Improvements to the Helium Flow Path in the US DCLL ITER Test Blanket Module

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ABSTRACT

Computational fluid dynamics simulations have demonstrated flow problems within the helium flow path in the current US DCLL ITER test blanket module design. New geometry for the helium flow path has been designed that will improve flow evenness and simplify the overall helium flow path within the test blanket module while maintaining the overall test blanket module geometry. Global changes to the test blanket module geometry can be implemented based on these improvements.

INTRODUCTION

A Test Blanket Module (TBM) design based on the dual coolant lithium lead (DCLL) blanket concept has been developed by the US in support of the ITER Test Blanket Module program. The ferritic steel structure is cooled by flowing helium within the structural panels. A lead-lithium (PbLi) breeder is circulated through the TBM in the poloidal direction for tritium breeding and power extraction. Around the PbLi are silicon carbide (SiC) flow channel inserts (FCI), which reduce the MHD pressure drop on the flowing PbLi and thermally isolate the high temperature PbLi from the ferritic structure.

The current design of the TBM involves a complex flow path for the helium coolant. Sections of the flow path are in series while others are in parallel. This causes some flow irregularities that are addressed in this paper. Potential design changes for the US TBM are presented for the following areas of concern: asymmetrical helium flow in the entry region, helium distribution in the headers between first wall passes, a point of local structural stress, a hot spot due to neutron and gamma heating, and the potential for uneven flow to the lead lithium internal cooling structure known as the grid plates and dividers. Design modifications that will resolve each of those problem areas have been made.

The improvements include a new inlet section which alleviates asymmetric flow in the entry region, new header geometry options between the first wall passes, and a completely new grid plate/divider helium flow scenario. These changes can be incorporated into a global redesign of the TBM based on results of thermal hydraulic analysis. The global redesign greatly simplifies the helium flow path within the TBM. Further thermal hydraulic and flow analysis will be performed.

PbLi HOT SPOT DUE TO NEUTRON AND GAMMA HEATING

a. The Cause of the Hot Spot

The TBM design routes the molten PbLi poloidally along the front of the TBM from the top to the bottom, where the PbLi turns toward the back of the TBM and flows upwards to the PbLi outlet. When the PbLi flow enters it splits into three separate channels before if flows poloidally. Should the operation of ITER be interrupted it may be desirable to have the capability to drain the PbLi from the TBM. Therefore when the current design was produced, based on the grid plate/divider geometry, a triangular “drain” opening was located at the front end, nearest the plasma, of the bottom of the grid plates/dividers to allow for the PbLi to drain to the center channel where the PbLi could be routed out of the TBM through the main PbLi drain.

Neutronics analysis has shown this to be a hot spot with high levels of neutron and gamma heating [1]. The PbLi flow at this point could become stagnant which would enhance the negative effects of the neutron and gamma heating. This hot spot is undesirable for the design.

b. The Solution

A solution can be found by simply adjusting the location of the PbLi drains between the channels. By removing the triangular drain opening between channels from the front and replacing it with a more rectangular drain opening towards the rear of the grid plates/dividers the problem can be solved. While the flow will likely still be stagnant in this region during operation of the TBM, the placement will yield far less neutron and gamma heating since the drain will be further from the plasma, deeper within the TBM, where neutron and gamma heating values have been shown to be lower.

Figure 1 illustrates the results from neutronics analysis of the elevated heating in the PbLi channel drains.

