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A. Khodak, P. Titus, T. Brown, J. Klabacha, H. Neilson

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3D THERMAL ANALYSIS FOR CFETR PRE-SUPERHEATED WATER COOLED BLANKET

A. Khodak, [a]* P. Titus, [a] T. Brown, [a] J. Klabacha, [a] H. Nielsen, [a] X. Cheng, [b] S. Liu [b]
[a]*PPPL, PO Box 451, Princeton University, NJ, 08543 USA*
[b]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, Anhui, China*
akhodak@pppl.gov

Initial CFETR (China Fusion Engineering Test Reactor), blanket design, includes water cooled ceramic breeder blanket (WCCB) operating in pre-superheated regime. This condition allows efficient cooling; however it requires accurate control and analysis to avoid zones with excessive heat flux. Analysis of the coolant flow and heat transfer in CFETR Pre-Superheated Blanket was performed using ANSYS CFX and included: 3D coolant flow analysis, external volumetric and surface heating effect, and two-phase wall boiling. ASIPP CAD Model imported directly into ANSYS Workbench Design Modeler as a STEP file. Fluid volume is created using Design Modeler Fill operation, and converting Inlet and Outlet surfaces. This operation ensures that there are no leakages in the model. Meshing was performed using CFX method available within the framework of the ANSYS mesh generator. Application of tetrahedral elements for meshing of the internal regions allowed automatic mesh generation. Advanced sizing functions were used with automatic mesh inflation depending on wall proximity and curvature. Combined mesh of 454 million elements was initially created with 6 layers of boundary elements. To make mesh more manageable smaller model was created using periodic and symmetrical nature of the blanket geometry. Symmetry conditions are used on the sides of the model for solid and liquid parts. Combined mesh of 17 million elements was created with 5 layers of boundary elements. Conjugated heat transfer analysis was performed using ANSYS CFX software. CFX software allows solution of heat transfer equations in solid and liquid parts, and solution of the flow equations in the liquid parts. Coolant flow in that was assumed turbulent and was resolved using Reynolds averaged Navier-Stokes equations with Shear Stress Transport turbulence model. RPI model for wall driven boiling is used. Inhomogeneous two-phase flow is resolved solving two sets of momentum and energy equations for liquid and steam. Results showed ability of the model to simulate two-phase boiling flow in complex configuration.

I. INTRODUCTION

One of the CFETR blanket variants is a Water Cooled Ceramic Breeder WCCB operating at reduced coolant pressure level of 7 MPa. This condition allows wall boiling condition in the blanket with superheated steam at the outlet. Such scheme has several advantages namely, efficient heat transfer at constant temperature, due to phase change, low neutron absorption by the superheated steam flowing in the first wall channels to the neutrons, as well as reduced structural requirements due to lower pressure levels. Detailed description of the CFETR WCCB designs can be found in [1, 2]. Figure 1. shows structure of the blanket including U shaped first wall, ceramic breeders and neutron multipliers in the form of pebble beds. Ceramic breeders are two sizes mixed pebble beds of Li_2TiO_3 and $Be_{12}Ti$. Beryllium pebble beds are used as independent neutron multiplier.

