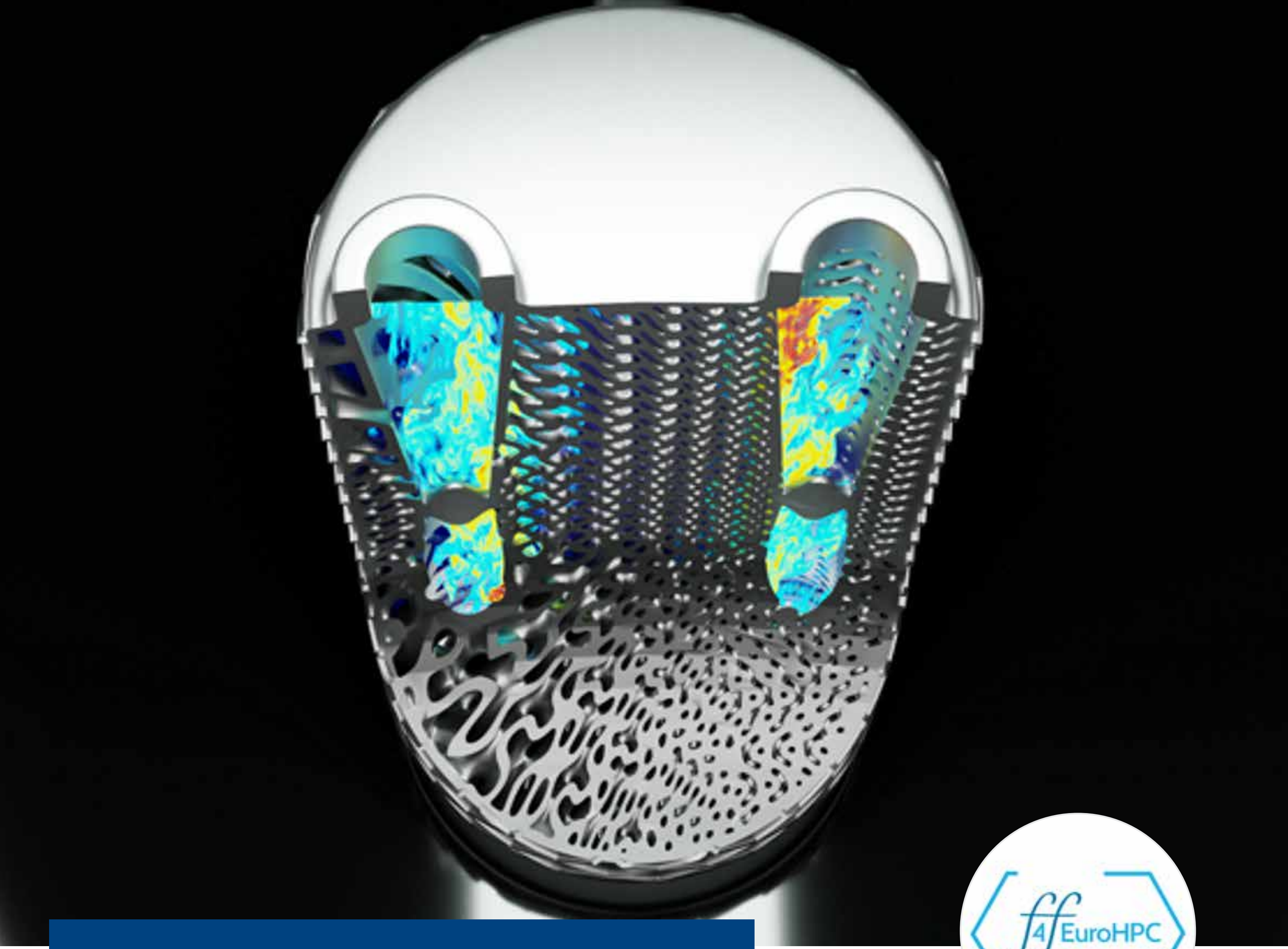

Topology optimization of micro-channel heat exchangers

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1. Optimad - 2. Cineca - 3. Aidro

The success story presented in this article was developed during the first tranche of the FF4EuroHPC project. Partners Optimad, Aidro and CINECA teamed up to address a specific business challenge in the manufacturing sector and overcome it with the help of high-performance computing.

