Quantifying the Advantages of Counter Flow Helium First Wall Cooling
A Thermal-Hydraulic Comparison of ITER TBM First Wall Cooling Designs

G. Sviatoslavsky\textsuperscript{a}, M. Dagher\textsuperscript{b}, P. Calderoni\textsuperscript{b}, C.P.C. Wong\textsuperscript{c}

\textsuperscript{a} University of Wisconsin, Madison, USA
\textsuperscript{b} UCLA, Los Angeles, USA
\textsuperscript{c} General Atomics, San Diego, USA

Abstract - Three dimensional Computational Fluid Dynamic (CFD) calculations using the commercial software FLUENT \cite{1}, were performed to evaluate the thermal hydraulic performance of a counter flowing helium First Wall (FW) cooling system compared to a more simple unidirectional flowing FW cooling system.

Keywords-CFD; ITER; test blanket module; first wall; helium cooling; thermal-hydraulic analysis

I. INTRODUCTION

In support of the ITER Test Blanket Module (TBM) program, the US team is developing a dual coolant Pb-17Li liquid Breeder (DCLL) blanket design. The US-ITER TBM design uses a reduced activation ferritic steel (RAFS) as the structural material, which limits the maximum steel structure temperature to 550°C. The design utilizes two counter flowing helium circuits, with each circuit making five passes of the first wall (FW) to remove heat flux in the FW.

Three dimensional Computational Fluid Dynamic (CFD) calculations using the commercial software FLUENT \cite{1}, were performed to evaluate the thermal performance of the FW cooling, specifically, the maximum first wall temperature, helium outlet temperature and the heat transfer coefficients in the channels. The FW is modeled with a single channel (out of eight) for each of the five passes of the two counter-flowing helium circuits. In this way the eighty-channel FW is simplified to a ten channel model.

The counter flow aspect of the FW helium circuits significantly increases the complexity of the cooling system design and requires approximately twice the manifold space compared to a unidirectional flow system. The term “unidirectional” is slightly misleading since the flow direction does change direction from pass to pass. For the purposes of this paper the term unidirectional shall mean the neighboring channel flow is counter flowing only when transitioning to a subsequent pass. This paper presents analysis of both a counter flowing design and unidirectional design. By comparing the results of the two models, this paper will quantify the advantages, in terms of required power, of a counter flowing helium cooling system compared to the performance of a more simple unidirectional flowing helium cooling system. This analysis does not consider the effects on stress or consequences of differences in thermal expansion likely found between a counter flowing and unidirectional FW designs.

II. FIRST WALL HELIUM COOLING DESIGN

The FW assembly is a ferritic steel U-shaped structure with internal He coolant channels (see Figure 1). The coolant channels are designed to allow multiple passes of coolant flow across the FW in order to maximize heat removal.

Figure 1. ITER TBM and First Wall Assembly.

Figure 2. Helium Flow Channel and Dual Circuit Detail

There are a total of 80 coolant channel 20 mm deep by 19.25 mm high. The channels of the two circuits alternate with one another, with the He flowing in a counter flow arrangement in order to promote uniform temperature distribution across the FW surface (see Figure 2). Each circuit contains 40 channels connected by a series of manifolds in the back plate. The manifolds of each circuit connect succeeding passes along the
FW. Since both circuits run the entire poloidal length of the FW, the TBM must be deep enough radially, to accommodate the manifolds of each circuit which also run the poloidal length of the TBM (see Figure 3). [2]

III. GENERAL MODEL SET-UP

A three dimensional model approximates the FW with a single channel representing each of the five passes of the two counter-flowing helium circuits. Therefore, the eighty channels in the FW are simplified to a ten channel model (see Figure 4). The model channel toroidal length is equal to the TBM plasma facing length of 64.5 cm. This geometry was used to develop both the counter flow and unidirectional CFD models.

The helium inlet temperature of the first pass was set at 360°C, with the inlet temperature of a downstream pass based on the outlet temperature of the preceding upstream pass. A flow velocity of 42.6 m/s was assigned for each channel in the circuit.

The plasma-side heat flux was set at 0.3 MW/m², while the Pb-17Li side was assumed to be adiabatic. A constant nuclear heating energy density of 7.75 MW/m³ [2] was set for the steel structure of the first wall.

The model’s plasma-side channel walls were defined as having a uniform sand-grain roughness height of 0.25 mm, while all other channel walls were smooth. Turbulence is accounted for by utilizing the k-epsilon turbulence model. Material properties used in the model are listed in Table I.

