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Thermalhydraulic Optimization Of Hypervapotron Geometries For First Wall Applications

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Abstract: Plasma disruptions and Edge Localized Modes (ELMS) may result in transient heat fluxes as high as 5 MW/m^2 on portions of a tokamak reactor first wall (FW). To accommodate these heat loads, a large percentage of the first wall may need Enhanced Heat Flux (EHF) panels equipped with water-cooled hypervapotron heat sinks. Recent advances in computational fluid dynamics (CFD) enable designers to predict thermal performance even under transient two-phase flow conditions. The challenge is to design a heat sink that operates well under nominal 0.5 MW/m^2 conditions, but still has enough design margin to accommodate off-normal events. We present the results of a CFD study to investigate the tooth height and backchannel depth of 50-mm-wide hypervapotrons with 3-mm-pitch and 3-mm side slots as proposed for the fingers in the EHF FW panels. The typical EHF panel contains approximately 40 hypervapotron fingers connected to a common manifold. The water inlet temperature is 70 ^{o}C at a pressure of 2.7 MPa and a mass flow rate of 0.435 kg/s per finger. The heated surface of the CuCrZr hypervapotron fingers are armored with 8-mm-thick beryllium tiles of various areas. The standard design with 4-mm-high teeth and a 5-mm-backchannel is compared to a more optimal case with 2-mm-high teeth and a 3-mm-backchannel under nominal heat loads and single-phase flow conditions. Better heat transfer in the latter case and the smaller backchannel permit a factor of two reduction in the required mass flow while maintaining the same beryllium armor surface temperatures near 115 ^{o}C. The shallow teeth and smaller back channel allow the 40 fingers in a typical panel to flow in parallel and simplify the water circuit. The two hypervapotron designs are then compared during off-normal loading and two-phase flow. The design with 2-mm teeth has a 3.5% higher beryllium surface temperature of 648 ^{o}C and reduces the CHF margin by ~10%. This study highlights the necessary compromise between design margin during transient events, effective heat transfer under nominal conditions and the simplicity needed in the water circuit design.

Introduction

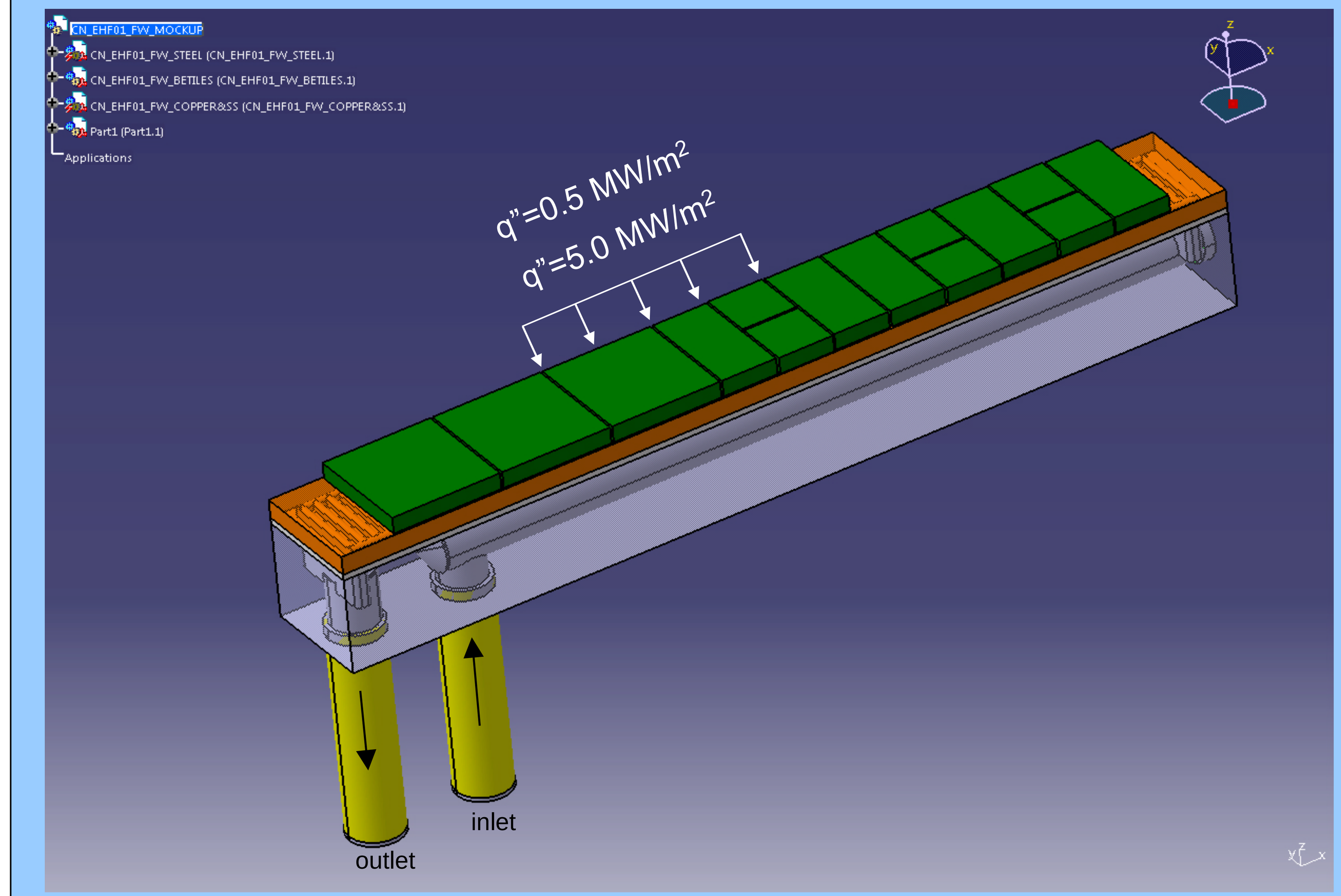
This study optimizes the geometry and flow parameters of hypervapotron heatsinks for first wall applications under nominal operating conditions. The flow parameters and flow circuit design are just as important as the internal dimensions of the hypervapotron. If multiple hypervapotron fingers can be flowed in series, it can simplify the coolant routing significantly. We also describe optimized geometries for off-normal heatloads in two-phase flow and discuss the trade-offs required in selecting the best configuration for nominal single-phase operation with sufficient safety margin for the off-normal events provided in part by boiling heat transfer.

Description

The hypervapotron heat sink in the reference case consists of a copper alloy faceplate, CuCrZr (Elbrodur G) with machined teeth or fins transverse to the flow direction. The total mock-up length is 410 mm, and the width is 52 mm. The area exposed to the highest heat loads is 100 mm x 52 mm. The strongback under the hypervapotron channel is 47 mm thick and is comprised of 316 LN stainless steel. The teeth height is 4 mm and the groove and teeth width are 3 mm. Two slots, 3-mm-wide, run the length of the hypervapotron channel and detach the teeth from the channel sidewalls. The open channel under the teeth is 5 mm deep by 42 mm wide.