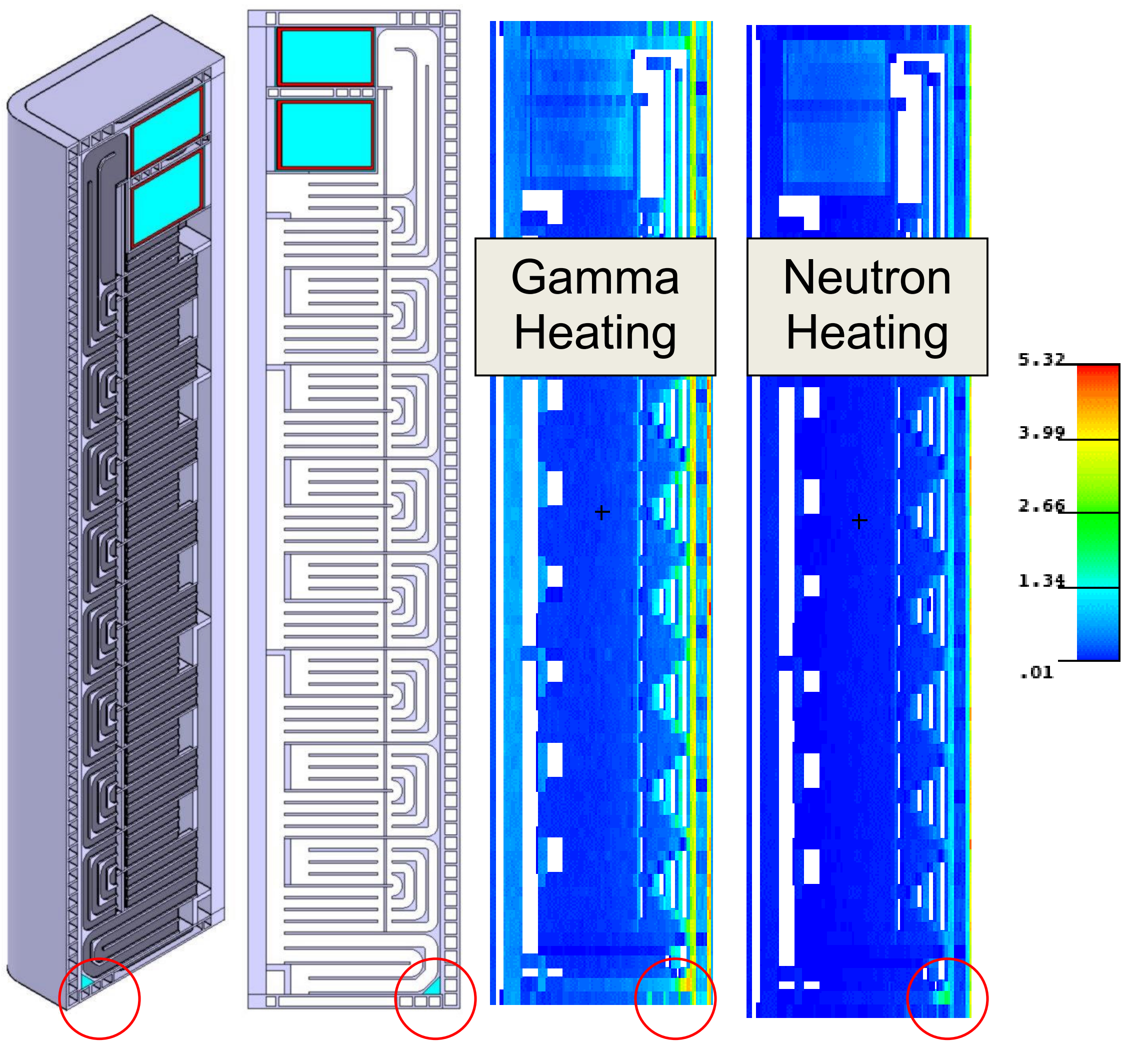

Figure 1. Neutronics results illustrating the elevated neutron and gamma heating in the stagnant PbLi channel location.

Figure 2 shows how the improved location and geometry of the PbLi drain can be configured. If the grid plate/divider assembly geometry remains unchanged then the lowest channel in the divider will see a larger pressure drop due to this change. However, the proposed grid plate/divider geometry shown below will alleviate any potential problems introduced with this local geometric change. Overall it is proposed to include this hot spot geometry change with a full redesign of the grid plate/divider assembly.

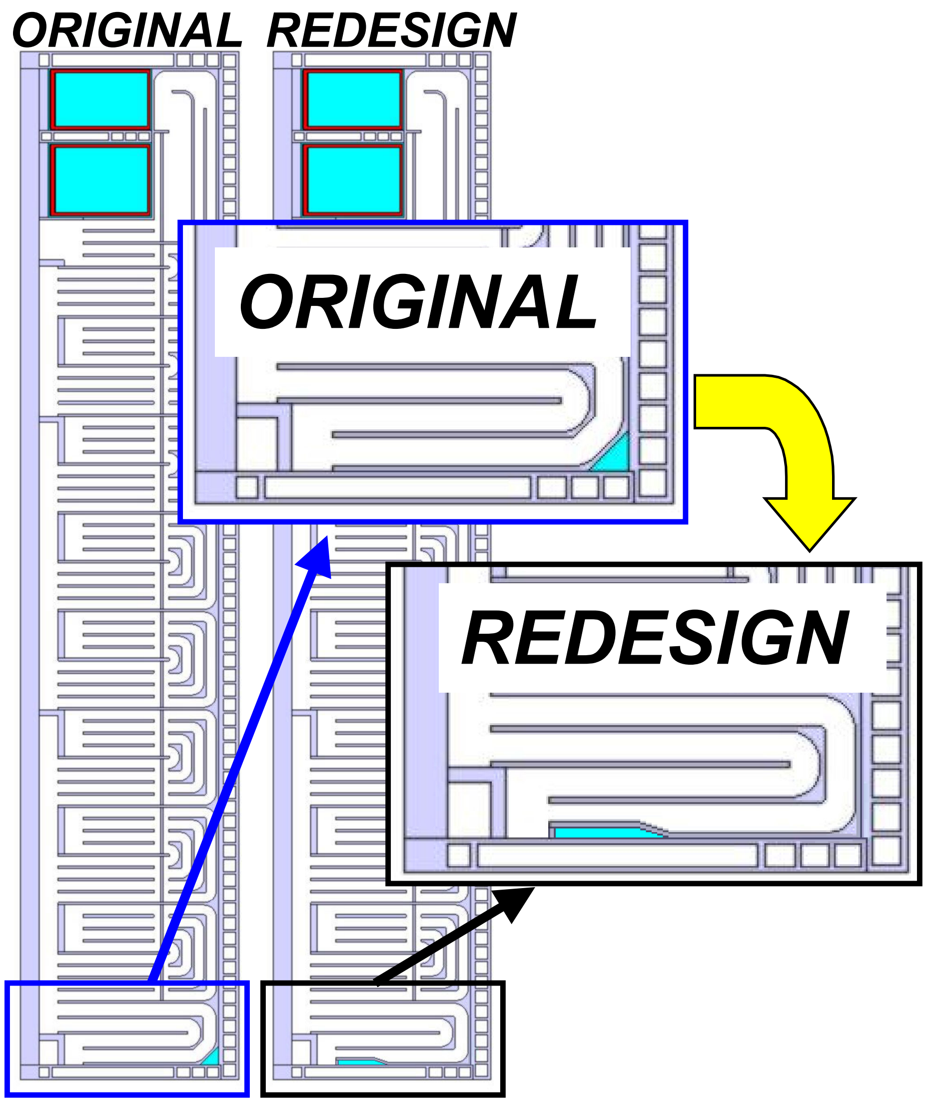

Figure 2. Illustrating the local solution to improve the hot spot in the PbLi due to neutron and gamma heating.

HELIUM ENTRY ASYMMETRY

a. Helium Entry Asymmetry Problem

Helium enters the TBM in the back plate, flows downward, around the PbLi drain pipe, and then splits to the two first wall counterflow circuits. Each circuit routes flow to five first wall channels and half of the bottom plate in parallel. It is desired that each channel experience equal flow, and each half of the bottom plate experience equal flow. However, the design itself tends towards asymmetry in the two flow circuits due to the asymmetric design.

On one side the flow enters the bottommost first wall channel and the bottom plate at the same vertical location. On the other side the flow enters the bottommost first wall channel above the bottom plate. This is illustrated in Figure 3. On the latter side there is a tendency for less flow to enter the bottom plate. This is undesirable because the side that receives more flow will have different heat transfer characteristics than the side that receives less flow.