<table>
<thead>
<tr>
<th>TABLE I. MATERIAL PROPERTIES</th>
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<tbody>
<tr>
<td>Material</td>
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<tr>
<td>----------</td>
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<tr>
<td>Helium [3]</td>
</tr>
<tr>
<td>Fe-(8-9)%Cr [4]</td>
</tr>
</tbody>
</table>

a. (Cp is a piecewise-linear function of temperature)
IV. COUNTER FLOW ANALYSIS

A. Counter Flow Model Set-up and Procedure

The counter flow model set-up is as described in section III. Figure 5 illustrates the model geometry and counter flow arrangement. The analysis procedure involved solving for steady-state flow, turbulence (k-epsilon model) and thermal conditions.

B. Counter Flow Thermal/Hydraulic Results

The maximum FW temperature of 523 °C occurs locally along the pass in the fifth channel of each circuit. Figure 6 shows resulting temperature contours of the FW.

With the inlet helium temperature set at 360 °C in the first pass, the exiting helium reaches a temperature of 432 °C at the outlet of the fifth pass.

The resulting average heat transfer coefficient for the plasma side channel wall is 6674 W/m²-C.

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V. UNIDIRECTIONAL FLOW ANALYSIS I - EQUIVALENT MASS FLOW

A. Unidirectional Flow Model Set-up and Procedure

Similar to the ten-channel counter flow model, the unidirectional model set-up is as described in section III. However, rather than modeling two circuits and all five passes with a single ten channel model, a single circuit with two passes are represented with five neighboring channels for each pass (see Figure 7). The resulting two pass, steady-state model is then solved separately four times (pass 1 & 2, pass 2 & 3, pass 3 & 4 and pass 4 & 5). In each case the resulting latter pass helium temperature of the previous model is used to define the inlet helium temperature for the initial pass channels of the subsequent model. In this way the eighty channel first wall is represented with an equivalent twenty-five channel model (five passes with five channels each), that is built-up with four separate calculations.

B. Unidirectional Flow Model Thermal/Hydraulic Results

Using the same mass flow rate as the counter flow design, a maximum FW temperature of 538 °C occurs locally along the fifth pass channels, an increase of 15 degrees over the counter flowing case. Figure 8 shows pass four and five (worst case) resulting temperature contours of the FW.
As in the counter flow case, the first pass helium inlet temperature is set at 360°C and the exiting helium reaches a temperature of 432°C at the outlet of the fifth pass. Therefore, the increase in helium temperature is the same for both the unidirectional and counter flowing cases.

The resulting average heat transfer coefficient for the plasma side channel wall is 6859 W/m²·C, or 3% higher than the counter flow case.

VI. Unidirectional Flow Analysis II – Equivalent Cooling

In order to quantify the thermal-hydraulic advantage of the counter flow design, a series of unidirectional flow cases were performed to determine the increase in helium flow rate and additional power required to attain the same maximum FW temperature as the counter flow design.

The analysis showed that increasing the helium flow velocity to 48.75 m/s, lowered the maximum FW temperature to 522°C, approximately the same temperature as the 42.6 m/s velocity of the counter flow case. This 6 m/s velocity increase requires a mass flow increase of 1.1 kg/s for the FW. Based on affinity laws, power is proportional to the change in flow rate cubed [5]. Therefore the expense for the higher velocity is an increase of 51% in required pumping power. Table II compares the results of the counter flow case to that of the unidirectional flow cases.

<table>
<thead>
<tr>
<th>System</th>
<th>Max FW Temp (°C)</th>
<th>Mass Flow (kg/s)</th>
<th>He Outlet Temp (°C)</th>
<th>Avg. h (W/m²·K)</th>
<th>Power Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counter Flow</td>
<td>523</td>
<td>7.5</td>
<td>432</td>
<td>6674</td>
<td>NA</td>
</tr>
<tr>
<td>Unidirectional I (equivalent mass flow)</td>
<td>538</td>
<td>7.5</td>
<td>432</td>
<td>6859</td>
<td>0</td>
</tr>
<tr>
<td>Unidirectional II (equivalent cooling)</td>
<td>522</td>
<td>8.6</td>
<td>423</td>
<td>7827</td>
<td>51</td>
</tr>
</tbody>
</table>

VII. Conclusion

Computational Fluid Dynamic analysis has quantified the improvement in thermal hydraulic performance of a counter flowing FW cooling system over a unidirectional flowing system for the ITER TBM.

This analysis does not consider the effects on stress or consequences of differences in thermal expansion likely found between a counter flowing and unidirectional FW designs.

The design and fabrication of a counter flow system is significantly more complex and requires approximately twice the amount of manifold space as a unidirectional flowing system. However the counter flowing system is capable of maintaining a given maximum FW temperature with 51% less pumping power than the more simple unidirectional flowing system.

The significant reduction in required power offers a persuasive argument for the increased complexity and additional space requirements of a counter flowing helium cooling system.

Acknowledgment

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References