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# Thermal performance augmentation by rib-arrays for helium-gas cooled First Wall applications

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## HIGHLIGHTS

- V-shape rib-arrays are more efficient than comparable smooth channel flows.
- Heat transfer is significantly increase for channels structured by V-shaped rib-arrays.
- Thermal performance is significant increased by the investigated rib-arrays.
- Structured heat transfer surfaces provide an efficient cooling for the First Wall.

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## ABSTRACT

Rib-roughening the helium-gas cooling channels in the plasma facing components of DEMO (First Wall, limiters or the divertor) enhances heat transfer and reduces structural material temperatures. In the present study the applicability of six different surface-attached rib-arrays and of two different detached rib-arrays was examined for increasing the thermal performance within the helium-gas First Wall cooling concept. The rib-arrays consisted of transversally oriented or upstream directed 60° (with respect to the centerline) V-shaped ribs with different rib cross section (square, trapezoid, 2 mm radius round-edged front- and rear-rib-surface). Turbulent flow and heat transfer for 8 MPa pressurized helium-gas with a helium mass flow rate of 0.049 kg/s were computed by the Detached-Eddy-Simulation approach. A constant heat flux density of 0.75 MW/m$^2$ and 0.08 MW/m$^2$ was applied at the plasma-facing and breeding-blanket-facing First Wall structural surface respectively. The results showed that structuring the thermally highly loaded cooling channel surface with rib-arrays of 60° V-shaped ribs provides an efficient heat transfer and increases the cooling performance of the First Wall. The corresponding heat transfer coefficient was in the range from 7.1 to 7.5 kW/m$^2$ K and from 7.6 to 8.1 kW/m$^2$ K for the attached and detached V-shaped ribs respectively. Compared to smooth channel flows, only 14–16% of the pumping power is required to obtain an equivalent heat transfer performance or, from another point of view, the heat transfer coefficient can be increased by 168–172% for a constant pumping power.



## 1. Introduction

Pressurized helium-gas is a coolant in several breeding blanket (BB) design concepts of the envisaged DEMO fusion power reactor. Compared to water and liquid metals, helium is inert for chemical and nuclear reactions, causes no corrosion or activation and offers a wide temperature range for cooling without phase transformation. Improved designs of the First Wall (FW) cooling channels (CC) with rib-roughened or structured CC surfaces enhance the heat transfer and can compensate the comparable low volumetric heat capacity and thermal conductivity of helium-gas. The ribs placed at the thermally highly loaded CC surface induce a three-dimensional, unsteady flow field and heat transfer is augmented by mixing the fluid in the near wall regions and boundary layers providing a reduction of the maximum FW structural temperature [1]. It increases the functionality of the FW cooling performance and can raise the degree of efficiency of the primary heat transfer system and of the balance of plant. On the other hand, the ribs increase the flow resistance, and thus, the pumping power is raised (for unchanged mass flow rate) [2]. Furthermore, the manufacturing of rib-roughened CC surfaces is complex. However, the disadvantages due to increased flow resistance and complex manufacturing can

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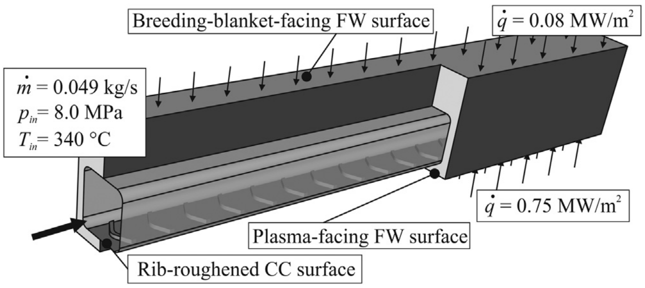


**Fig. 1.** Computational domain of the First Wall cooling channel.

**Table 1**
Geometry parameters.

| | |
|---|---|
| Rib-height and width e | 1 mm |
| Rib-pitch $p$ | 10 mm |
| Hydraulic-diameter $D_h$ | 15.668 mm (attached)<br>15.324 mm (detached) |

be small compared to the benefits of the enhanced heat transfer, e.g. increased component life time. Flow and temperature fields of attached rib-arrays were investigated extensively for decades [3–5]. The applicability of rib-roughened CC for helium-gas cooled FW applications and their prospects of success in efficiency and effectiveness were depicted by Ruck and Arbeiter 2016 [1], Arbeiter et al., 2016 [6] and Chen and Arbeiter 2015 [7].

The objectives of the present study were to evaluate the pressure drop, heat transfer coefficients and the efficiency of FW CC structured by several rib-array configurations. The presented CC designs were studied for the 'integrated' FW concept, but can be adopted to the 'de-coupled' FW concept.

