

A Multiscale Approach for the Thermo-Hydraulic and Structural Performance Prediction of Compact Cross Flow Heat Exchangers

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Abstract. The design of compact heat exchangers (HXs) for hydrogen fuel cell and battery-electric aircraft presents unprecedented challenges in terms of thermal management and structural integration. This study introduces an open-source multiscale–multiphysics framework for predicting the thermo-hydraulic and structural performance of cross-flow HXs based on repeated unit cells. The framework combines detailed microscale conjugate heat transfer simulations with macroscale modelling through two complementary reduced-order strategies: upscaling and homogenisation. The reduced-order models are benchmarked against fullscale, high fidelity simulations. Results demonstrate good agreement of both the upscaled and homogenised models with full-scale CFD simulations, particularly deviations below 4 % for fluid temperatures, with the upscaled model performing consistently better.

Introduction

The design methodologies for HXs have evolved significantly over recent decades, transitioning from traditional empirical correlations to advanced numerical simulation and multiscale modelling techniques. Multiscale approaches are particularly relevant for aircraft-scale systems, where sustainable propulsion architectures such as battery-electric and hydrogen fuel cells generate large quantities of low-grade heat that must be rejected efficiently. As direct high-fidelity analysis of fullscale configurations is computationally prohibitive, performance evaluation and optimisation down to the microscale can deliver significant system-wide gains, particularly in the case of additively manufactured periodic HX cores. While previous studies have applied multiscale methods to compact HXs in automotive applications [1, 2], they have primarily focussed on thermo-fluidic performance. More recently, researchers have adopted high-fidelity CFD to study novel configurations enabled by additive manufacturing [3]. On the structural side, Imediegwu et al. [4] used a multiscale approach for thermo-structural coupling to improve thermal performance in a heat sink. On the thermo-hydraulic side, porous flow modelling and homogenisation techniques have also emerged as promising alternatives means to accurately characterise complex, periodic geometries [3]. Despite these advances, the explicit coupling of multiphysics effects combining thermofluidic and structural responses, which are particularly important in aerospace applications, remains rare.



Methodology

Overview. A novel open-source framework is introduced for multiscale and multiphysics analysis of a compact cross-flow HX with repeating unit cells (RUCs). The framework starts with a parametric model for a microscale unit cell of the HX core, as seen in Figure 1a, generating a multi-region mesh that can then be used for thermofluid and structural analysis. As part of the multiscale strategy, two reduced order models (ROMs) are considered, namely upscaling and homogenisation. The performance of these ROMs is evaluated against high-fidelity macroscale simulations to determine their accuracy and efficiency.

Microscale. A conjugate heat transfer (CHT) model is first solved using the multi-region mesh by means of the continuity, momentum and energy equations. The structural domain is solved using Cauchy's momentum equation for solids using combined mechanical loading and thermal stresses.

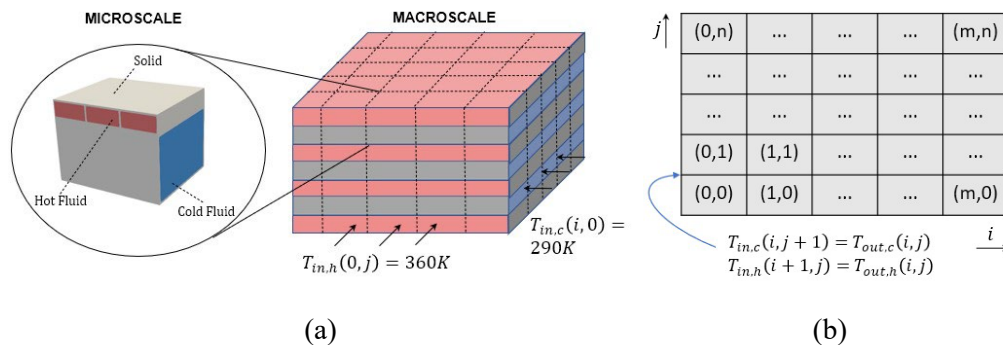


Figure 1: (a) The microscale and macroscale HX multi-region domain (b) boundary conditions transfer using the upscaling algorithm.

Macroscale. For the upscaling procedure, the algorithm originally proposed by Ciuffini et al. [2] is first implemented in a single layer of the HX block consisting of RUCs, and later adapted to a 3-dimensional framework. Each RUC represents a fully resolved microscale CHT simulation. The coupling between neighbouring RUCs is achieved through a sequential mapping procedure, defined by the boundary transfer relationships shown in Figure 1b, with the initial conditions of the hot and cold fluids defined as shown in Figure 1a.

Subsequently, homogenisation is employed as an alternative reduced-order approach to predict the effective thermo-mechanical behaviour of the HX. This method enables two-scale coupling, where heat-transfer and structural properties are first evaluated at the microscale and then averaged to define equivalent parameters at the macroscale. While upscaling relies on cell-to-cell coupling, homogenisation replaces detailed local variations with averaged quantities that preserve the overall physical response.