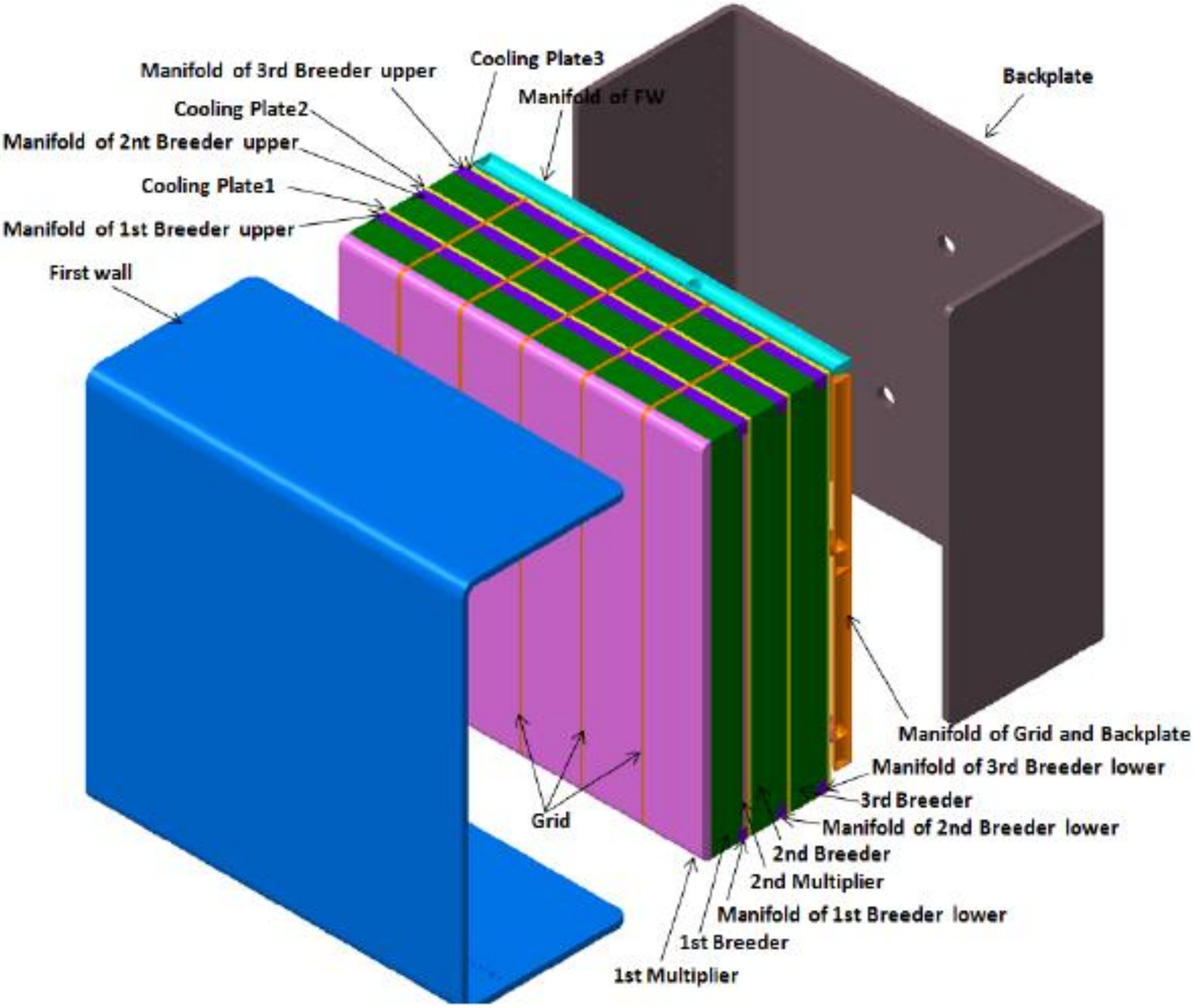

Fig. 1. CFETR Water Cooled Ceramic Breeder (WCCB) blanket concept

Conjugated heat transfer analysis was performed using ANSYS CFX software. CFX software allows solution of heat transfer equations in solid and liquid part, and solution of the flow equations in the liquid part. Coolant flow in the DFW was assumed turbulent and was resolved using Reynolds averaged Navier-Stokes equations with Shear Stress Transport turbulence model. Detail description of the models used in the analysis is presented in [3]. Figure 2. shows solid and liquid parts of the heat transfer analysis, as well as solid-fluid interface surface. Thermal and hydraulic analysis of the WCCB was performed using conjugated heat transfer approach, in which heat transfer was resolved in both solid and liquid parts, and simultaneously fluid dynamics analysis was performed only in the liquid part. This approach includes interface between solid and liquid part of the system. In such interface conservation of the heat flux is assumed together with the non-slip wall boundary conditions for the liquid. Since the flow in the cooling system is for the most part turbulent, non-slip wall boundary conditions take the form of wall functions.

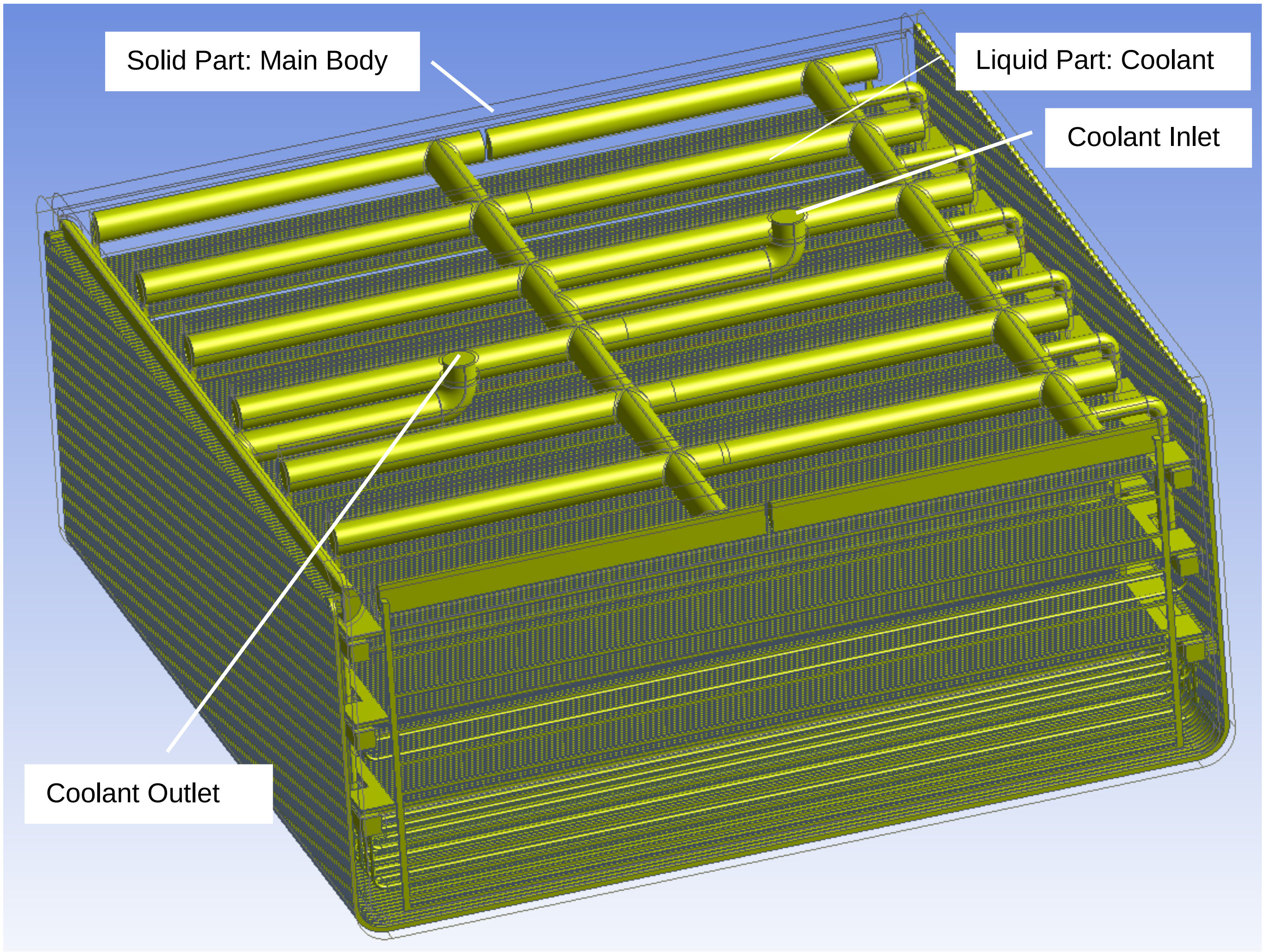

Fig. 2. Solid and Liquid Parts of the Blanket

II. HEAT TRANSFER ANALYSIS

II.A. Model Import and Simplification

ASIPP CAD Model imported directly into ANSYS Workbench Design Modeler as a STEP file. Fluid volume is created using Design Modeler Fill operation, and covering Inlet and Outlet surfaces. This operation ensures that there are no leakages in the model. No other modifications of the model were performed.

