis of aN EXTREME ENVIRONMENT heat exchanger co-designed for manufacturability and thermal-hydraulic performance |

by

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Dissertation submitted to the Faculty of the Graduate School of the

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