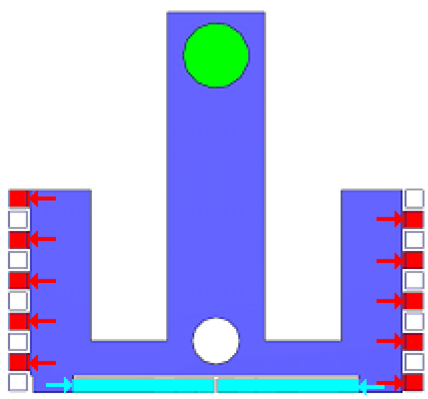

Figure 3. An illustration of the cause of flow asymmetry in the helium entry region. Green represents the entry tube, red represents flow to the first wall channels, light blue represents flow to the bottom plate.

b. Helium Entry Asymmetry Analysis

To determine the extent of the asymmetry the computational fluid dynamics software ANSYS CFX was used to simulate the helium flow in the entry region including the bottom plate and the first pass through the first wall. Though heat transfer is important for the performance of the TBM it was neglected in this analysis to simplify the simulations. The results, illustrated in Figure 4, demonstrate that there is significant flow asymmetry, not only between the sides of the bottom plate, but also between the first wall channels.

Once the significance of the asymmetry was understood it was important to apply those results to the development of an improved design that would alleviate the flow asymmetry as best as possible. An improved design should supply even flow to the bottom plate, and balance flow to all of the first wall channels.

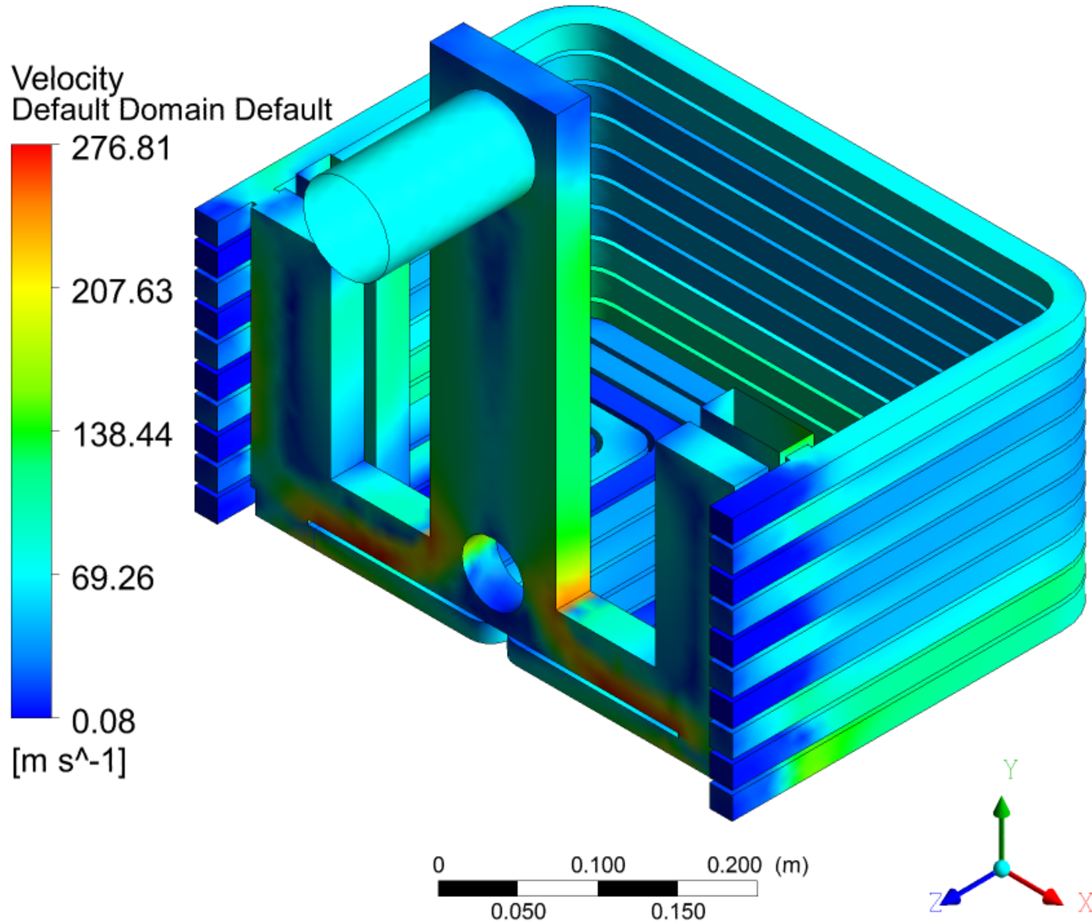

Figure 4. ANSYS CFX results illustrate the flow velocity within the current design of the helium entry region of the TBM.

On the assumption of an improved grid plate/divider system, as will be discussed further down, it was possible to develop a completely new helium entry region. In the improved geometry the helium spreads out in the back plate prior to entering the bottom plate and first wall channels. Then flow enters the bottom plate symmetrically near the middle of the TBM as opposed to entering near the side walls. The spreading flow from the inlet can also now enter the first wall channels much more evenly. Figure 5 shows the velocity characteristics in the improved geometry.

c. Assessing the Improved Design

After the analysis was complete it was possible to assess the extent of the improvement. To assess the improvement several measurements were taken from the simulation output. The first measure of improvement was to obtain the ratio of mass flow rates out of the outlets. If flow is even between the two circuits, then the mass flow rates from the two outlets should be equal, and thus their ratio should be as near to 1 as possible.