II.B. Geometric Model Meshing for Fluid Flow and Heat transfer calculations

Meshing was performed using CFX method available within the framework of the ANSYS Workbench mesh generator. Application of tetrahedral elements for meshing the internal regions, allowed automatic mesh generation even in most complex cases. Advanced sizing functions were used with automatic mesh inflation depending on wall proximity and curvature. Combined mesh of 454 million elements was initially created with 6 layers of boundary elements. Figure 3 shows representation of the mesh. Smaller mesh of 154 million elements was created with 3 layers of boundary elements. Boundary layer elements created for this mesh are presented on Figure 4

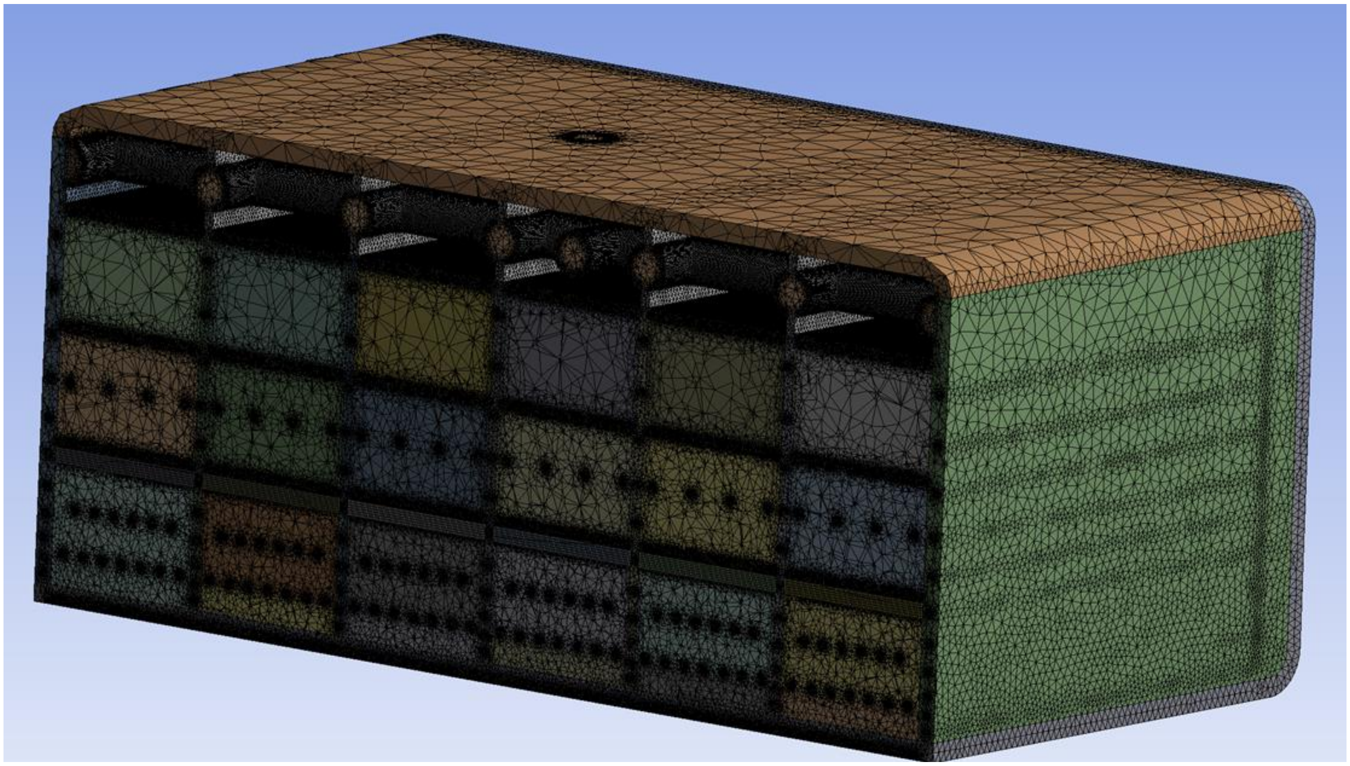

Fig. 3. Combined mesh of 454 million elements

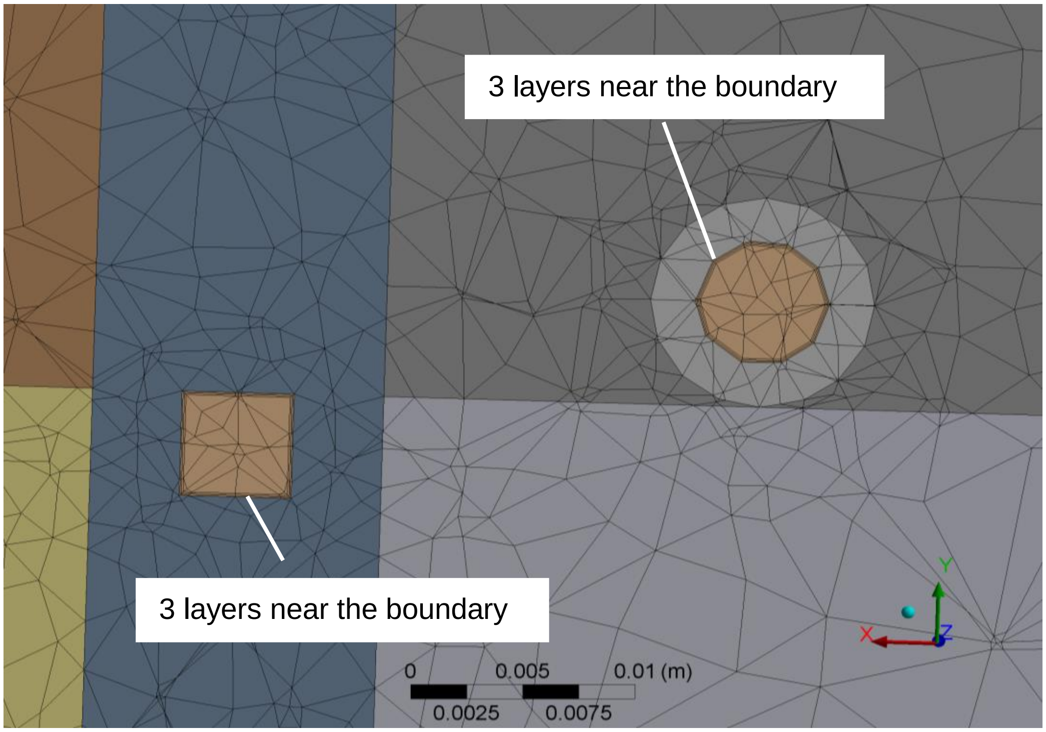