A micro channel heat exchanger (MCHX) is a heat exchanger in which fluid flows in millimetre-sized lateral confinements. Due to their high specific properties, efficient flow distribution, and light weight, they are gaining popularity in various industries, including aerospace, bioengineering, electronics, and oil & gas.

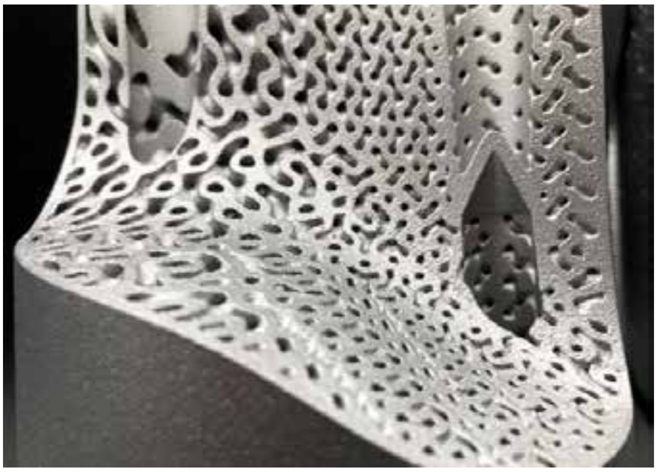

Fig. 1. An example of MCHX (3DHX, courtesy of Aidro). The internal lattice structure is obtained using a TPMS (gyroid) with variable frequency and wall thickness.

The challenge: to develop an advanced design methodology to generate innovative micro channel heat exchanger configurations

The performance of MCHX is strongly influenced by the design (shape and topology) of the micro-channels. Design approaches based on experimental campaigns require many iterations, resulting in significant R&D costs and long times to market. In practice, due to budget and time constraints, only a few configurations are evaluated leading to sub-optimal solutions. On the other hand, a simulation-centred design approach poses several challenges including modelling, software integration, and robustness. Furthermore, due to the inherent multiscale nature of the problem, conjugate heat transfer (CHT) simulations of MCHX require high-resolution computational models to resolve fluid dynamics well at the smallest space-time scale of microchannels.

Consequently, the costs associated with these calculations severely restrict the comprehensive exploration of the design space. Optimization is also a fundamental requirement for any ICT infrastructure. In-house HPC solutions are generally under-dimensioned for these tasks, especially for small and medium-sized enterprises.

As a result, some shortcuts are taken to accommodate the limited computational resources (e.g. the feasible design space is limited heuristically in advance, or simplified models are developed on an ad-hoc basis for a single use case) leading to workflow entropy, further increases in R&D costs, and ultimately poorer market competitiveness. Therefore, it becomes imperative to use parallel computing to maintain development times that are compatible with industrial turnarounds.

Topology optimization (TO) is an advanced design methodology used to generate innovative configurations that are difficult to achieve with conventional design techniques. The complex shapes resulting from TO are not easily produced by established techniques such as computer numerical control machining, injection moulding, or vacuum casting. The technology readiness level (TRL) of different types of additive manufacturing (AM), e.g. laser-sintering, has soared over the past decade, making these technologies key to new business models in the manufacturing industry. AM offers several advantages such as a faster production cycle and flexible design, and creates possibilities that traditional manufacturing technologies could not by enabling the production of components with complex geometries at relatively low costs. Therefore, the combination of TO with AM is a promising application for MCHX design. Notwithstanding the enormous potential, however, MCHX manufacturers are prevented from taking advantage of the freedom provided by the TO+AM paradigm due to the difficulties mentioned previously.