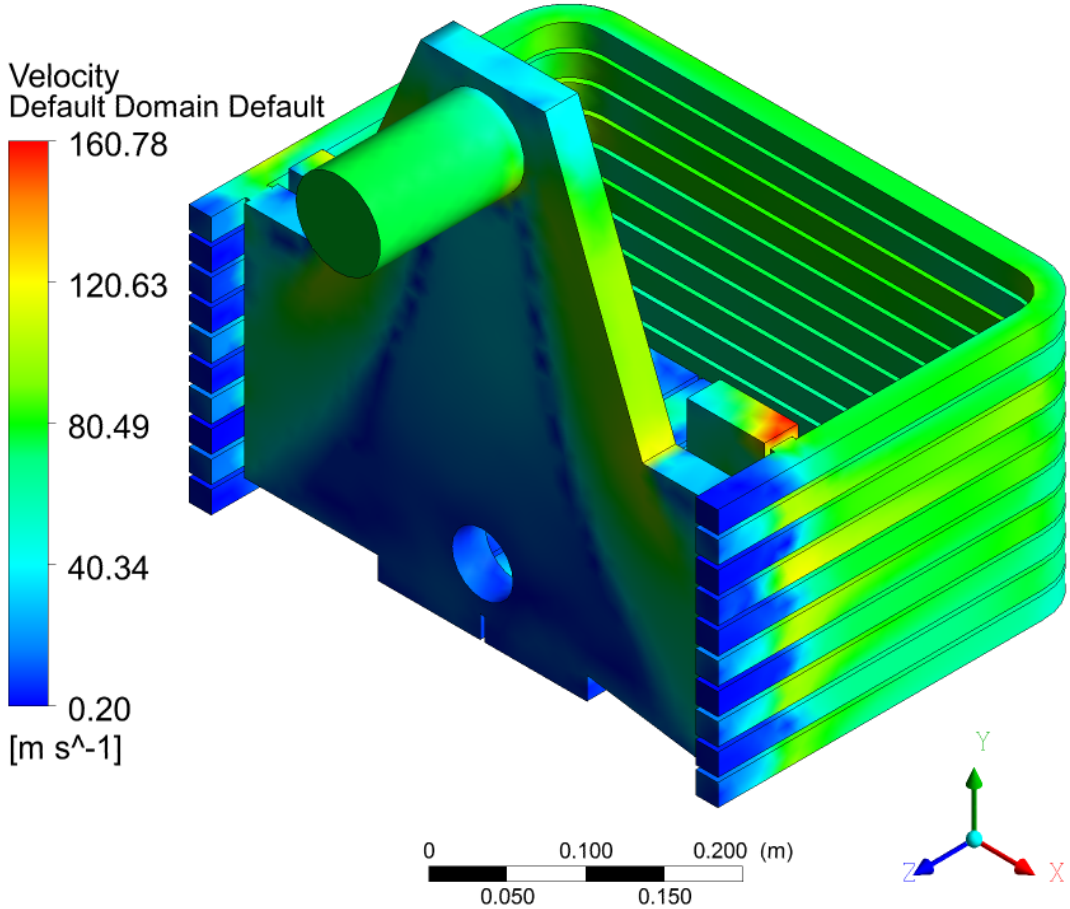

Figure 5. ANSYS CFX results illustrate the flow velocity within the improved design of the helium entry region within the TBM

Another assessment calculation would be to determine the ratio of maximum channel mass flow rate to minimum channel mass flow rate. This number is also desired to be as near to one as possible.

Table 1 shows these results.

Table 1. Mass Flow Rate Results Comparing the Current Helium Entry to the Improved Helium Entry.

	CURRENT DESIGN	IMPROVED DESIGN
Maximum Channel Mass Flow Rate [kg/s]	**0.2594**	**0.2027**
Minimum Channel Mass Flow Rate [kg/s]	**0.0971**	**0.1562**
Channel Mass Flow Rate Ratio [max/min]	***2.672***	***1.298***
Average Channel Mass Flow [kg/s]	**0.1550**	**0.1809**
Ratio of Outlet 1 Mass Flow to Outlet 2 Mass Flow	***0.8839***	***1.0011***

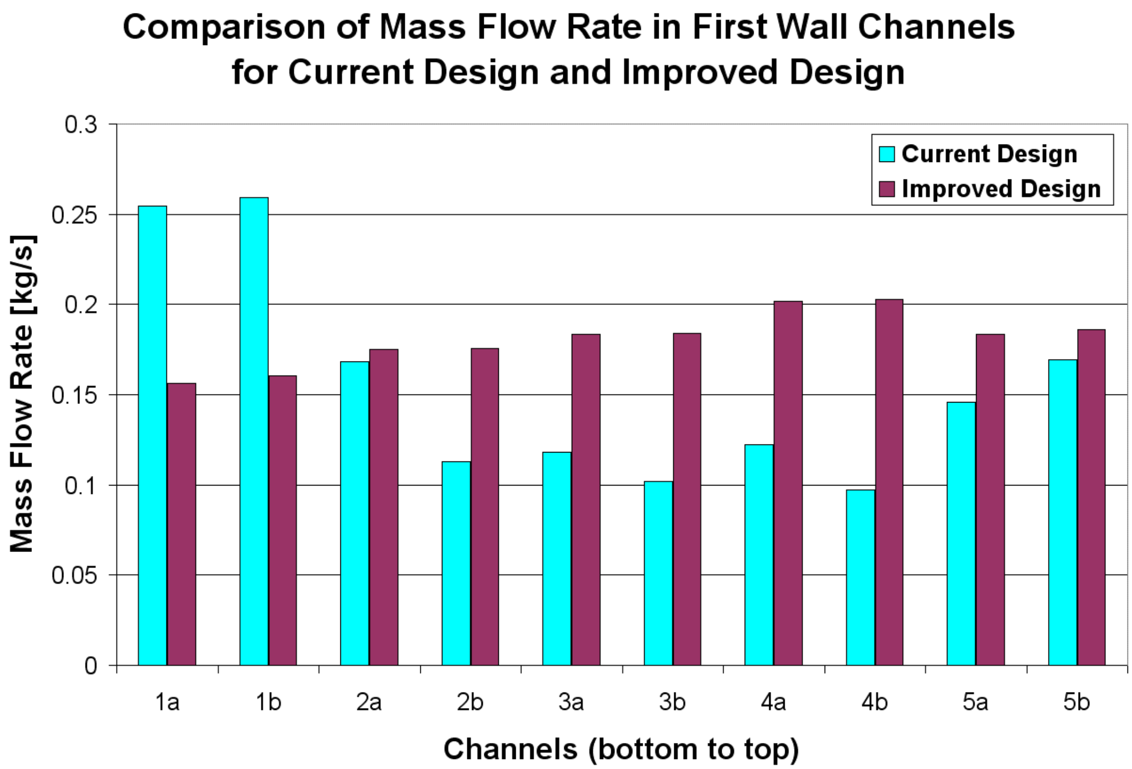

Figure 6. Mass flow rates for the first wall channels in the current design and improved design analysis results.

The results in Table 1 show a significant improvement in both areas of concern. The ratio of outlet mass flow rates improved from 0.8839 to 1.0011. This means that a nearly equal amount of helium is flowing to each circuit. The other result of significance is the improvement of the ratio of maximum channel flow rate to minimum channel mass flow rate. The current design produced a channel flow ratio of 2.672 while the improved design decreased that ratio to 1.298. That is a considerable improvement. This is also illustrated in Figure 6.