Fig. 4. Boundary layer elements on 154 million element mesh

To make model more manageable smaller mesh was created using periodic and symmetrical nature of the blanket geometry. Symmetry conditions are used on the sides of the model for solid and liquid parts. Combined mesh of 17 million elements was initially created with 5 layers of boundary elements

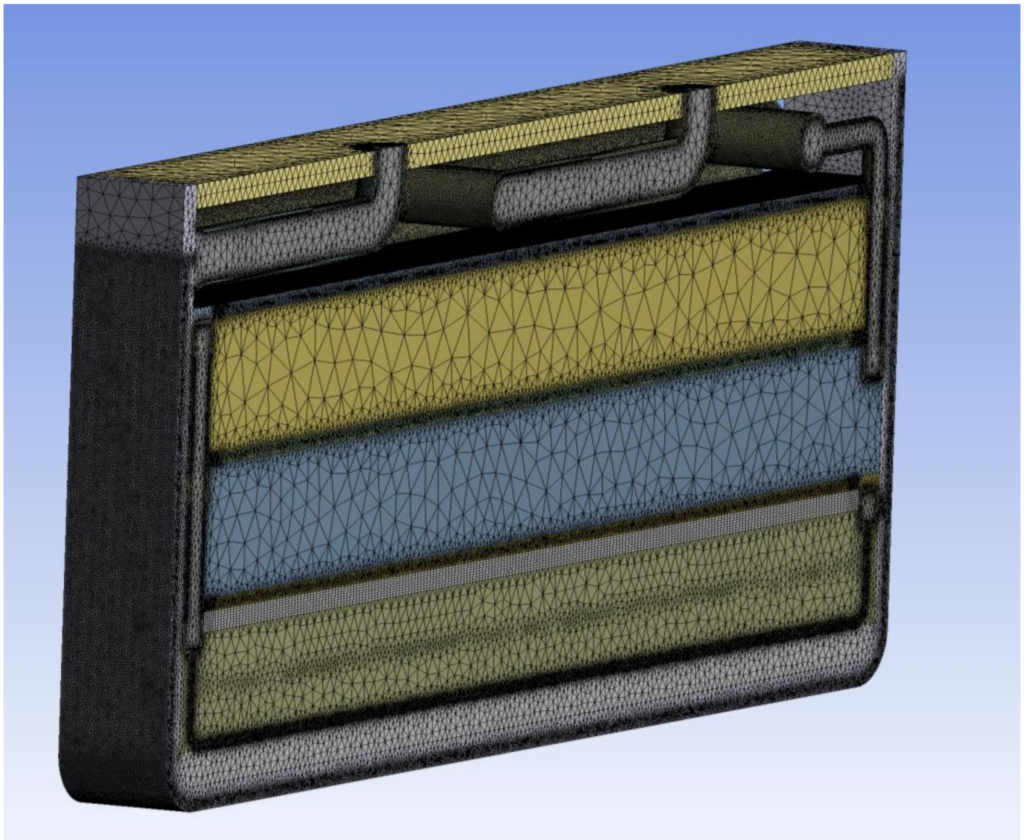

Fig. 5. Partial mesh of 17 million elements.

II.C. External Thermal Loads

Volumetric Heat Source distribution generated externally by Attila software can be imported into CFX as described in [3]. In current analysis approximation of the ASIPP results [2] was used as shown on Figure 6. Constant surface heat flux of 0.3 MW/m2 was imposed on a front wall (Figure 7).

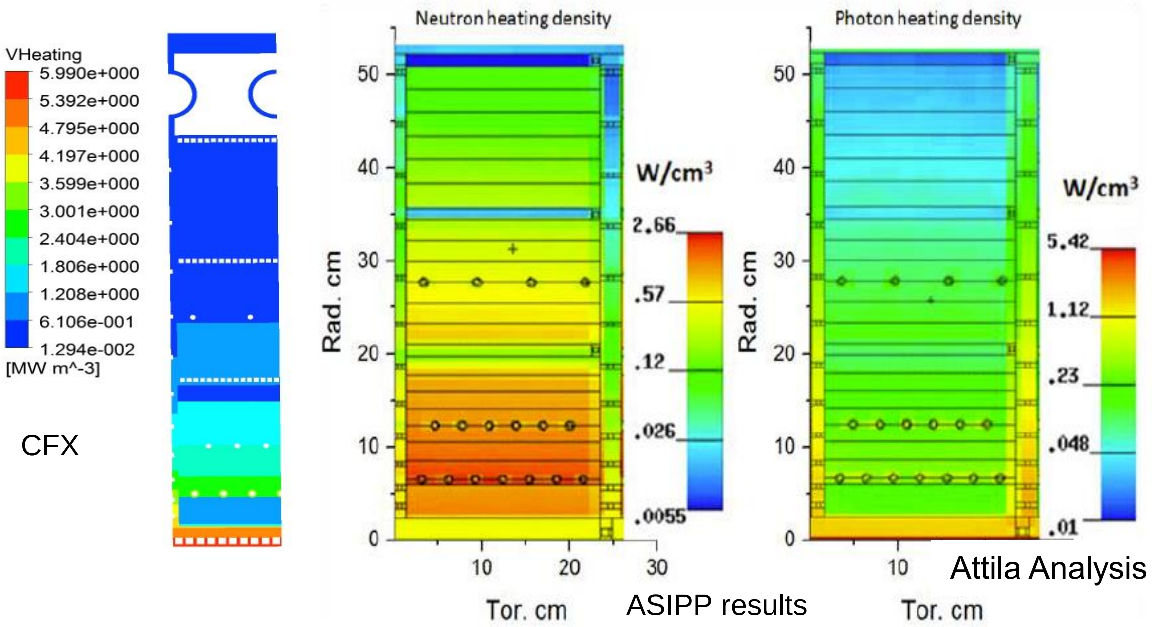

Fig. 6. Volumetric heating distribution.

