

Thermalhydraulic Optimization of Hypervapotron Geometries for First Wall Applications

D.L. Youchison, M.A. Ulrickson

Fusion Technology Programs
Sandia National Laboratories
Albuquerque, NM, USA
dlyouch@sandia.gov

J.H. Bullock

Fusion Technology Programs
LMATA Government Services, LLC
Albuquerque, NM, USA

Abstract—Plasma disruptions and Edge Localized Modes (ELMS) may result in transient heat fluxes as high as 5 MW/m^2 on portions of the ITER first wall (FW). To accommodate these heat loads, roughly 50% of the first wall will have 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.

In this article, 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°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 130°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°C . 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.

Keywords—first wall; hypervapotron; computational fluid dynamics; critical heat flux; two-phase

I. INTRODUCTION

Engineers are often faced with a choice in designing actively cooled heatsinks for plasma facing components. Either they can design for the worst case heatloads expected for off-normal transient conditions, or they can optimize the design for nominal operating conditions with enough safety margin to survive most expected off-normal events. 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. This article also describes optimized geometries for off-normal heat loads in two-phase flow and discusses 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.

II. HYPEVAPOTRON GEOMETRY

We previously performed extensive CFD heat transfer analysis of a Chinese (CN) first wall mock-up consisting of beryllium armor tiles bonded to a water-cooled CuCrZr hypervapotron heatsink attached to a 316LNG stainless steel strongback. This model became the test bed for our geometry optimization study. Fig. 1 shows the geometry of the mock-up. The mock-up has 14 8-mm-thick beryllium tiles of various dimensions including $50 \times 50 \text{ mm}^2$, $50 \times 25 \text{ mm}^2$ and $25 \times 25 \text{ mm}^2$. The CFD mesh appears in Fig. 2. The initial hypervapotron design became our reference geometry known as “long teeth, deep channel”, where channel refers to the open back-channel below the teeth.

The coolant is 70°C water at 2.7 MPa. For the 5-mm-backchannel, we used a mass flow rate of 435 g/s . For the 3-mm-back-channel, the mass flow rate was less, 263 g/s . This provided an average flow velocity of 2 m/s in the backchannel for both cases. Otherwise, the flow velocity near the teeth would be drastically different, and the comparison would be meaningless. We applied two heat fluxes of 0.5 MW/m^2 and 5.0 MW/m^2 on the surface of the beryllium tiles. The 0.5 MW/m^2 case represents the nominal operating conditions. Since coolant temperatures do not exceed the saturation

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temperature of 227 °C at 2.7 MPa, a single-phase steady state analysis is sufficient. The 5 MW/m² case is an off-normal heat load caused by ELMS or mild disruptions. The coolant temperature exceeds the saturation temperature; so the analysis must proceed using a transient, two-phase Eulerian approach. The heated length is 100 mm based on the footprint expected on any one finger in ITER during a disruption, and the heated width is 50 mm [1,2]. The analysis used temperature dependent physical properties for all materials [3].

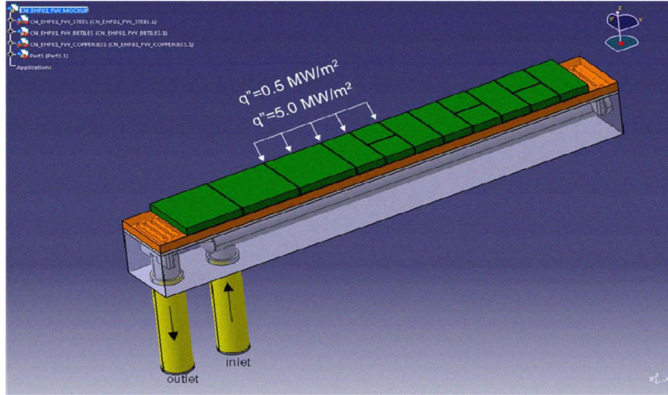


Figure 1. CN mock-up geometry contains 14 8-mm-thick beryllium tiles bonded to a CuCrZr hypervapotron heatsink.

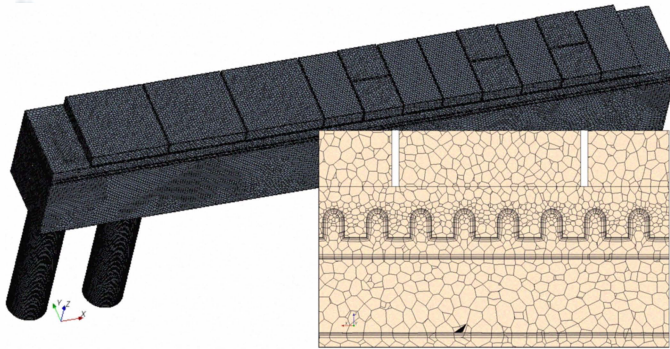


Figure 2. CFD mesh contains 1.4 M polyhedral cells and 4 prism layers shown in the inset.