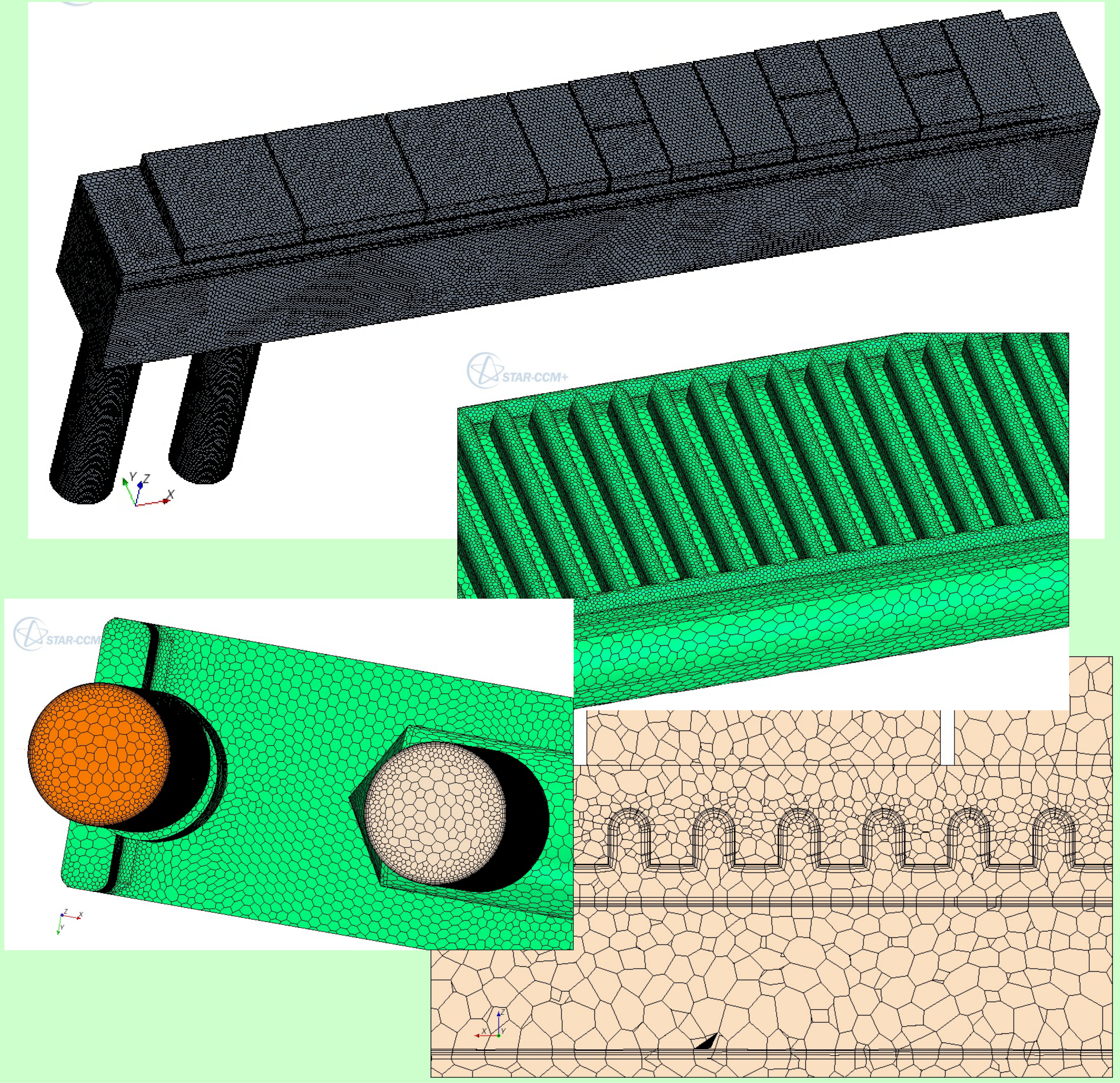
Model

Beryllium armored hypervapotron



410 mm long x 52 mm wide

Mesh



1.4 M cell polyhedral mesh with 4 prism layers

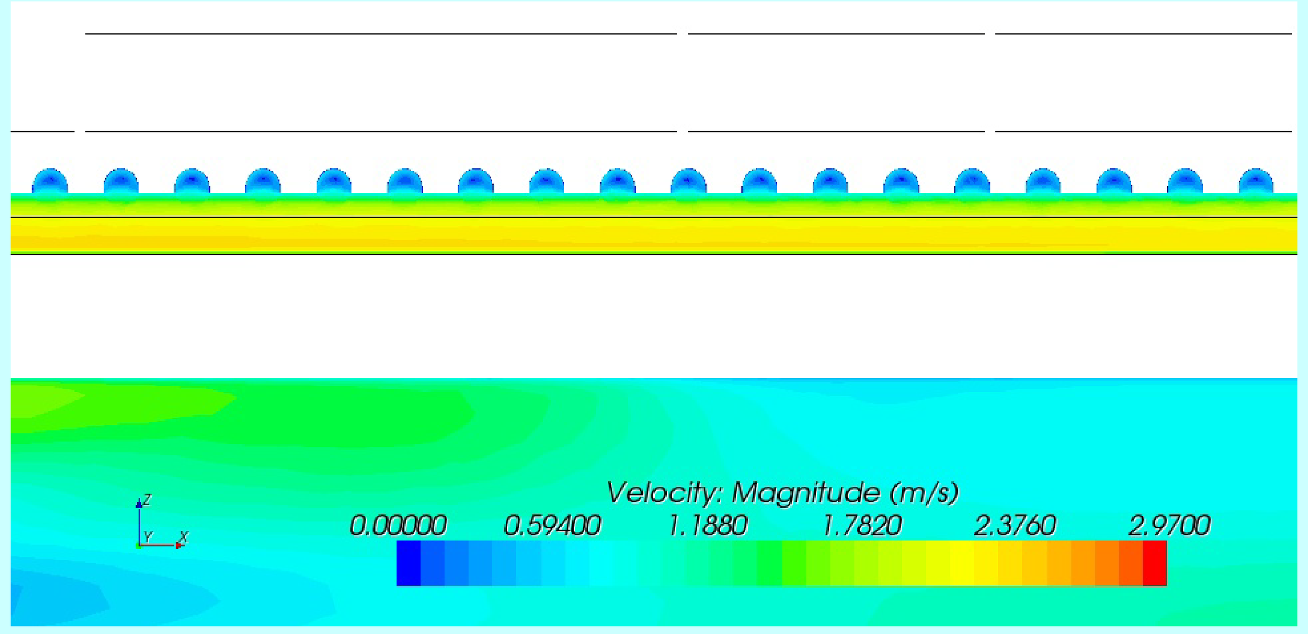
Results

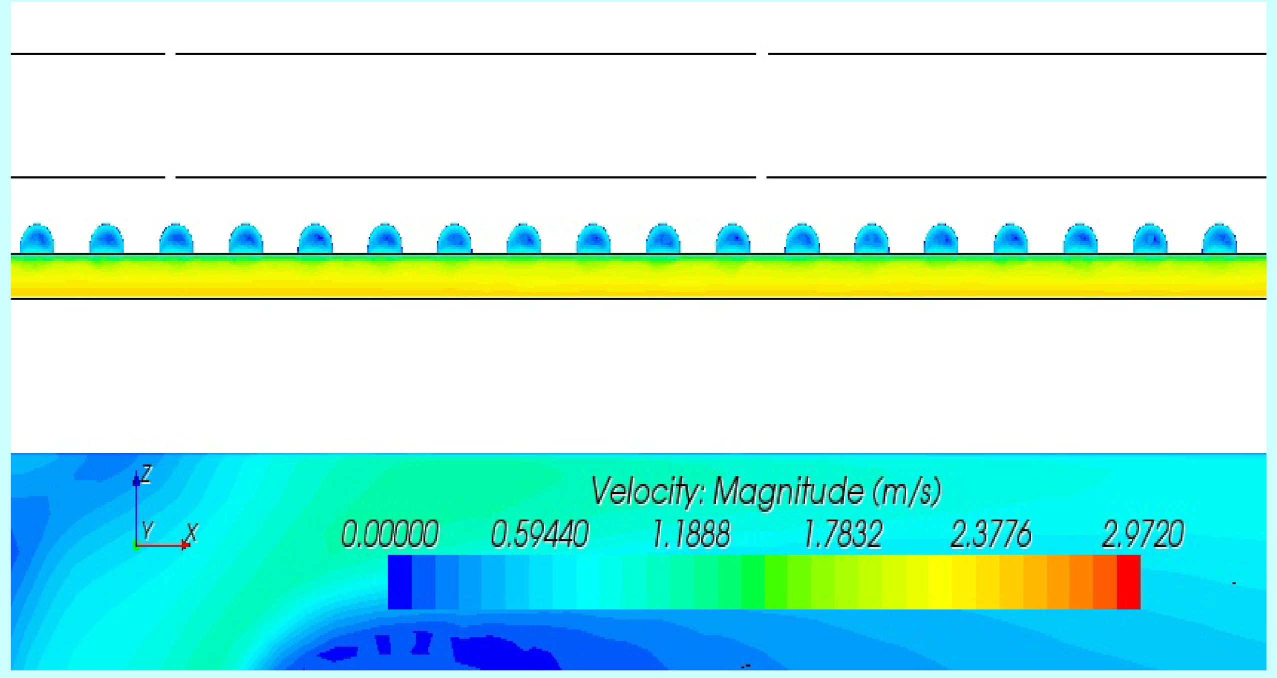