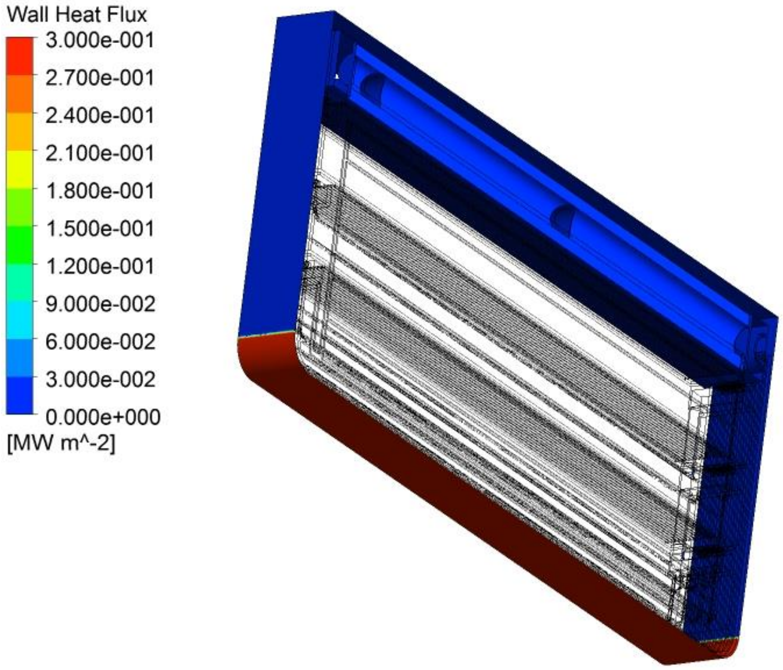

Fig. 7. Surface heat distribution.

II.D. Material Properties, and Wall Boiling Model

IAWPS properties of water and steam [4] are included in ANSYS-CFX. The following values were used for thermal conductivities of the solid materials:

$\lambda_{\mathrm{Breeder}} = 0.2\lambda_{\mathrm{Li2TiO3}} + 0.8\lambda_{\mathrm{Be12Ti}}$

$\lambda_{\mathrm{Li2TiO3}} = 1.26[\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})]\cdot(1+0.08\cdot(T-420[^{\circ}\mathrm{C}])/(775[^{\circ}\mathrm{C}]-420[^{\circ}\mathrm{C}]))$ [5]

$\lambda_{\mathrm{Be12Ti}} = 2.5[\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})]\cdot(1+2\cdot(T-0[^{\circ}\mathrm{C}])/1000[^{\circ}\mathrm{C}])$ [5]

$\lambda_{\mathrm{Multiplier}} = \lambda_{\mathrm{Be}} = 3.5[\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})]\cdot(1+(T-0[^{\circ}\mathrm{C}])/1000[^{\circ}\mathrm{C}])$ [6]

$\lambda_{\mathrm{Steel}} = 60.5[\mathrm{W}/(\mathrm{m}\cdot\mathrm{K})]$

Other properties used can be found in [2,3]

Current analysis used ANSYS CFX RPI Evaporation Model in which Inhomogeneous two-phase flow is resolved solving two sets of momentum and energy equations for liquid and steam. Detailed description of the model and validation results can be found in [7]

III. ANALYSIS RESULTS

Temperature distribution in the blanket is presented on Figure 8. Results show that water cooling system can create efficient breeding regime in the blanket. Main source of heat of the blanket is volumetric heating, which depends on the material properties and also declines at exponential rate from front to back for the same material. Maximum temperature in DSM is below 610K.