All simulations discussed here are 3d involving stationary boundaries with k-ε turbulence. The boiling analysis uses a multi-phase mixture physics model, transitioning to volume-of-fluid during film formation. The simulations also include surface tension, gravity, and segregated flow. The two-phase analysis uses an implicit, unsteady solver and time steps of 10 ms with 10 to 16 inner iterations. Details involving the application of a boiling model to hypervapotrons are available in the literature [4,5]. Experimental results from high heat flux testing of various geometries including widths and side slot variations are also in the literature[6,7].

A. Long Teeth, Deep Channel

The reference geometry consists of 4-mm-deep hypervapotron teeth, 3-mm-wide on a 6-mm-pitch. Slots, 3-mm-wide and 4-mm-deep, run down the sides of the teeth the entire length of the back-channel. The back-channel is 43-mm-

wide and its height is 5 mm. A cross-section of this geometry appears in Fig. 3 in the upper left.

B. ShortTeeth, Shallow Channel

The next case consisted of 2-mm-deep teeth, 3-mm-wide on a 6-mm-pitch. The side slots were 2-mm-deep and 3-mm-wide. The back-channel height is reduced to 3 mm to maintain the same average velocity at a reduced mass flow. Fig. 3 shows the geometry dimensions in the upper right.

C. Long Teeth, Shallow Channel

The third case consisted of 4-mm-deep teeth, 3-mm-wide on a 6-mm-pitch. The side slots were 4-mm-deep and 3-mm-wide like the reference geometry. However, the back-channel height is reduced to 3 mm for comparison to the previous case. A cross-section of the geometry is shown in the lower left of Fig. 3.

D. Short Teeth, Deep Channel

The final case consisted of 2-mm-deep teeth, 3-mm-wide on a 6-mm-pitch. The side slots were 2-mm-deep and 3-mm-wide. The back-channel height is 5 mm and is identical to the reference case. Fig. 3 displays the dimensions of this geometry in the lower right.

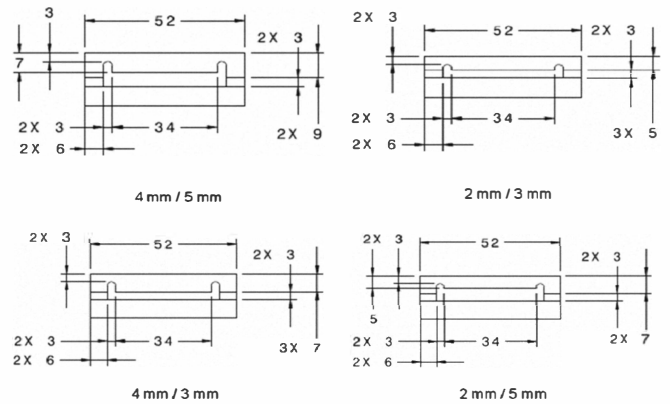


Figure 3. Study evaluated four hypervapotron geometries (only heatsink shown).

III. CFD MODELING RESULTS

The most important results from the CFD simulations are the surface temperature distributions on the beryllium tiles, the velocity profiles in the grooves of the hypervapotron, and the calculated local convective heat transfer coefficient (HTC) in the grooves. The HTC between the nominal heat flux case and the off-normal case are compared for each geometry as well as the beryllium surface temperature.

Fig 4 shows a contour plot for beryllium surface temperatures for the four geometries under the nominal heat load of 0.5 MW/m². Likewise, Fig. 5 presents the surface temperature distributions for the 5 MW/m² off-normal case. Fig. 6 shows the comparison between the various geometries and conditions. Surface temperatures are lowest for the 4/3

case under nominal conditions and the 2/5 case during off-normal heating.