Velocity distributions

5 mm backchannel	3 mm backchannel

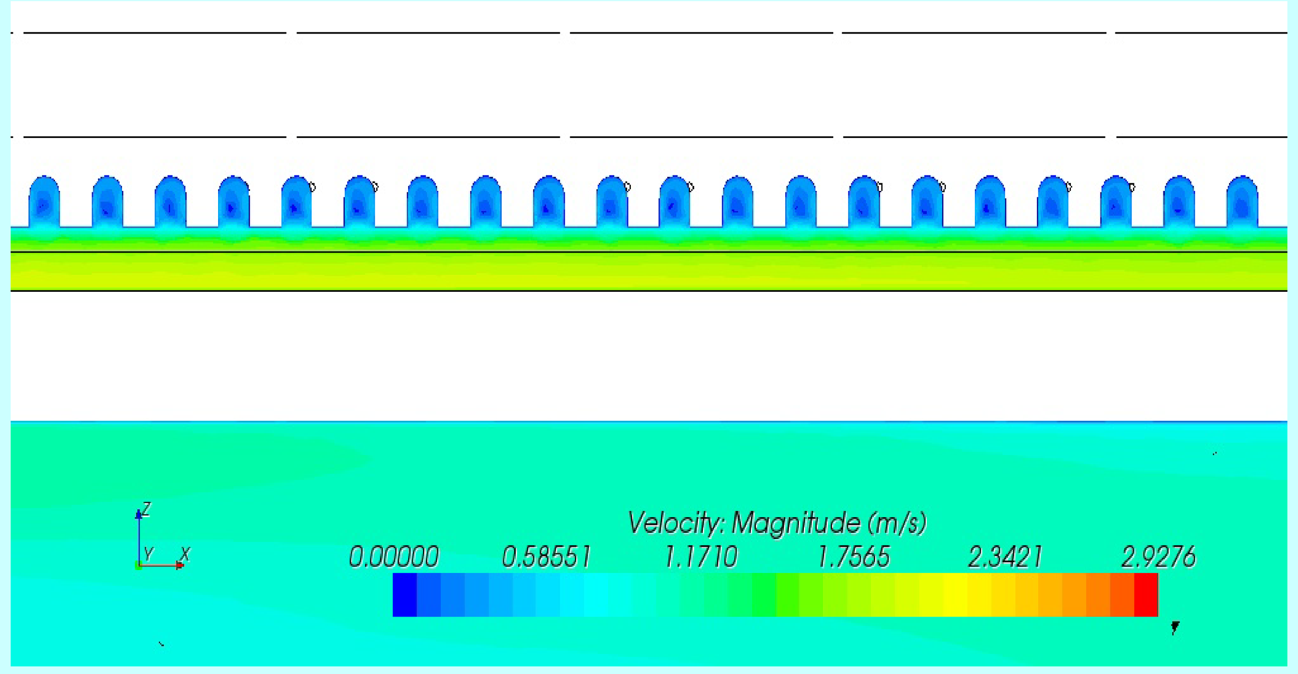
2 mm teeth

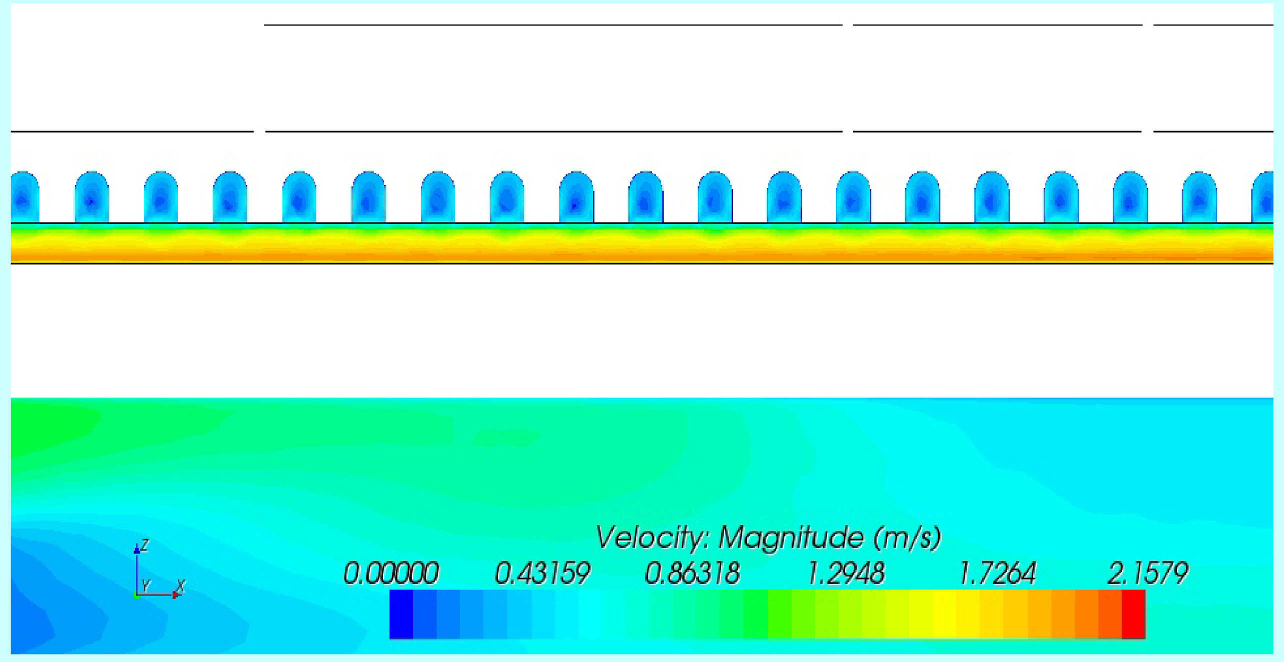
2mm teeth depth and 3-mm spacing optimized to produce a simple reverse eddy in the groove.