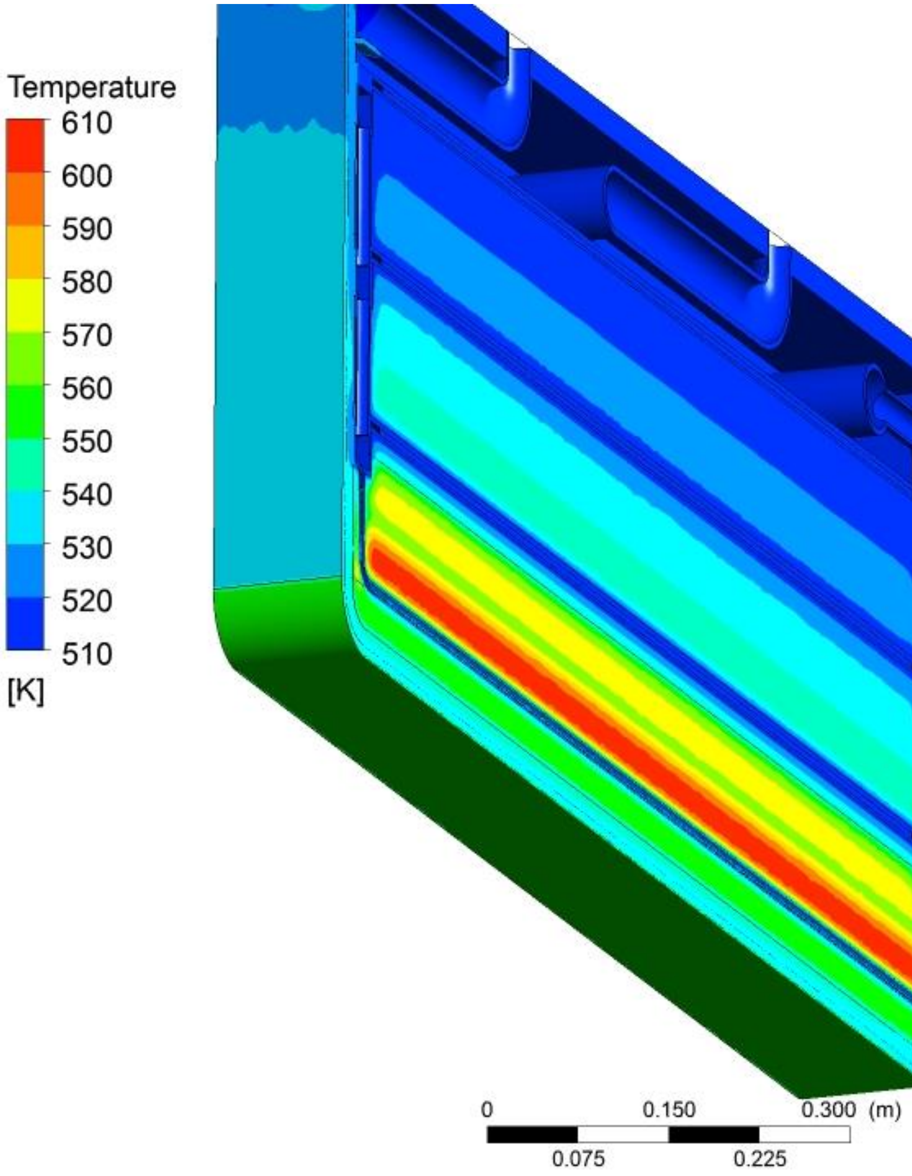

Fig. 8. Blanket temperature distribution.

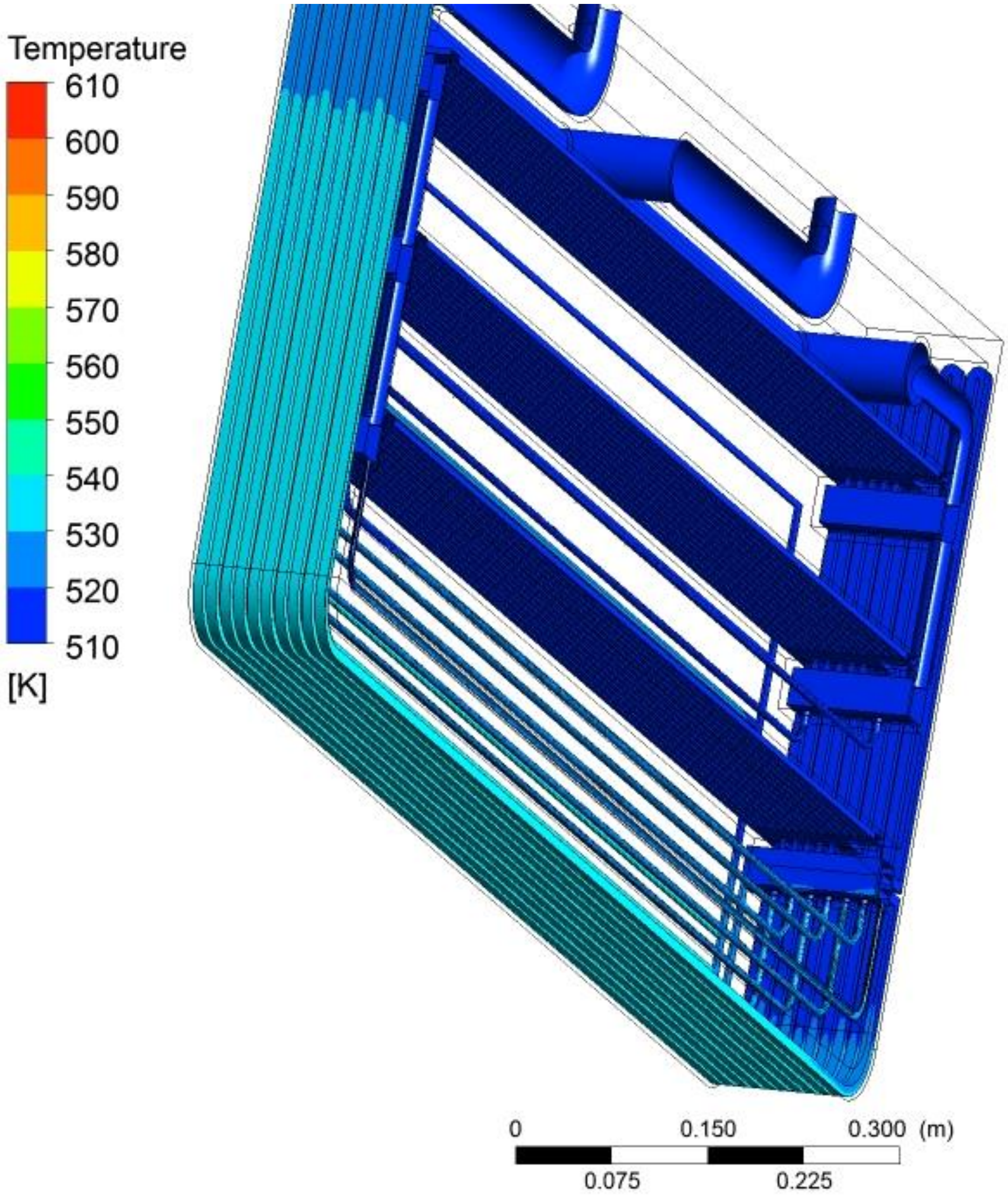

Fig. 9. Coolant temperature distribution.

Figure 9 shows coolant temperature distribution. Due to the phase change condition coolant temperature distribution is very uniform without visible hot spots. Temperature of the cooling channel walls changes within 20K range creating favorable conditions for breeding.