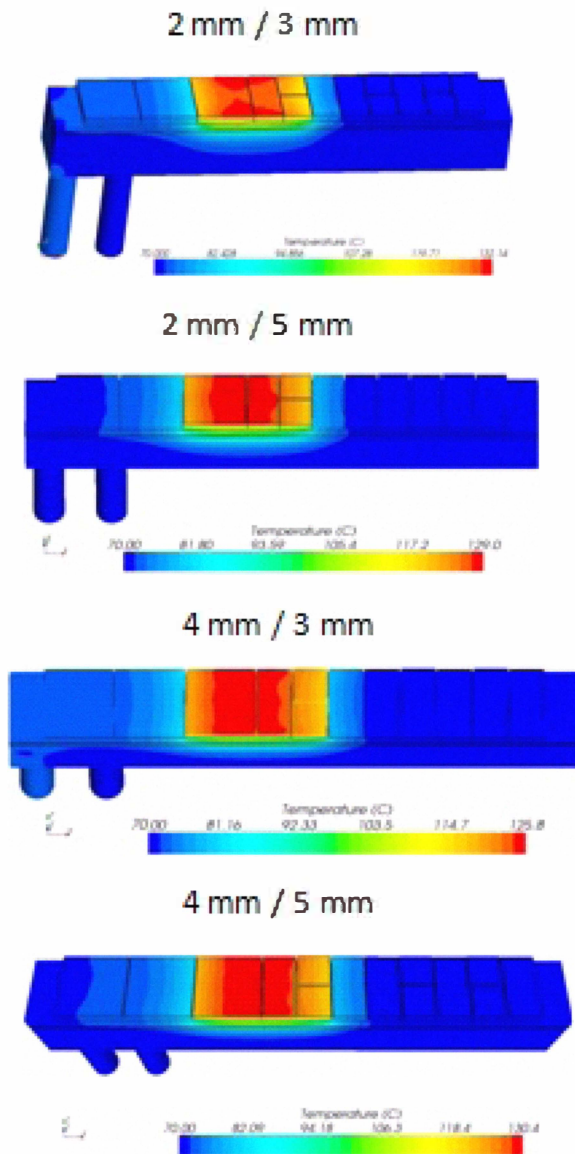


Figure 4. Peak surface temperature under nominal heat loads shows little change with hypervapotron geometry.

The velocity distributions for the four geometries appear in Fig. 7. The average velocity in the back-channel is about 2 m/s. Note that with the short teeth, the velocity in the bottom of the grooves is higher than the long teeth (0.8 m/s compared to 0.2 m/s). The pressure drops range between 14.5 and 15.6 kPa.

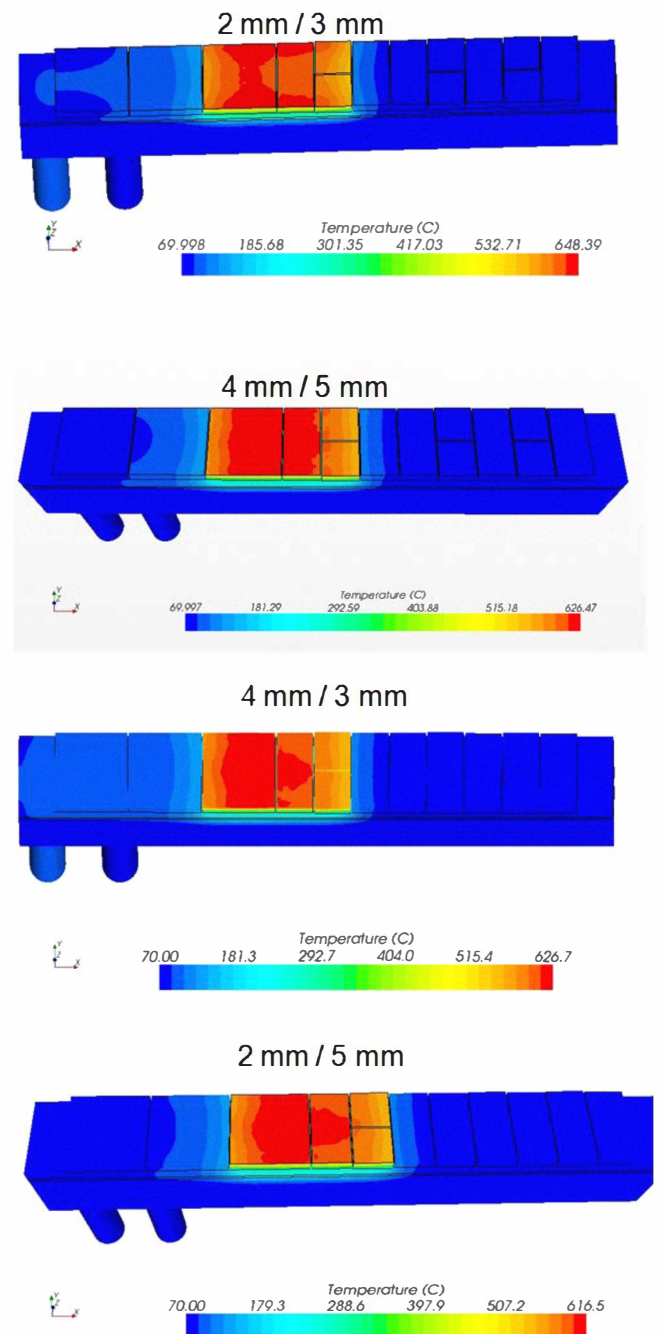


Figure 5. Peak surface temperature during off-normal heating is more dependent on hypervapotron geometry.