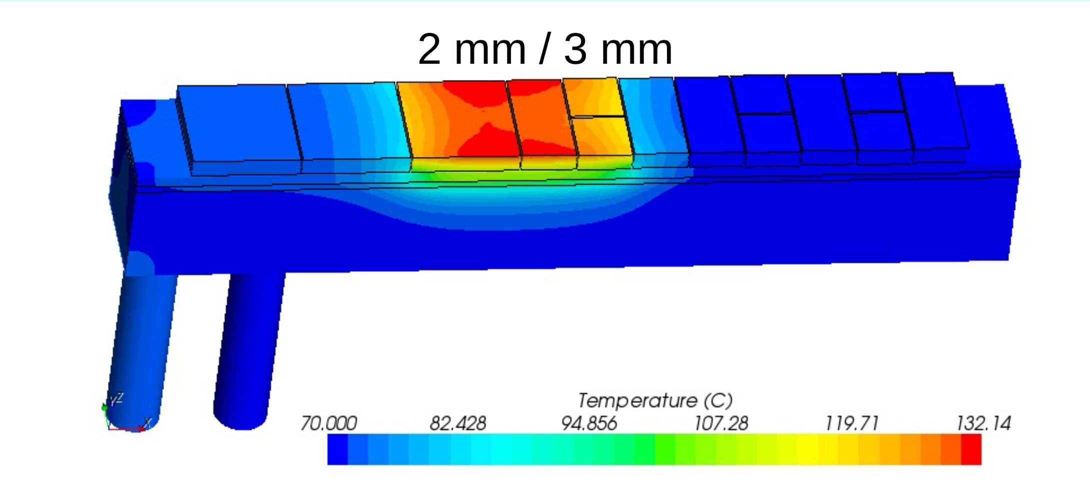


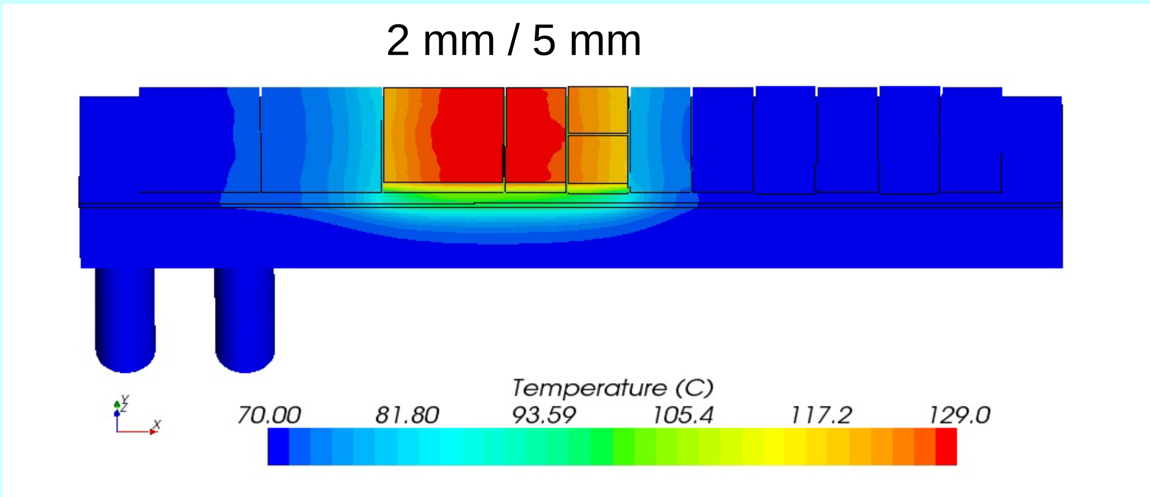
4 mm teeth

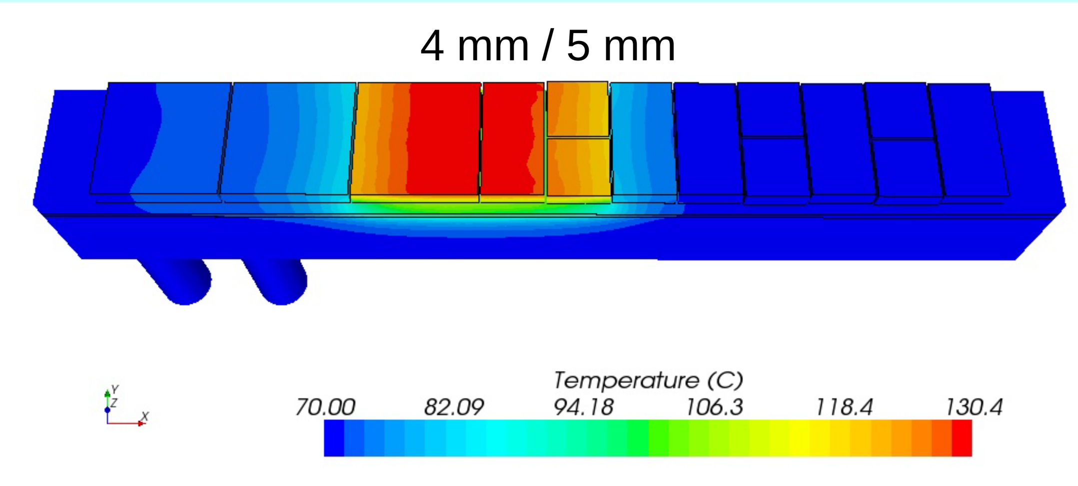




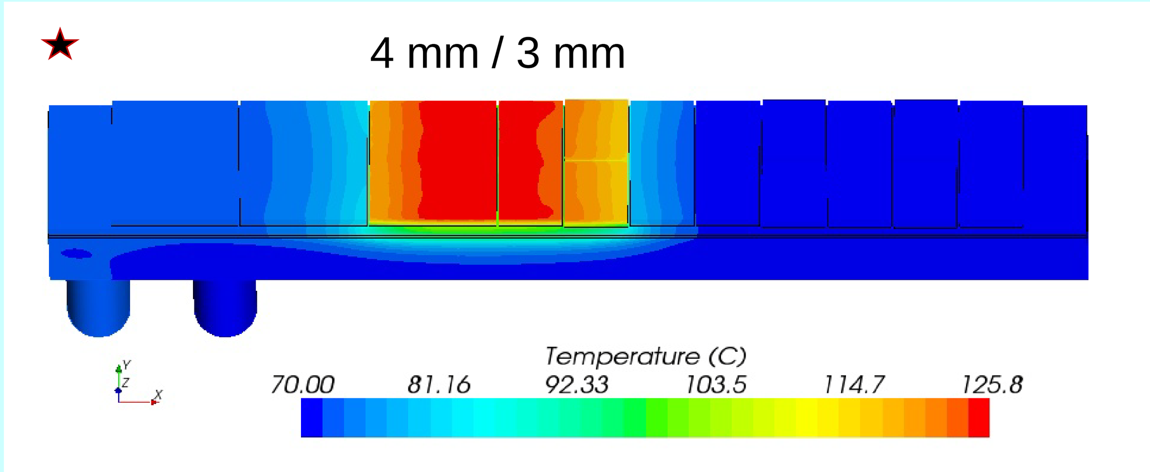
Temperature distributions – 0.5 MW/m²

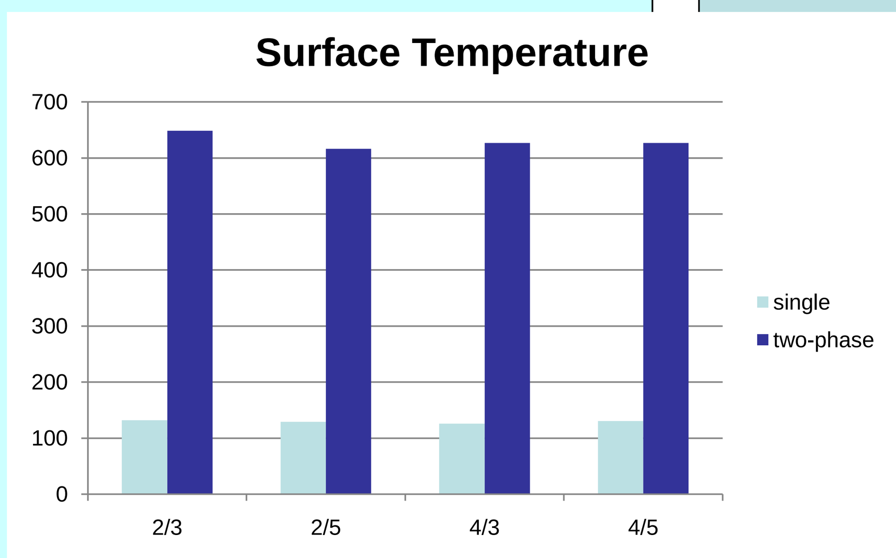






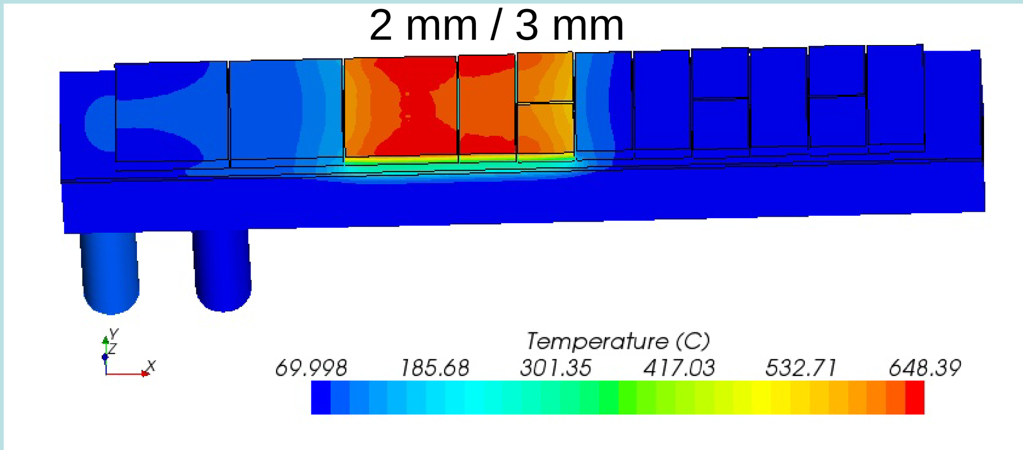
★

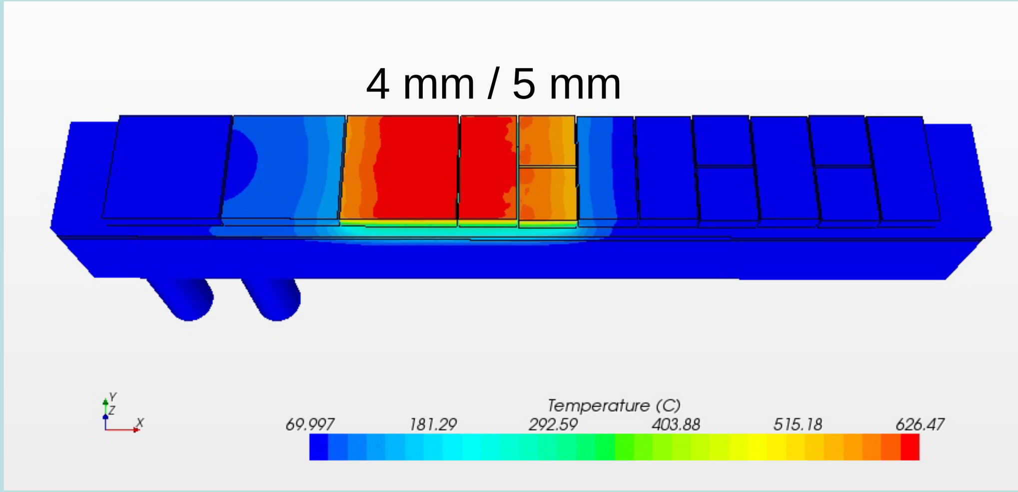