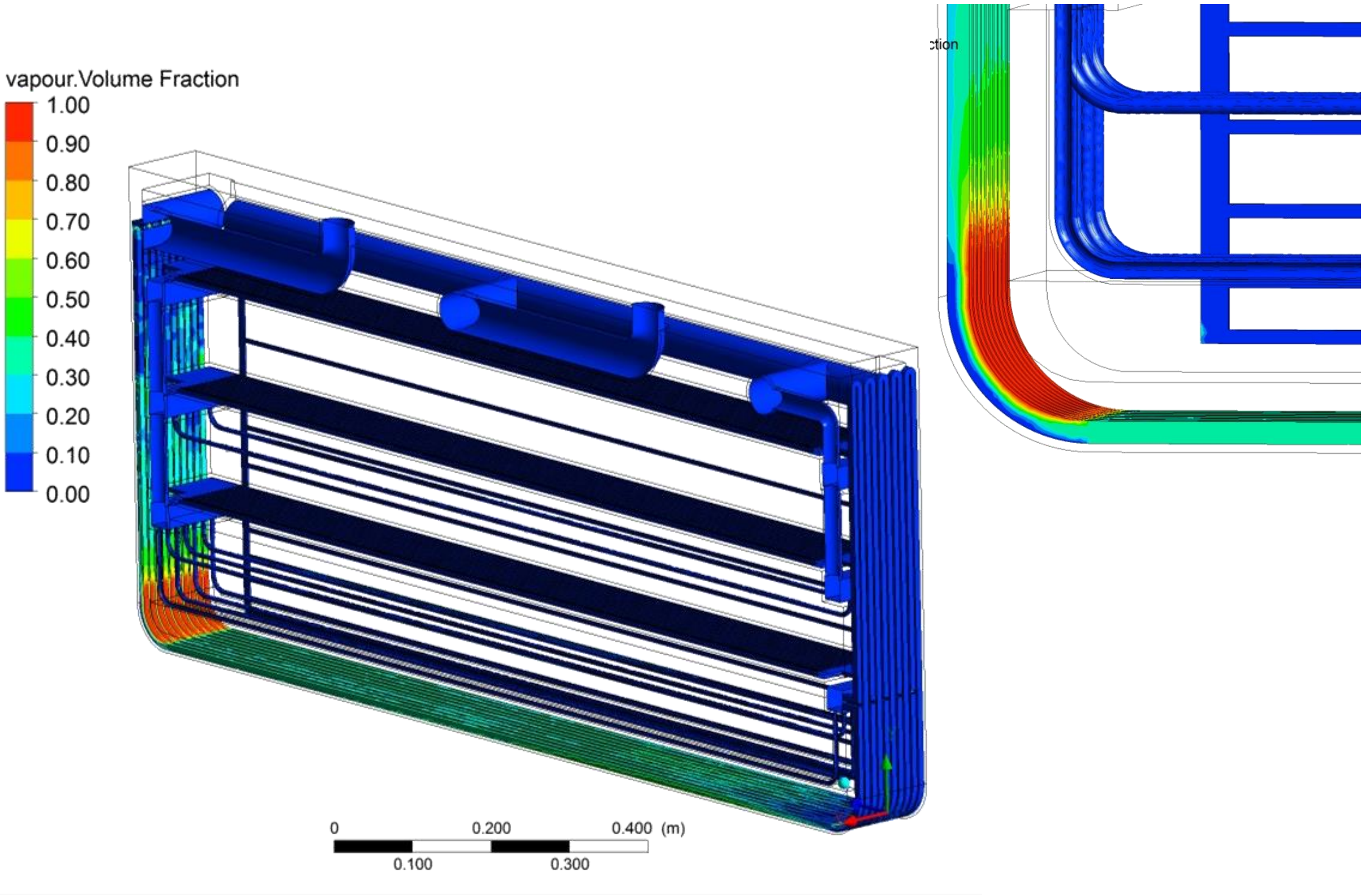

Fig. 10. Coolant vapor volume fraction distribution.

Vapor volume fraction distribution in the coolant system is presented on Figure 10. Vapor fraction is mostly created in the front wall portion of the blanket cooling system. Noticeable separation of liquid and vapor phase current is created at the turn of the coolant channels which follow the front wall geometry. Denser liquid portion of the coolant is pushed by inertia force towards the outer edge of the turn, creating high vapor volume fraction near the inner edge. This is favorable situation from heat transfer point of view since liquid coolant is concentrated closer to the region affected by both volumetric and surface heating.