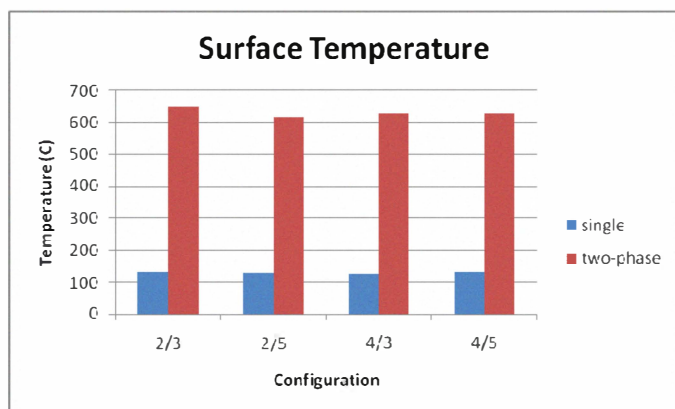


Figure 6. Comparison of surface temperatures for nominal and off-normal conditions.

The vapor fractions for the off-normal heat loading appear in Fig. 8. The short teeth/shallow channel has more boiling with a vapor fraction of 6.7% compared to 5.1% for the deep teeth/deep channel. This is a small amount of water vapor that only partially fills the hypervapotron grooves and side slots. No vapor appears under the teeth; so some margin is available before reaching critical heat flux.

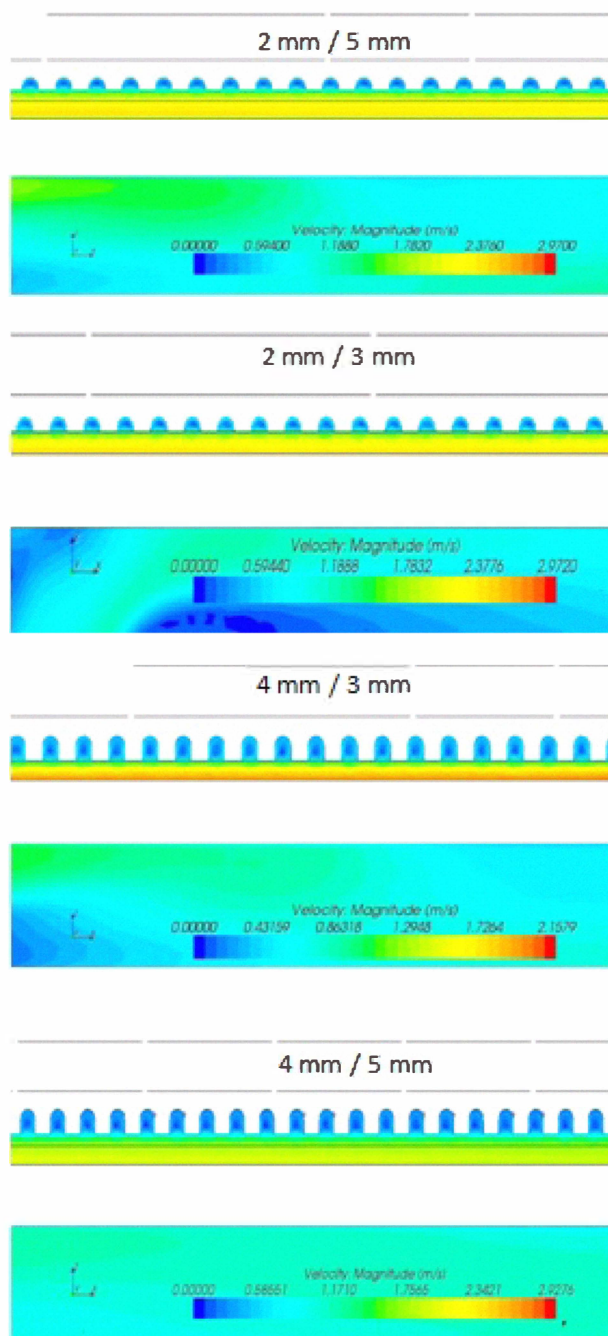


Figure 7. Velocity profiles for the geometries affect single-phase heat transfer.