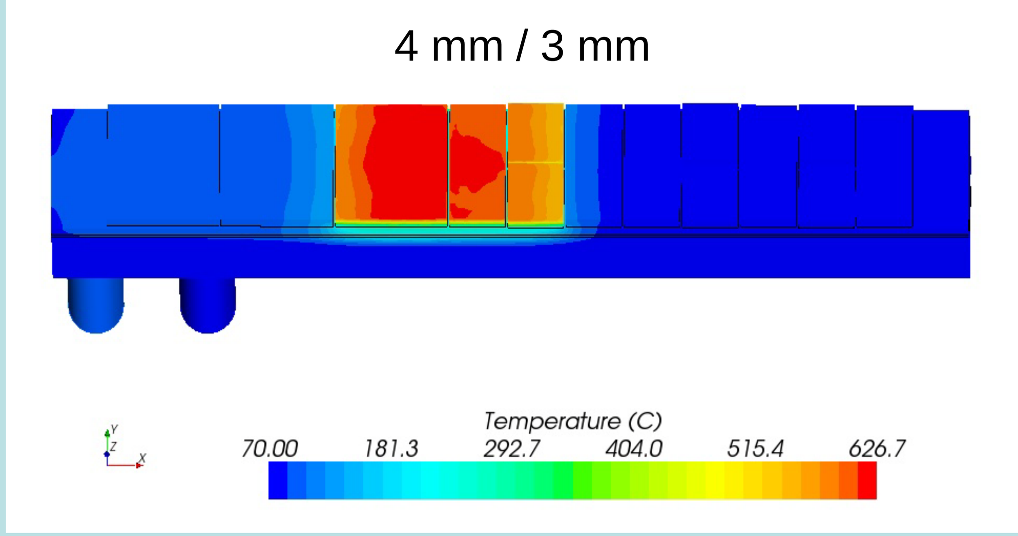


★ longer teeth / shallow backchannel is best combination for nominal conditions.

Temperature distributions 5 MW/m²







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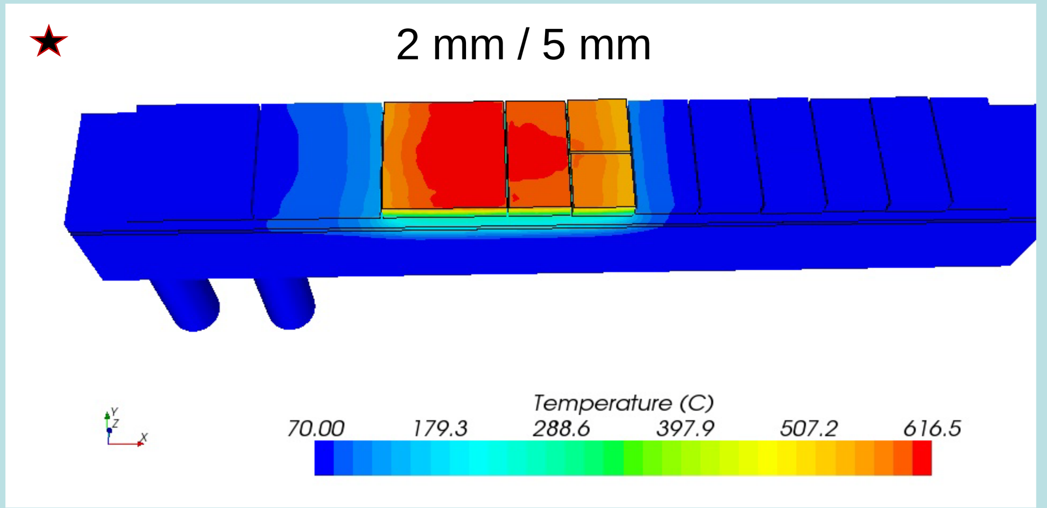
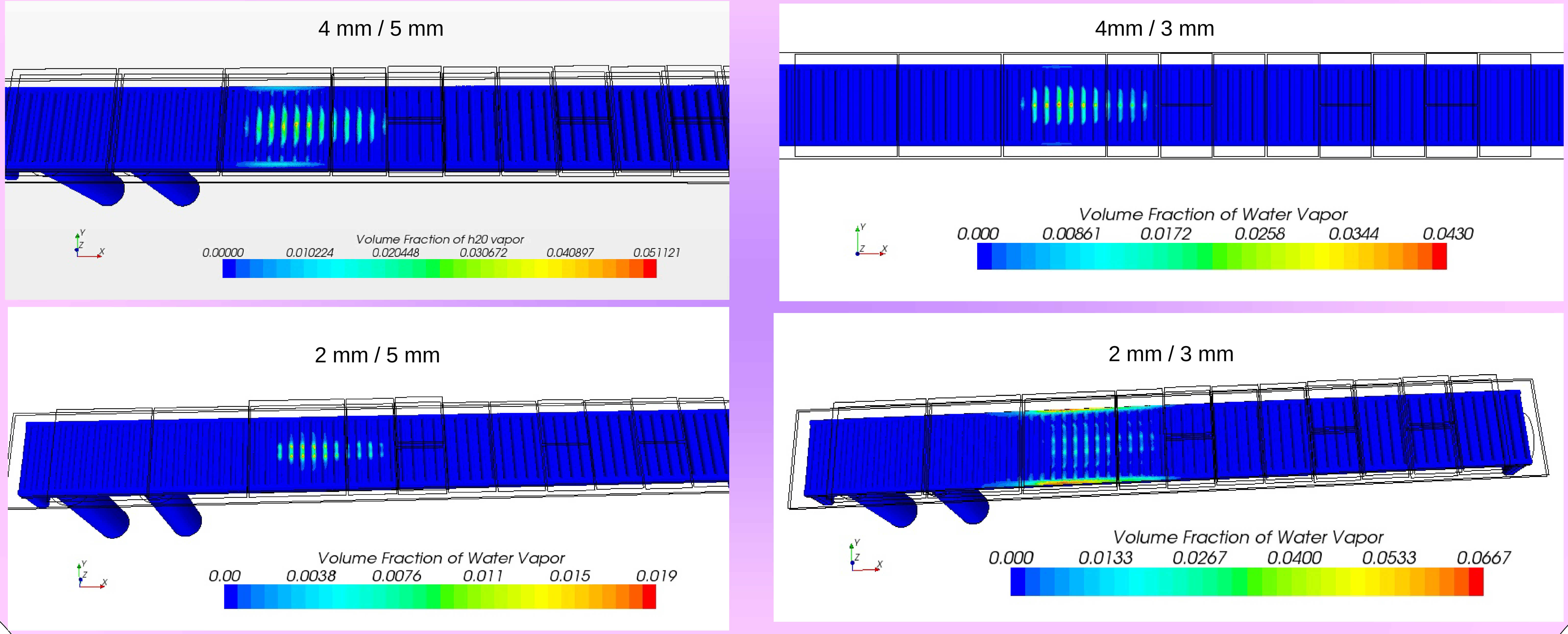
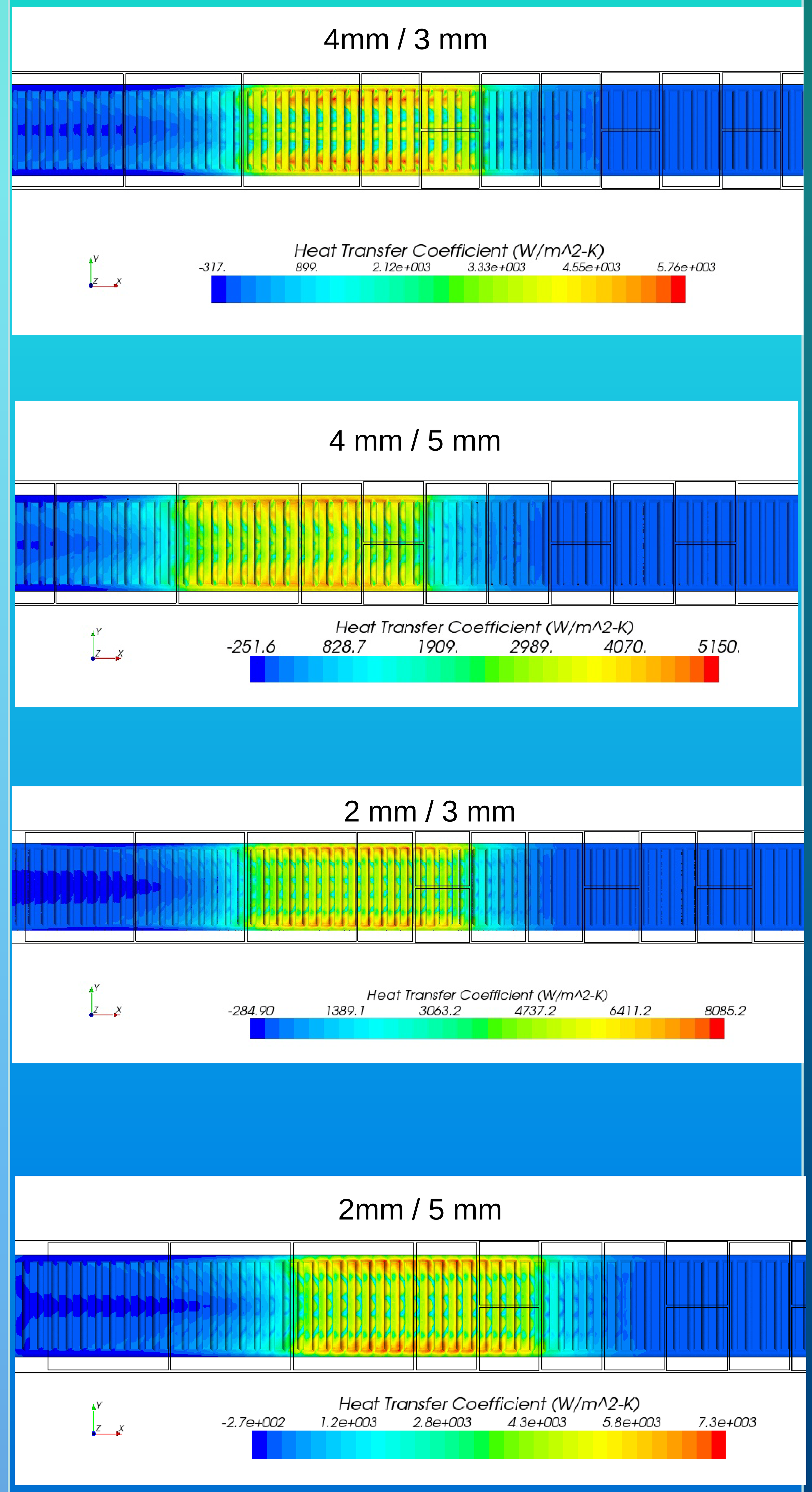