FLOW UNEVENNESS IN FIRST WALL HEADERS

a. The Problem of Uneven Header Flow

It is believed that uneven flow within the first wall channels may lead to hot spots and potential melting of the first wall. It is critical that the first wall remain below the melting temperature. Therefore it is important to achieve even flow to each of the first wall channels. Analysis has shown that uneven flow exists with the current design of the first wall headers [2].

b. Potential Solutions and Analysis

There are several design improvements that could be made to this region of the TBM. Two such improvements are illustrated in Figure 7. The "Flow Continuation" option routes flow directly from one channel to the next through the header without allowing for channel-to-channel

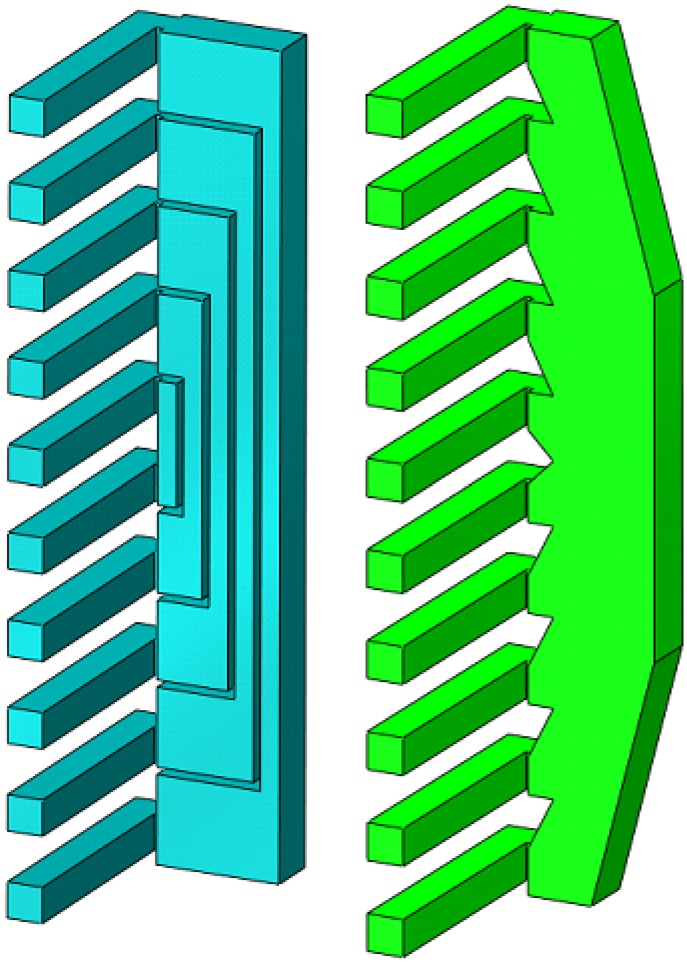

Figure 7. Two potential header design improvements: Left – Flow Continuation, Right – Flow Steering.

mixing. The “Flow Steering” option introduces baffle-like geometry that is intended to even the flow between the five channels. This latter option also has truncated corners that are meant to aid in evening the flow.

Only the “Flow Steering” option was analyzed in comparison to the current design. The “Flow Continuation” option was not analyzed due to the lack of mixing between channels within the headers, which is believed to aid in heat transfer within the headers.

The analysis of the current design and the flow steering design each consisted of three simulations. The initial, or “primary,” simulation involved setting the initial mass flow rate for each of the five inlet channels. The outlet mass flow rates from the primary simulation were used as the inlet values for a “secondary” simulation. The outlet mass flow rate values from the secondary simulation were used as inlet values for a “tertiary” simulation. The analysis was performed this way to see if the flow unevenness was compounded from one header to the next. The simulations were performed in ANSYS CFX. Figure 8 shows the velocity streamlines from the analysis of the current design.

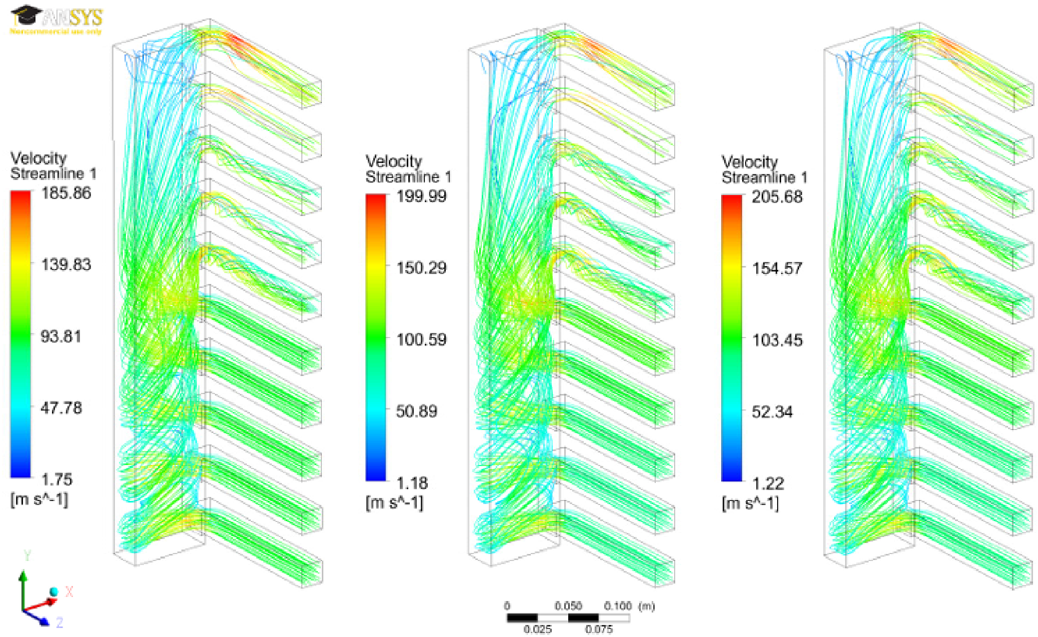

Figure 8. Velocity streamlines from analysis of the current header design.

c. Results

The results from the simulations made it clear that the figure of merit on which to base the improvement of the flow steering option was the standard deviation of mass flow rates within the channels. It would be desired to have the smallest standard deviation, and thus the most even flow within the channels. Improvement would be demonstrated by having a smaller standard deviation in the flow steering design than the current design.