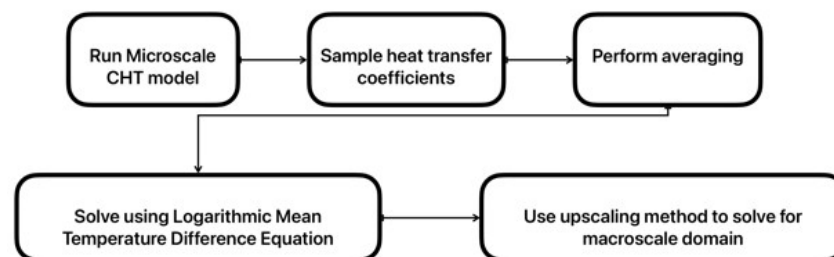


Figure 2: Homogenisation steps to reconstruct the macroscale temperature distribution from microscale simulations using LMTD equation and upscaling

The procedure for reconstructing the macroscale temperature distribution using homogenisation is highlighted in Figure 2. For the structural characterisation, the unit cell is evaluated under six independent loading cases to determine the uniaxial and shear components of the effective stiffness matrix. The resulting properties, which are orthotropic because of the geometric configuration of the RUC used, are subsequently used to solve a macroscale model of homogenised material with equivalent overall dimensions.

Results and Discussion

The upscaling algorithm from Ciuffini et al. [2] is implemented on a two-dimensional 10×10 RUC array representing a layer of the compact cross-flow HX and is subsequently benchmarked against full-scale CFD results with the same configuration. A direct error comparison between the upscaling and homogenisation approaches is performed to assess their predictive accuracy. As shown in Figure 3a, the upscaling method achieves excellent agreement with the full-scale solution, with deviations below 4% for the cold-fluid domain. Figure 3b further confirms that the upscaling approach outperforms homogenisation for the hot fluid region. Future work will focus on integrating surrogate models to reduce the number of microscale simulations required for homogenisation, thereby extending the framework's applicability to a wider range of inlet flow and thermal conditions.

Conclusion

This work presented an open-source multiscale–multiphysics framework for predicting the thermo-hydraulic and structural performance of cross-flow HXs. The upscaling and homogenisation approaches were benchmarked against full-scale CFD, with the upscaling method achieving higher accuracy at reduced computational cost. The framework's consistent use of a single multi-region mesh enables efficient extraction of coupled thermal and structural properties, providing a foundation for future optimisation and design of lightweight, multifunctional HXs for sustainable aircraft.

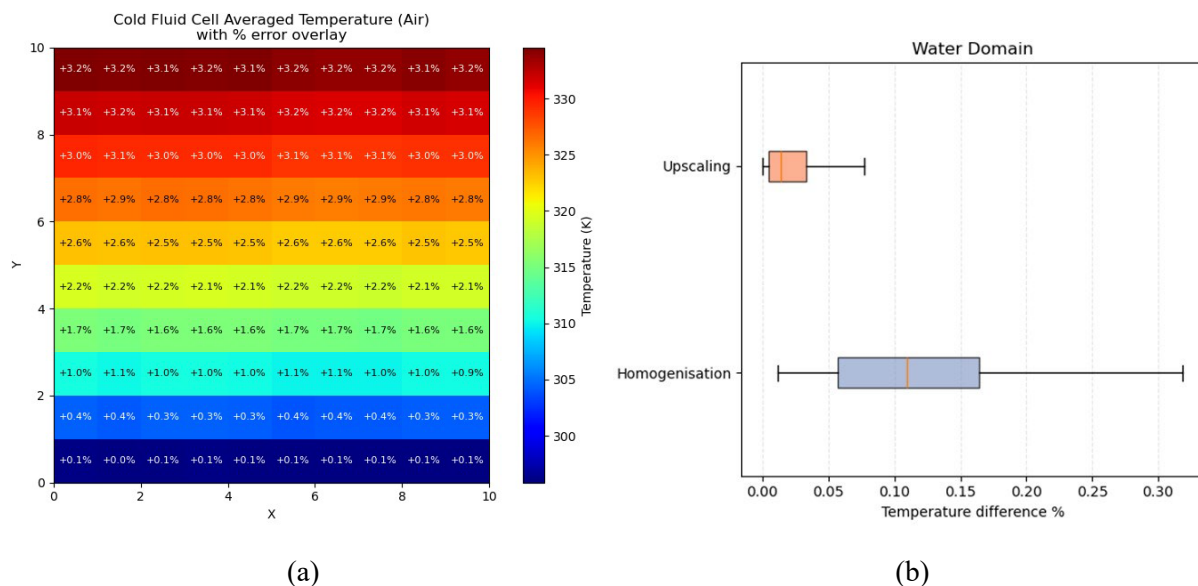


Figure 3: (a) Temperature distribution and cell percentage deviation of the cold fluid domain using upscaling (b) Comparison of the reduced order models against fullscale CFD for the hot fluid domain

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