★ Deeper backchannel is more effective in mixing and condensation of vapor. Shorter teeth / deep backchannel is best for off-normal conditions.

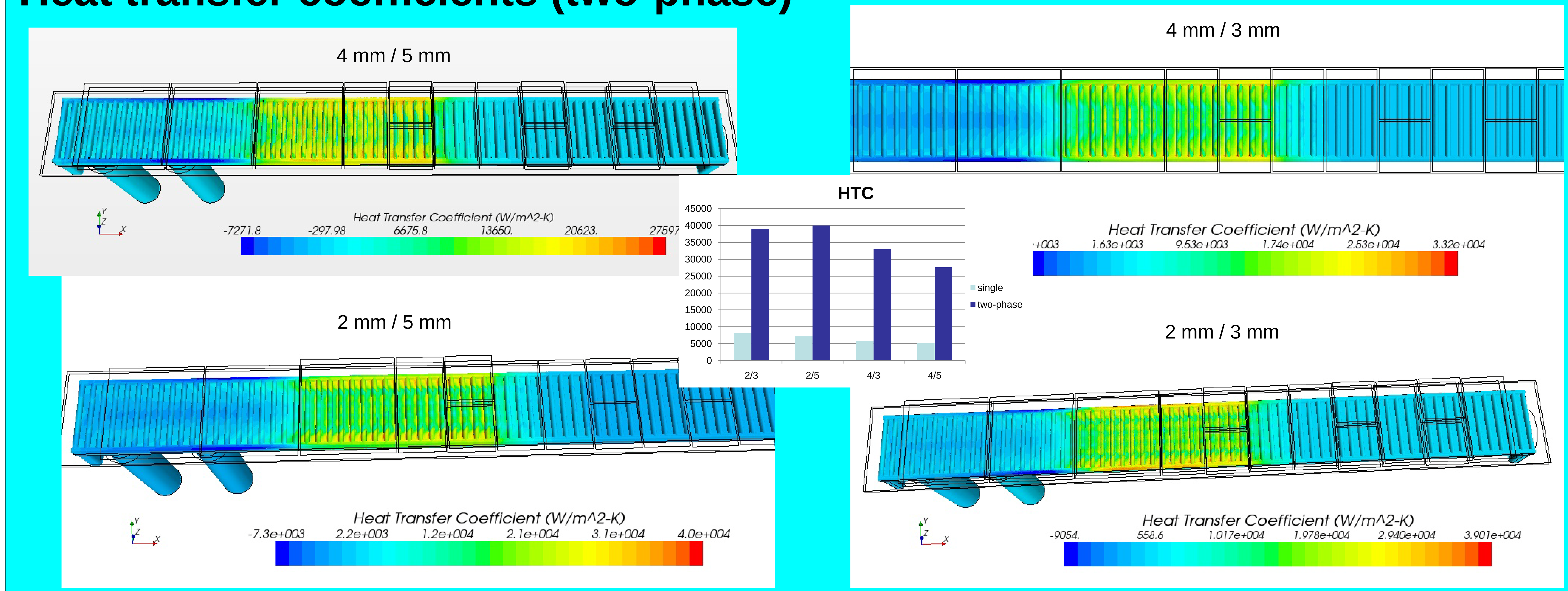
Vapor fraction (5 MW/m²)



Heat transfer coefficients (single-phase)