These results are shown in Table 2. As can be seen the standard deviation dropped slightly from just over 7 kg/s in the current design to just less than 7 kg/s in the flow steering design. This is not a significant improvement but it does illustrate that an improvement can be achieved.

Table 2. Standard Deviation of Mass Flow Rates in Simulations of the Current and Improved Design of the First Wall headers.

	Current Geometry	Improved Geometry
Primary Out – Secondary In	7.33	6.51
Secondary Out – Tertiary In	7.18	6.79
Tertiary Out	7.18	6.90

UNACCEPTABLE STRUCTURAL STRESS POINT

a. The Cause of the Structural Stress

The current design of the grid plates/dividers produces a point of significant structural stress [3]. This is shown in Figure 9. The location is near the intersection of the grid plates and the dividers where a turnaround point exists for the helium.

b. Potential Solutions

One way to alleviate the stress point without making drastic changes to the TBM would be to extend the plate further into the divider component. This could easily be done without any negative effects to the flow characteristics of the grid plate/divider assembly.

However, it is proposed that this problem is solved by completing a full redesign of the grid plate/divider assembly, as shown below. A full redesign would eliminate the turnaround point where the stress is located.

FLOW UNEVENNESS IN THE GRID PLATE/DIVIDER ASSEMBLY

a. The Cause of Uneven Flow

After the helium has flowed through the first wall, bottom plate, and top plate via two counterflow circuits, it then recombines and flows to the grid plate/divider assembly. At this point the helium must enter 68 separate channels in nine sections, as seen in Figure 10. After the

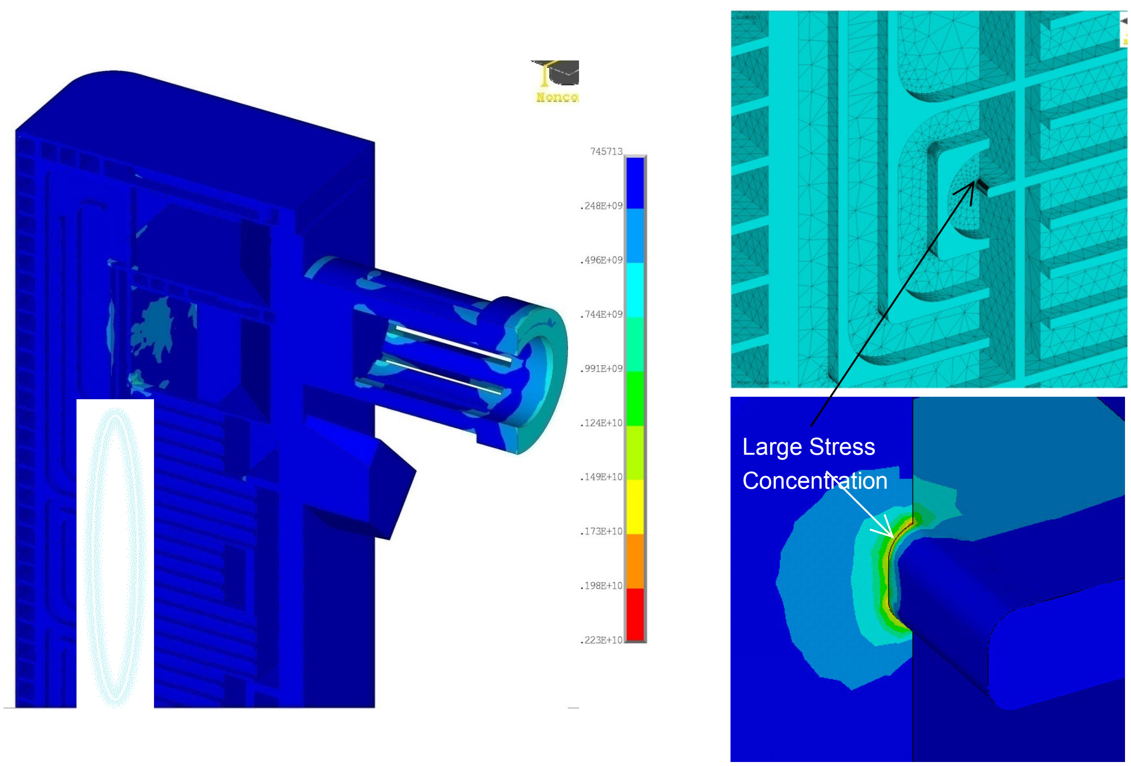

Figure 9. An illustration of the high structural stress within the grid plate/divider assembly.

helium enters the 68 channels it then spreads and flows around a plenum. On the other side of the plenum flow will combine and flow through u-turn channels. Then the helium splits to flow around the plenum again, recombines on the other side, and flows out of the grid plate/divider assembly.

There are several concerns with this geometry. First, with the 68 separate channels it is believed that flow will not enter all of them evenly. If this happens then the grid plate/divider assembly would be susceptible to hot spots and potential melting. The next concern is that due to the large number of channels and turns within those channels that the pressure drop through the grid plate/divider assembly will be unacceptably high. For the purposes of this paper the pressure drop is not investigated due to the unacceptable nature of the flow unevenness seen below. Had the flow been even within the 68 channels, then the pressure drop would also have been investigated.