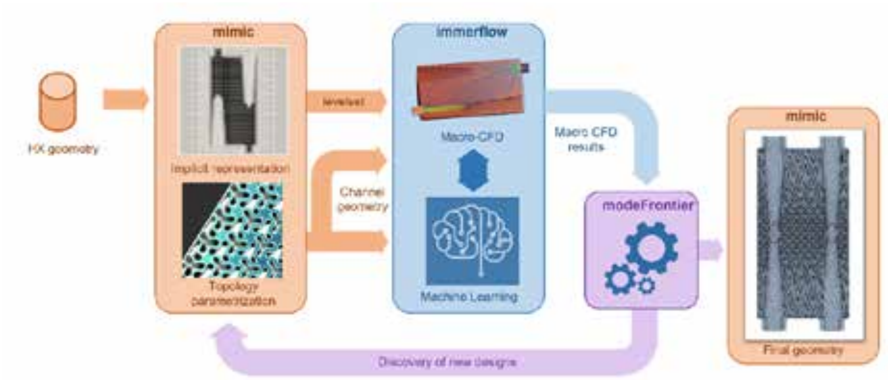

Fig. 2. Schematic representation of the TOLOMHE optimization workflow. New designs are discovered by the optimizer based on the results of CFD simulations performed at the macroscale. Macroscale simulations use an ML model to infer the local permeability and heat exchange coefficients based on local flow field and channel topology. At the end of the optimization loop, the optimal geometry is calculated by merging the HX layout geometry with the optimal channel topology discovered by the optimizer.

The solution: TOLOMHE framework for topology optimization

TOLOMHE is a high-performance computing (HPC)-centric platform developed for MCHX topology optimization. Combining advanced optimization, simulation, machine learning, and deployment on an HPC infrastructure, the TOLOMHE platform aims to: 1) increase the competitiveness of MCHX manufacturers by providing a cost-effective design tool for MCHX; and 2) validate an innovative business model for the independent software vendor based on the "Optimization-as-a-Service" paradigm.

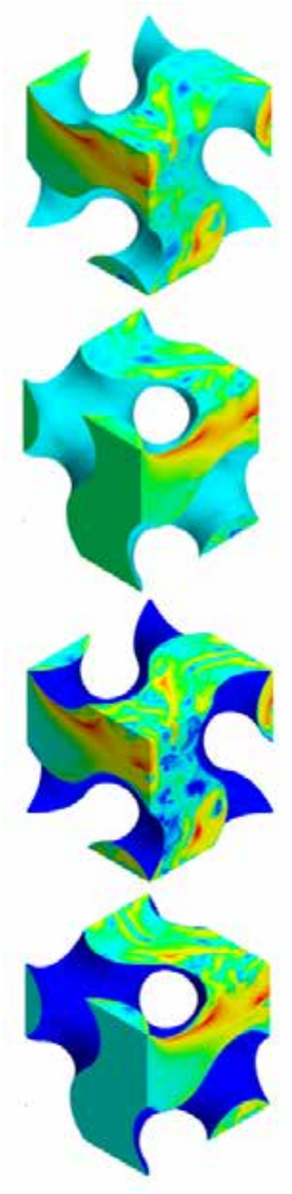

Fig. 3. Example of microscale simulation performed on "prototype" lattice topologies. The simulations are used to train an offline ML model to predict local permeability and heat transfer coefficient given local flow conditions and lattice topology.

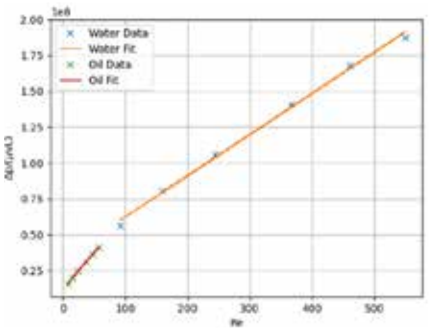

Fig. 4. Comparison between pressure gradient estimated by our ML model and numerical results of high-fidelity simulations at different Reynolds numbers for a gyroid cell.

The building blocks of TOLOMHE are a solver-independent optimizer (modeFRONTIER), a multiscale multi-physics solver for CHT simulation (immerFLOW), and geometry manipulation software (mimic). modeFRONTIER (ESTECO) is an industry-leading tool for multi-disciplinary design optimization; immerFlow (Optimad) is a high-throughput CFD (computational fluid dynamics) solver based on an immersed boundary paradigm that is particularly well-suited to automated workflows with complex geometries; mimic (Optimad) is a tool for computer-aided manipulation of geometry with implicit geometry topology parametrization.