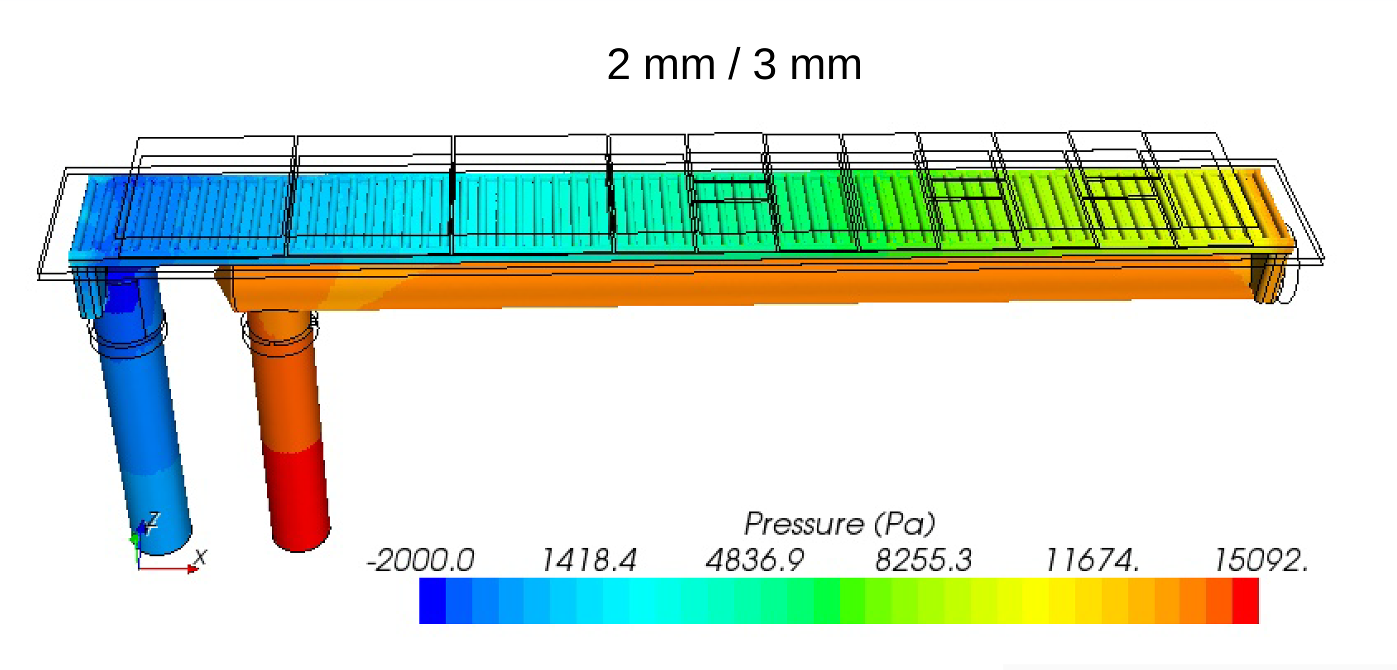


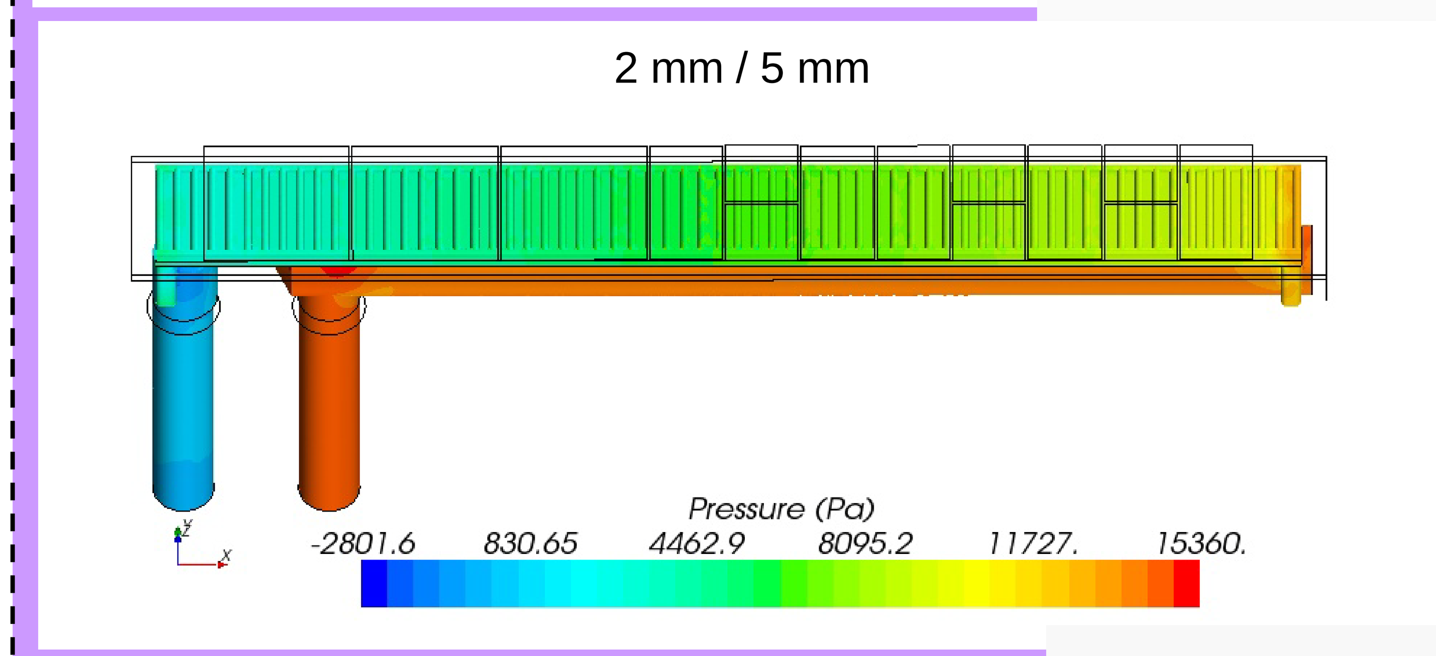
Heat transfer coefficients (two-phase)

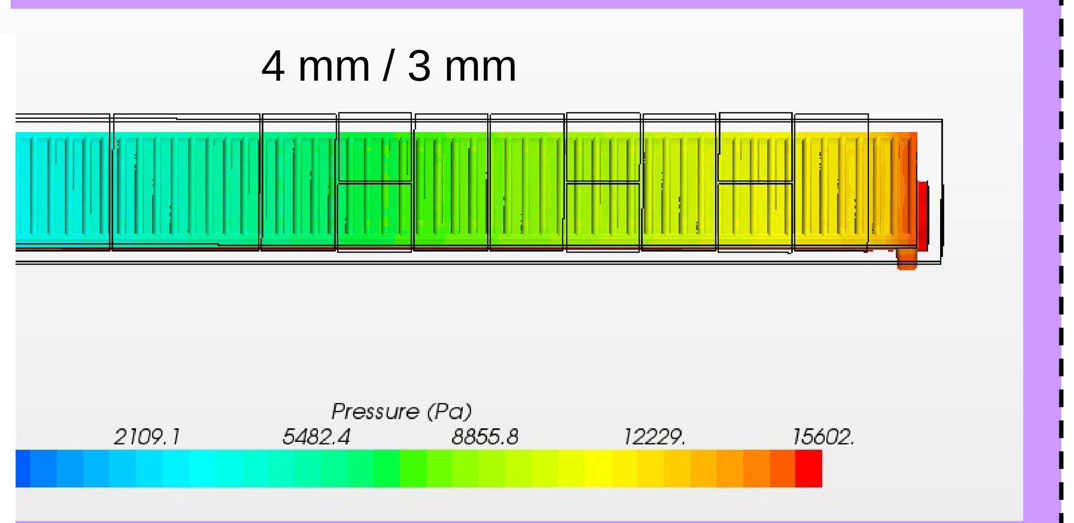


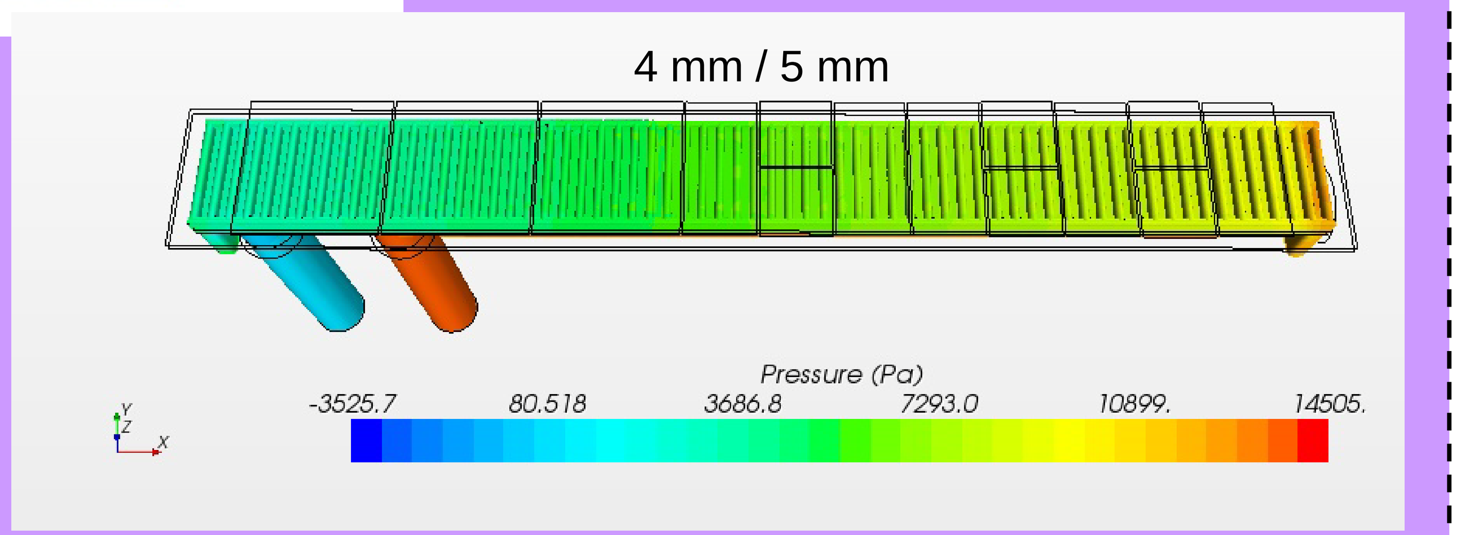
Heat transfer coefficients increase in grooves where boiling takes place ranging from 12,000 to 30,000 W/m²K.