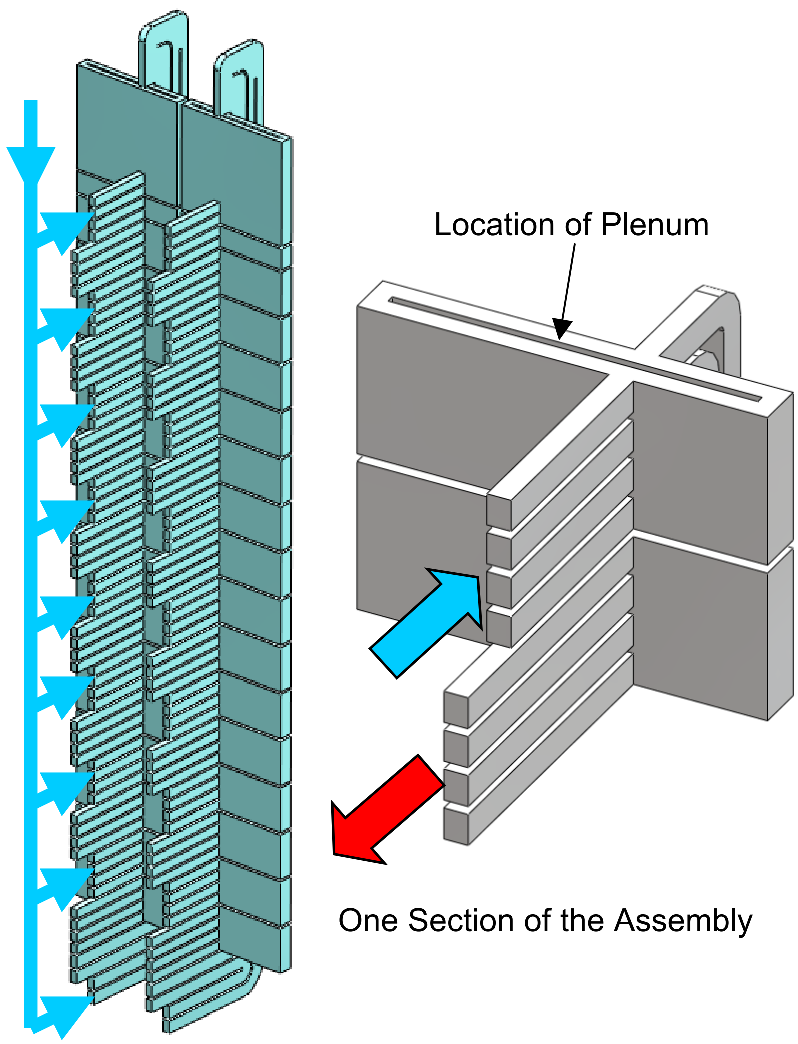

Figure 10. The grid plate/divider assembly showing the helium volume. Flow must enter 68 channels before following a complicated flow path.

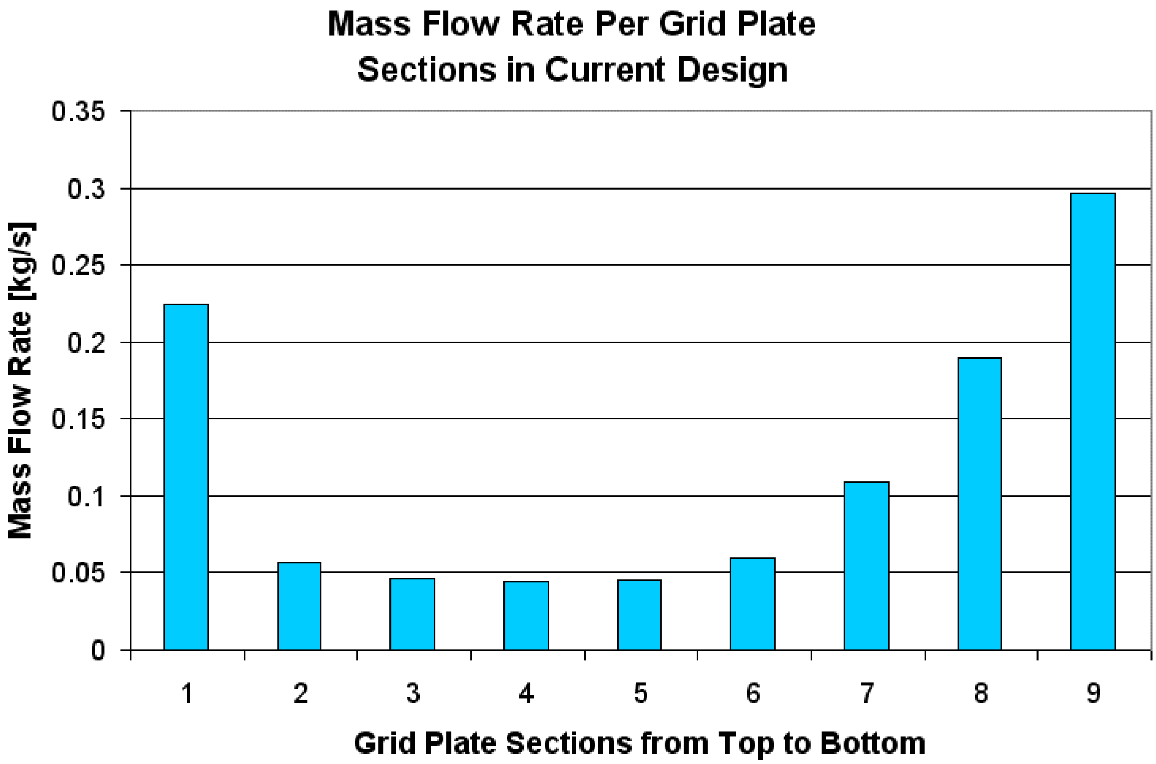

Figure 11. Results illustrating the uneven flow to the sections of the grid plate/divider assembly within the current design. Each section is a separate group of four channels except for section 9 with two channels.

b. Analyzing the Grid Plate/Divider Assembly

ANSYS CFX was used to analyze the current design and a proposed redesign. The results of the current design illustrated that flow is highly uneven to each section of the grid plate/divider assembly. These results can be seen in Figure 11. Three of the nine sections exhibit flow of less than 0.05 kg/s while two sections exhibit flow of greater than 0.20 kg/s. This clearly demonstrates that flow is not entering the 68 channels evenly. This can be seen in Figure 12.

c. Redesigning the Grid Plate/Divider Assembly

Based on the results of the uneven flow in the current design an improved design was established which would eliminate much of the parallel flow and decrease the number of turns through which the helium must pass. The improved design routes flow into 6 channels instead of 68. When helium enters, it flows vertically up the grid plates on the back side of the dividers. At the top it turns over to the front of the dividers and flows down. Then flow enters the dividers in the top half of the assembly from the front side. Inside the dividers helium splits and flows down the length of the assembly. In the bottom half flow combines and enters the grid plates once again, where it flows to the bottom of the assembly. After turning around to the back of the dividers,