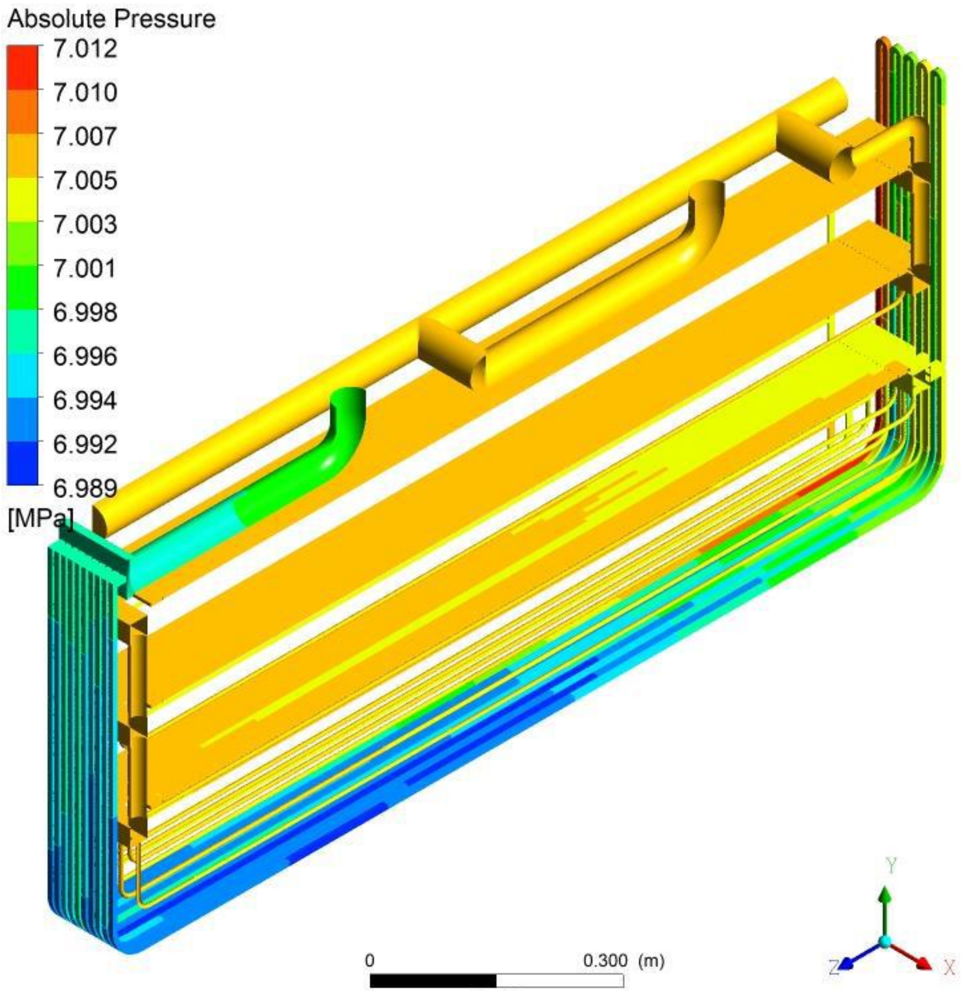

Fig. 11. Pressure distribution in the blanket.

Predicted pressure distribution in the blanket is presented on Figure 11. Pressure drop level of 0.03MPa is close to the one targeted by the design condition in [2].

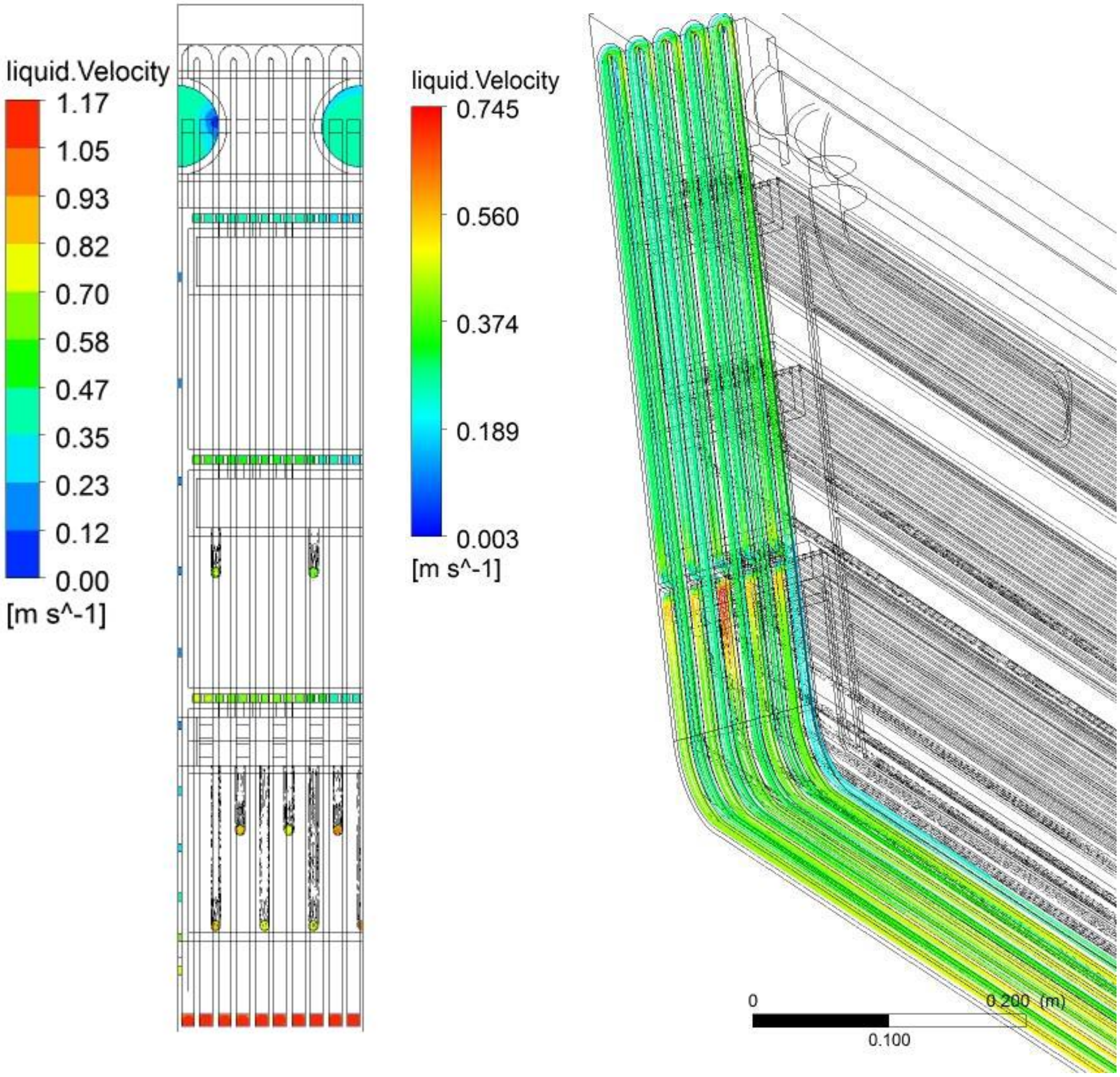

Fig. 12. Velocity distributions and coolant streamlines in the WCCB coolant system.

Figure 12 shows velocity distributions in the WCCB coolant system. Three-dimensional analysis allows detecting local high velocity zones as well as checking efficiency of individual coolant channels, indicating the areas where current design can be further optimized.

IV. CONCLUSIONS

Numerical simulations of the coolant flow in pre-superheated water cooled ceramic breeder blanket were performed using ANSYS CFX RPI model and included: 3D coolant flow analysis; external volumetric and surface heating, and wall boiling using RPI model.

Analysis results show validate blanket design, and show ability of the CFETR WCCB pre-superheated blanket to create favorable conditions for tritium breeding.

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