The multiscale nature of fluid dynamic/thermal coupling in MCHX is addressed through a machine learning (ML) model. The resulting approach is characterized by three nested mathematical/numerical models:

1. **A Micro-scale model.** This consists of a deep neural network that estimates the local permeability and heat transfer coefficients from the (local) channel topology and flow conditions. The (synthetic) dataset used for offline training was created on an HPC cluster (Galileo100, CINECA's infrastructure with 528 computing nodes, each with two Intel Cascade Lake 8260 CPUs with 24 cores each). Each data point corresponds to a high-resolution simulation performed on a single cell of a "prototype" lattice topology.
2. **A Macro-scale model.** This is used to simulate the macro-scale flow field for a given heat exchanger layout. The microscale effect is incorporated in terms of local permeability and heat transfer coefficients. These are calculated through inexpensive feed-forward evaluations performed by the ML model. The computational cost of a simulation for the entire heat exchanger is drastically reduced as a result.
3. **Evolutionary optimization.** This framework is used to explore the entire design space and improve the initial design. Genetic algorithms require the evaluation of a large number of models during the initial exploration of the design space (from a few hundred to several thousand, depending on the specific problem). To achieve this exploration in an acceptable amount of time, the optimization is performed on the HPC infrastructure, thereby harnessing the high scalability of the genetic algorithms. Furthermore, genetic algorithms are well suited to multi-objective and multi-constraint optimizations. A hybrid strategy combining SQP (sequential quadratic programming) and the NSGA-II (non-dominated sorting genetic algorithm) was selected as the optimization algorithm within modeFRONTIER. During topology optimization the design of the MCHX is implicitly described in terms of a level set function to avoid costly (and error-prone) remeshing cycles. At the end of the optimization, an explicit representation of the overall geometry of the heat exchanger is returned to the user in terms of the surface tessellation provided by mimic.

TOLOMHE business benefits and impact

TOLOMHE's value proposition revolves around three main concepts:

- Implementation on the HPC infrastructure, which guarantees access to an adequate computing infrastructure.
- No previous knowledge is required to use the HPC or optimization, which helps remove the barrier to entry for first-time HPC users.
- All the necessary tools are integrated into a single platform, which

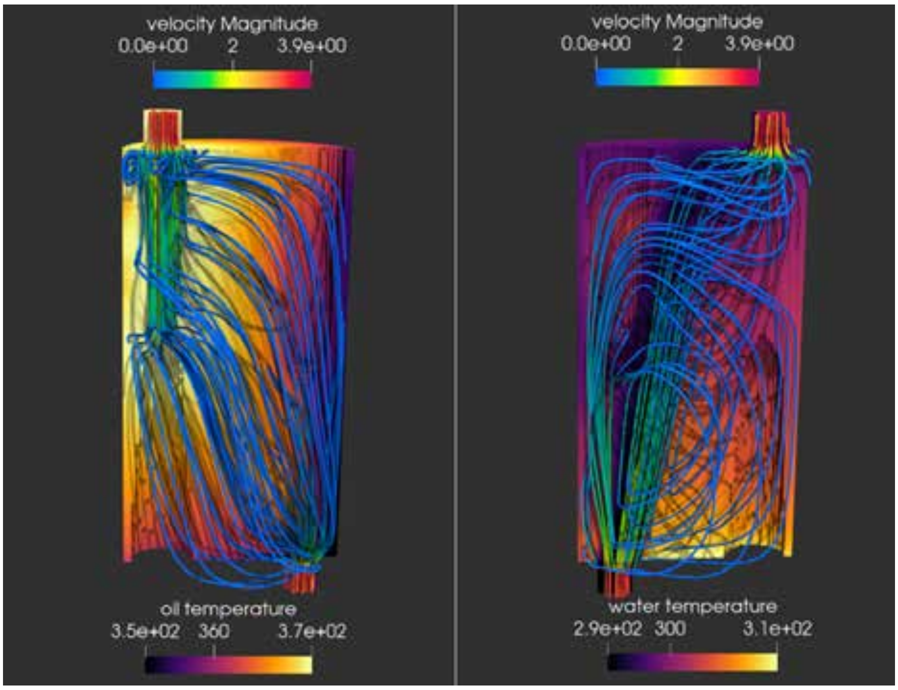

Fig. 5. Examples of results from a CHT simulation performed on an MCHX at macroscopic scale. The flow lines are coloured by the velocity and temperature fields for both hot fluid (left) and cold fluid (right). Microscale effects on both fluid perfusion and heat transfer are incorporated in terms of non-linear, spatially variable permeability and heat exchange coefficients. These coefficients are calculated on the fly by the ML model, thus achieving the bi-directional coupling between macro- and micro-scale.