## 2. Numerical methods

### 2.1. Computational domain

Flow and conjugated heat transfer were computed for an unscaled section of the FW of DEMO including the solid structure and fluid domain as shown in Fig. 1. The FW total thickness was 30 mm and the thickness of the plasma-facing side wall was 3 mm. The channel cross section was 15 mm × 15 mm. Depending on the rib-configuration, four or two channel corners were round-edged with 2 mm radius as displayed in Fig. 2. The geometry parameters of the CC are given in Table 1.

The plasma-facing CC surface was structured by (A) attached rib-arrays and (D) detached rib-arrays of 18 centrally positioned, (T) transversally oriented ribs or (V) upstream directed 60° V-shaped ribs with different rib cross sections ((1) square, (2) 2 mm radius round-edged front- and rear-rib-surface, (3) trapezoid). For the detached rib-arrays the clearance to the channel wall was $c$ = 0.1 mm. The length of the computational domain was 180 mm. The rib-array configurations are sketched in Fig. 2.

### 2.2. Simulation details and boundary conditions

Turbulent flow and heat transfer were computed by the delayed Detached-Eddy-Simulation (DDES) approach. The commercial finite-volume-method solver FLUENT V.15 [8] was used. Details of the applied algorithm and discretization schemes are described in Ruck and Arbeiter 2016 [2]. The computations were conducted for pressurized helium-gas with a mass flow rate of $\dot{m}$ = 0.049 kg/s (corresponding to a Reynolds number of Re = 1.05 × $10^5$ based on the hydraulic diameter $D_h$), with an inlet pressure of $p_{in}$ = 8 MPa(abs) and with an inlet temperature of $T_{in}$ = 340 °C. Assuming ideal gas conditions the specific heat capacity $c_p{}^{He}$, the thermal conductivity $k^{He}$ and the fluid viscosity $\mu^{He}$ were determined [9]. The baseline structural material for the FW was EUROFER steel [10] with the specific heat capacity $c_p{}^E$ [11], thermal conductivity $k^E$ [12] and a density of $\rho^E$ = 7620 kg/m³ for the expected temperature range. Symmetry conditions were employed at the outer side, rear and front walls of the solid domain. Peak heat flux densities on the FW were assumed to be in the range from 0.5 MW/m² to 1.0 MW/m² [13] and, thus, a constant heat flux density of 0.75 MW/m² was applied on the plasma-facing FW surface. A heat flux density of 0.08 MW/m² was assumed to occur on the breeding-blanket-facing FW surface, see Fig. 1. This non-uniform heat flux distribution around the channel perimeter is characteristic for the FW and motivates the application of one-sided heat transfer enhancement [6].

The inlet flow was fully developed. The corresponding velocity profile was obtained separately by isothermal, transient DDES flow simulations in a smooth CC with identical geometrical dimensions as the structured CC. Simulations were transient with a CFL number < 1.0. Time-averaging of the results were carried out, after a computationally developed state was reached, for a time period of hundred flow-throughs over one rib-pitch-section.

The fluid mesh size for the different rib-configurations was up to 24.4 × $10^6$ cells. Local grid refinement was performed in the vicinity of the ribs and within the inter-rib-spacing resulting in a focus region with maximum cells sizes of $\Delta x^+ \leq 40$ (streamswise) and $\Delta y^+ \approx \Delta z^+ \leq 25$ (span- and crosswise) and a wall-normal first spacing of $\Delta z^+ < 1$. Numerical uncertainty has been verified by the grid convergence index method as indicated by Roache 1994 [14] and recommended for CFD Studies [15].

### 2.3. Manufacturing concepts

The design of the structured FW CC depends on different manufacturing strategies, currently considered for the helium cooled FW. The presented design of the attached rib-arrays bases on the manufacturing strategy of fabricating the FW from two separate shells with the intersection plane at the channel symmetry plane and joining the upper and lower shell by the HIP technique [16]. The CC with the attached rib-arrays are designed for a generation of usual machining of mill cutting with cylindrical and spherical head cutters.

For generation the detached rib-arrays, ladder-like tapes of ribs can be inserted into support notches located at the CC side walls. The CC (including the support notches) can be fabricated by wire cutting electrical discharge machining [17]. The concept of inserting ladder-like tapes can be adopted for the design and fabrication of the attached rib-arrays by generating two support notches into the CC bottom. Both concepts of ladder-like tape insertion manufacturing are sketched in Fig. 3. Compared to concepts with the die sink erosion techniques for generating rib-roughened CC surfaces, a cost reduction for producing the rib-roughened CC surfaces per channel length is expected to be in the range of two orders of magnitude by the ladder-like tape insertion manufacturing. To improve the fitting and to ensure a fixation of the ladder-like rib-arrays, structural materials with a higher thermal expansion than the FW structural material can be considered for the ribs.

## 3. Results

### 3.1. Heat transfer coefficient and pressure drop

The local distributions of the heat flux densities at the rib-roughened CC surface varied along the CC. The heat transfer coefficient, evaluated with the spatially averaged coolant bulk tem-