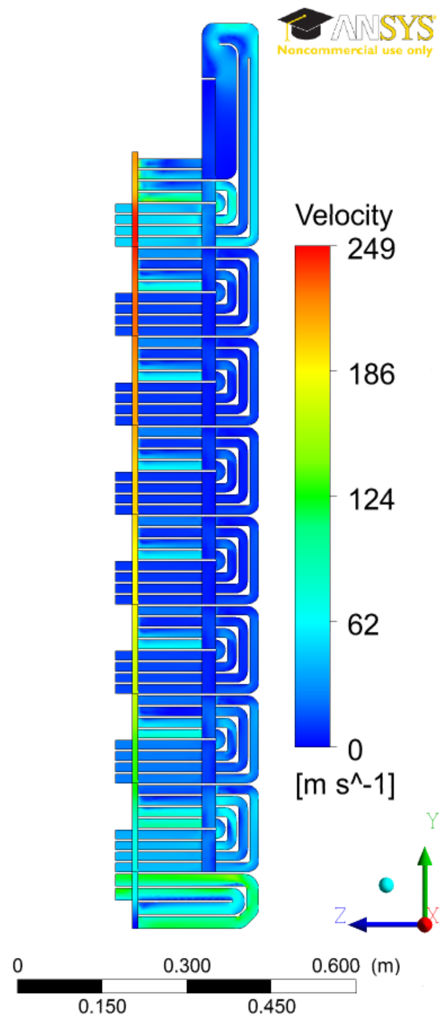

Figure 12. ANSYS CFX results for helium velocity within the grid plate/divider assembly of the current design.

the helium flows vertically to the exit of the assembly. This geometry, along with ANSYS CFX results, can be seen in Figure 13.

The results from the simulation for the improved design show that flow is even in terms of how much is delivered to each of the three channels (only half of the full grid plate/divider assembly was analyzed, thus there were three entry channels and three exit channels). The values for mass flow rate from the three exit channels were 0.347, 0.383, and 0.336 kg/s. Those values are much more even than the values for the sections of the current design, as was seen in Figure 11.

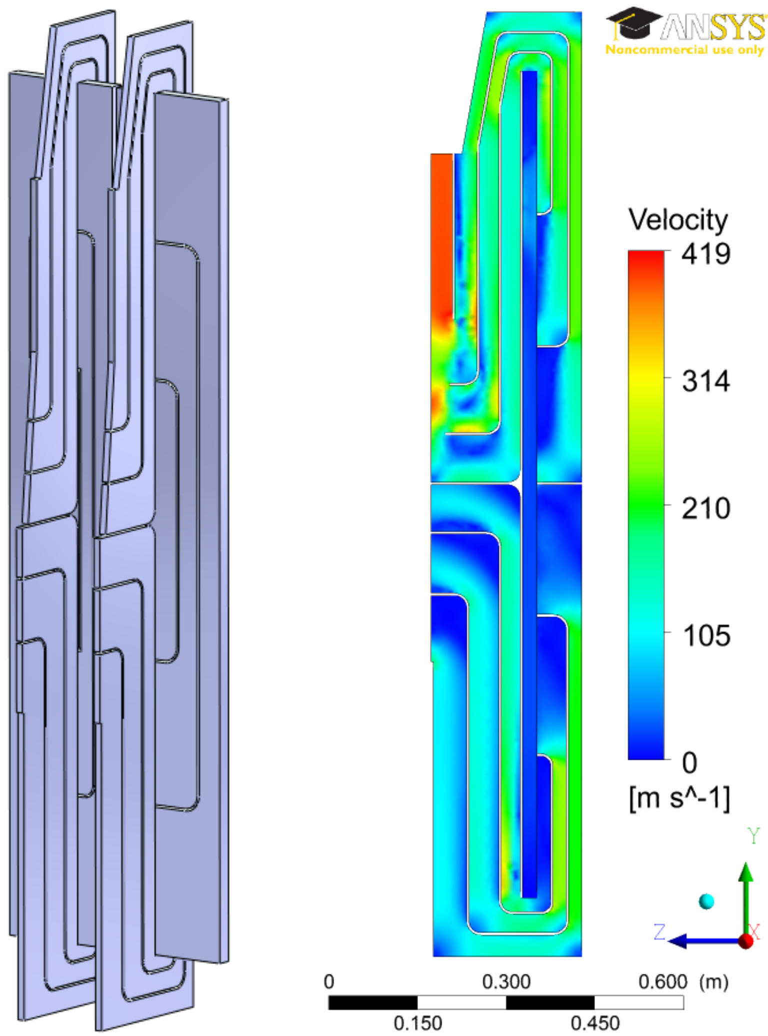

Figure 13. The geometry of the proposed redesign for the grid plate/divider assembly (left) and the ANSYS CFX results for helium velocity within the redesigned assembly.

One thing of concern is the velocity value of 419 m/s seen in the results in Figure 13. This can easily be alleviated with a graduated entry region introducing the helium to the grid plate/divider assembly. Also of concern are the regions of minimal flow seen in dark blue in Figure 13. The improved design would benefit from baffles within the structure to help steer the helium more evenly and to provide more structural support for the pressure difference between the helium and the PbLi.

What the improved design provides is a simpler flow path and more even flow. Despite not investigating pressure drop it is believed that the pressure drop within the improved design would be much less than the current design. This can be investigated further.

CONCLUSIONS

Analysis has been performed to demonstrate problems within the helium flow path of the US DCLL test blanket module. Once these problems were understood, improvements to the helium flow path were created and analyzed. These improvements demonstrated the following:

1. The PbLi hot spot can easily be adjusted.
2. Flow in the helium entry region can be made more even with a full redesign.
3. Modifications can be made to increase the flow uniformity through the first wall header regions.
4. A new grid plate/divider assembly would eliminate the point of structural stress and provide more even flow that would eliminate the potential for hot spots.

Putting all the improvements together into a full redesign would greatly simplify the overall helium flow path. The changes presented in this paper only modified the helium volume within the TBM while not requiring any changes to the PbLi flow path other than the channel drain location. Further work includes implementing and optimizing the improvements in a fully new TBM design.

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