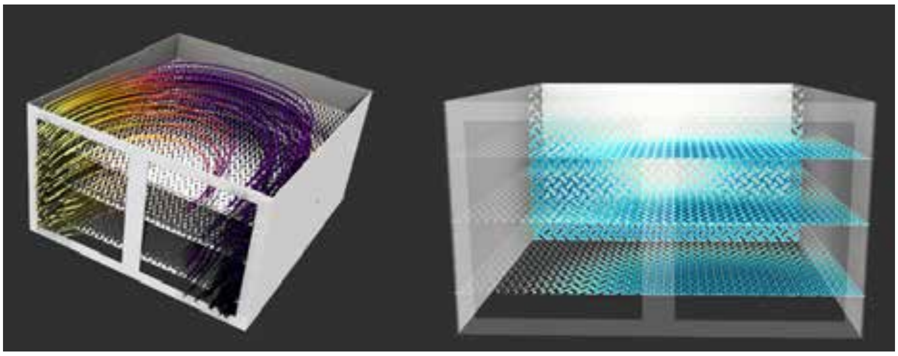

Fig. 6. Different sections of the optimized geometry for the ACOC heat exchanger. The optimized heat load (greater than 30kW) was calculated with an air inlet temperature of 50°C, an air mass flow of 0.5kg/s, an oil inlet temperature of 130°C, and a volumetric flow rate of 54l/min. The maximum pressure drop allowed was set to 130 kPa for oil.

eliminates all the problems related to the integration of different (CAE/CAD) tools and the related licenses.

By adopting TOLOMHE the end user should accelerate their transition from a build-to-print business model to a build-to-spec business model and reduce R&D costs and time-to-market for new products.

The work done in the TOLOMHE experiment provides further commercial benefits to the end user:

- Design workflow automation has the potential to reduce time-to-offer by 90%, and time-to-market by 50% (from a few months to a one month).
- By redirecting skilled labour to other value-added activities, the end user can potentially save up to €100,000 per year.

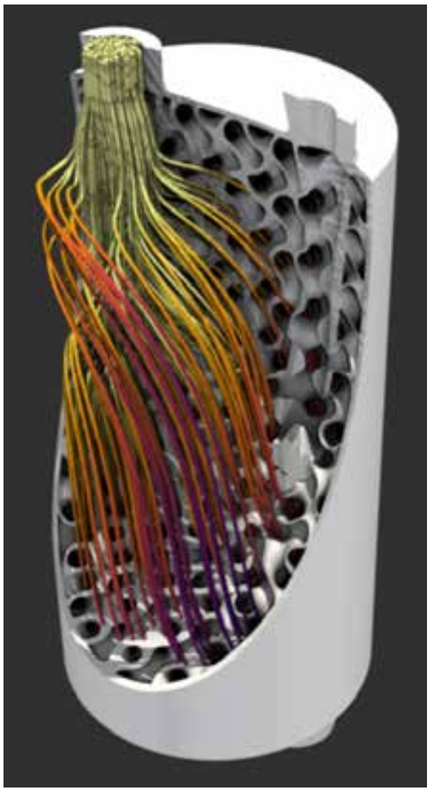

Fig. 7. Cropped view of the inner channel of an optimized two-fluid oil-water 3DHX (Aidro). Flow lines for the hot fluid (oil) are colored according to temperature. The objective of the optimization was to maximize the heat exchange by modulating the solid wall thickness within the design volume. Fixed mass flow rate and temperatures were prescribed at the flow inlets. A maximum 20kPa pressure drop constraint was imposed.

The success story presented in this article was developed during the first tranche of FF4EuroHPC Project. FF4EuroHPC supports the competitiveness of European SMEs by funding business-oriented experiments and promoting the uptake of advanced HPC technologies and services. The experiment is an end-user-relevant case study demonstrating the use of cloud-based HPC (high-performance computing) and its benefits to the value chain (from end-user to HPC-infrastructure provider) for addressing SME business challenges that require the use of HPC and complementary technologies such as HPDA (high performance data analytics) and AI (artificial intelligence). The successful conclusion of the experiment created a success story that can inspire the industrial community.

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