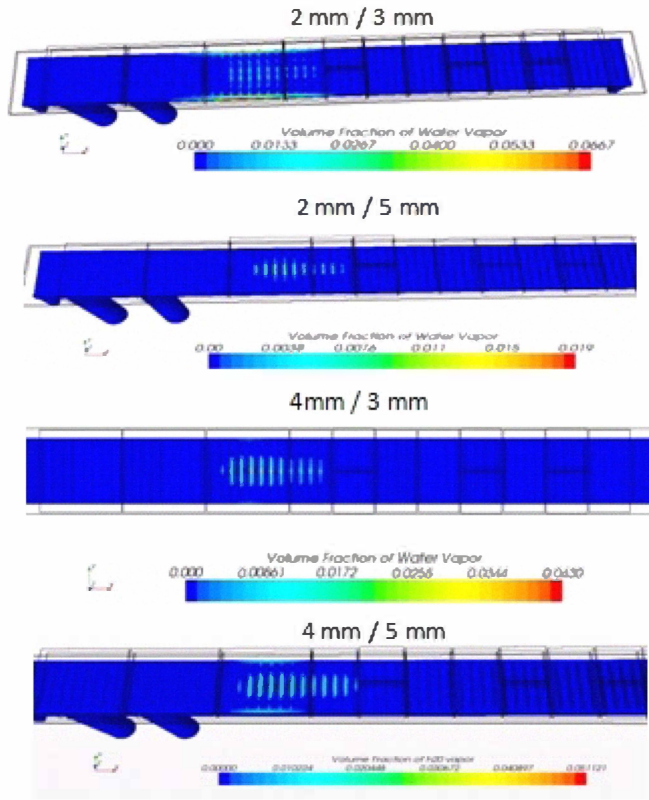


Figure 8. Vapor fractions during off-normal conditions correlate with temperatures.

A comparison of the local heat transfer coefficients appears in Fig. 9. Again, the 2/5 configuration has the highest heat transfer for off-normal conditions, while the 2/3 has the highest peak value for the nominal conditions, although it did not have the lowest surface temperatures. On average, the 4/3 performed better.

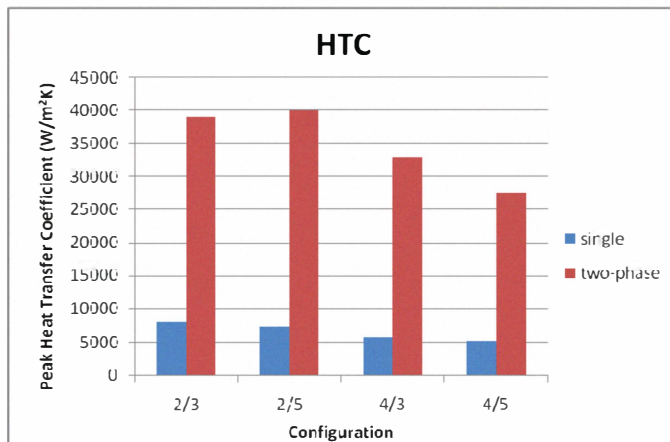


Figure 9. Comparison of peak heat transfer coefficients

IV. DISCUSSION

The advantage of the hypervapotron is that it relies on boiling heat transfer to provide the safety margin for off-normal conditions. The optimum for nominal heating and single phase flow is not the optimum geometry for boiling heat transfer. Therefore, a compromise between the two must be made. Ideally, one would like optimum performance under nominal conditions and sufficient performance under off-normal heating to survive any transients.

All the studied geometries have acceptable thermal performance, so the design drivers become the available mass flow and allowable pressure drop. In addition, layout of the cooling circuit and manifolding will impact the final choice of hypervapotron geometries.

V. CONCLUSIONS

The short teeth/shallow back-channel geometry boils in the bottom of the grooves more at 5.0 MW/m² case than the long teeth/deep back-channel geometry. This results in a reduction in surface temperature on the beryllium tiles. However, the short teeth/deep back-channel (2 mm / 5 mm) provides more water volume for downstream mixing and condensation of the vapor and has the best performance for off-normal conditions. The 0.5 MW/m² nominal case shows nearly equivalent temperatures between the cases. While the 2/3 configuration has the highest convective heat transfer coefficients in localized areas, the 4/3 configuration has the highest average heat transfer coefficient over a larger area, and thus the lower surface temperatures. The short teeth geometry with a shallow back-channel has a 4% increase in pressure drop even with the reduced mass flow.

A big advantage of the short teeth/shallow 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 a panel with limited space available.

We will include the effects of hypervapotron width on off-normal performance using these same cross sectional geometries in a more detailed future article.

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