Pressure distributions





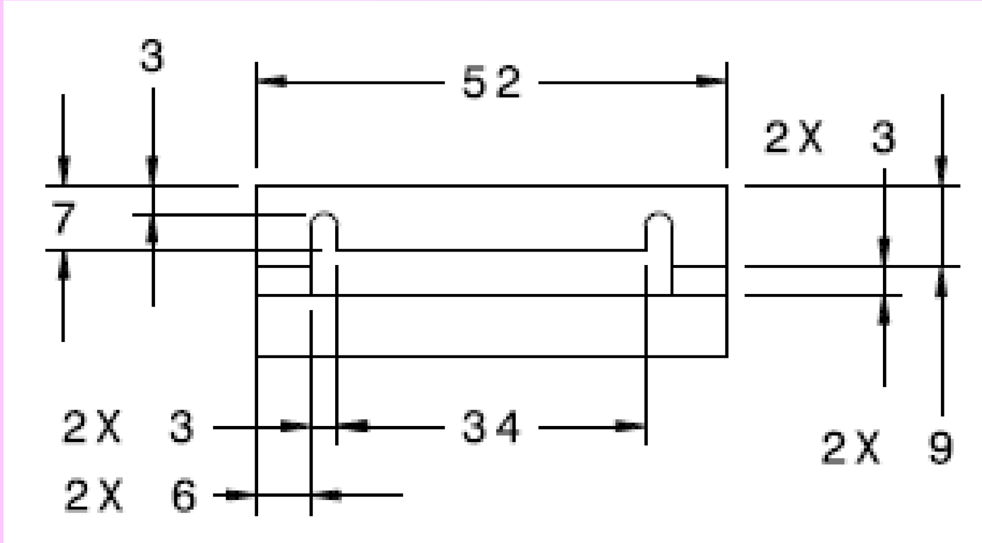




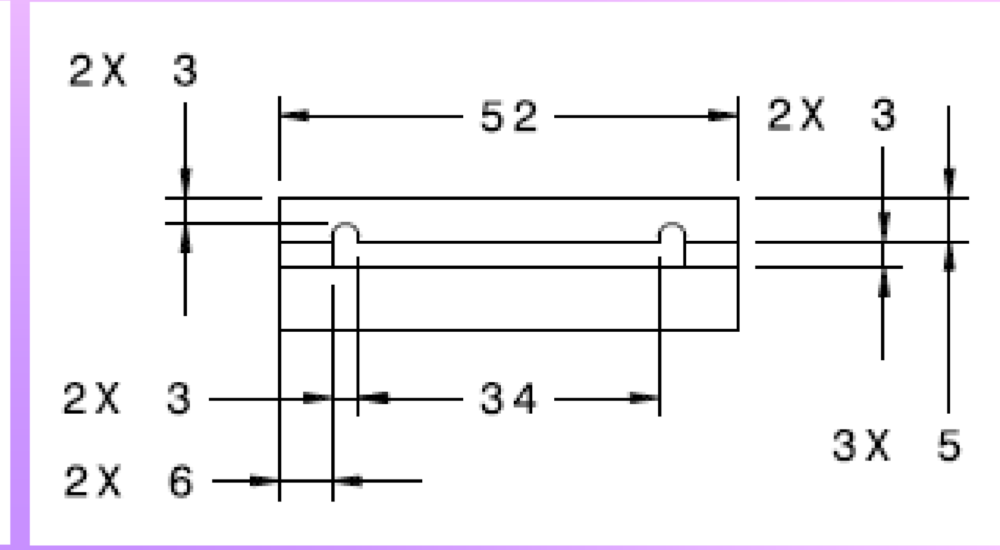
Flow parameters

2.7 MPa, 70 °C water
m-dot=0.435 kg/s 5-mm
m-dot=0.263 kg/s 3-mm
~ 2 m/s ave. in backchannel

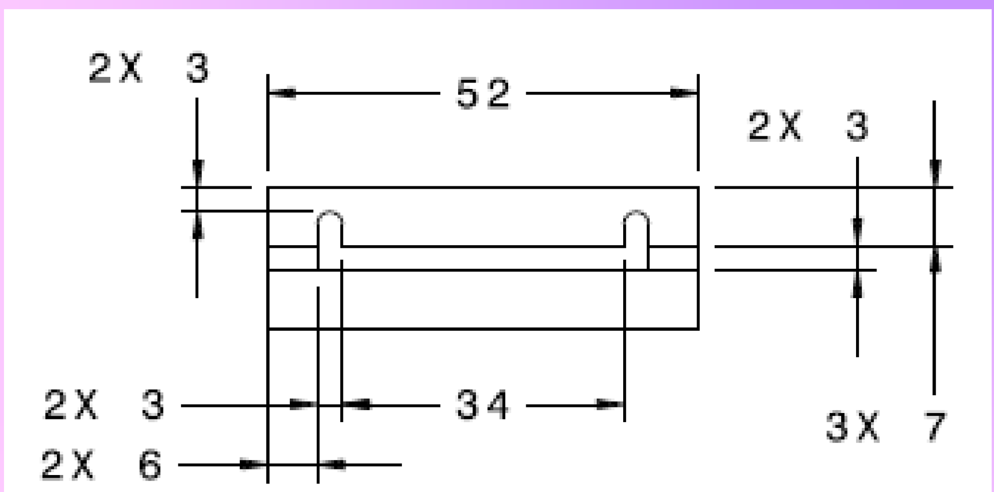
Geometry Comparison



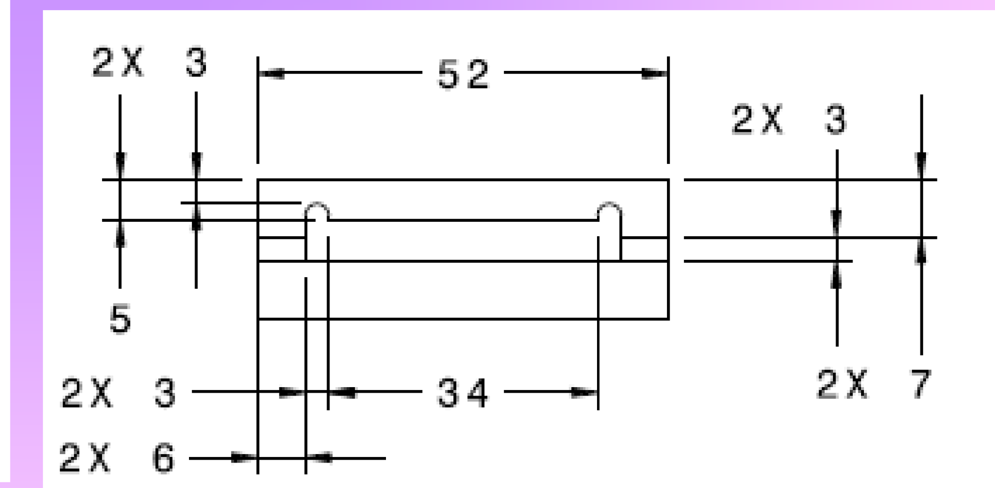
4 mm / 5 mm



2 mm / 3 mm



4 mm / 3 mm



2 mm / 5 mm

----- Conclusions -----

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The short teeth/deep back-channel geometry boils more at 5.0 MW/m^2 case than the long teeth/deep back-channel geometry. This results in a reduction in surface temperature on the beryllium tiles. The deep backchannel is more effective in condensing vapor and mixing. The 0.5 MW/m^2 nominal case shows equivalent temperatures between the two. The short teeth geometry with a shallow back-channel has a 9% increase in pressure drop even with the reduced mass flow.

Thermally, 2mm teeth/ 3 mm backchannel provides better performance for nominal operation.

A big advantage of the 2 mm teeth/3 mm backchannel design is the performance it provides at half the mass flow. Thus hypervapotron fingers can be fed in parallel with the same total mass flow. This greatly simplifies the water circuit for a forty-finger panel. Flowing pairs in series requires an additional flow return for each pair in the panel where space is limited.

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