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Flow Optimization Studies for the ITER Shield Modules

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Abstract

A 3-d, 4-channel prototypical model representing a subset of an ITER neutron shield module was analyzed using computational fluid dynamics. We used this model to optimize the radial gaps in the coaxial flow drivers along with the depth of the radial holes or channels in the stainless steel modules. In addition to redirecting the flow first to the back of the module and then to the front, the flow drivers increase the pressure drop in the radial tubes to allow for more uniform flow distribution from the back-drilled manifolds. They also increase the fluid velocity near the wall for improved heat transfer. We sized the flow drivers to allow for 2, 3 and 4-millimeter (mm) gaps along the annuli. The depths of the radial channels below the manifold were 10, 15, 20, 25, and 30 mm for each of the 2, 3, and 4 mm radial gaps. The objective of the study was to ascertain if a fixed 90-mm length on the bottom flow driver could be utilized for radial channels of varying depth below the back-drilled manifold and still provide adequate cooling for the neutron thermal load. Our group also performed an optimization of the gap around the tee vane in the shield module front header. Tee-vane gaps of 1, 2 and 3 mm were studied to assess the flow bypass and wall velocities at the end of the model. In this article, we present the results of a full matrix of flow simulations using the CFdesign CFD package. The study indicates that a 90-mm-long flow driver with a 4-mm radial gap can keep the steel around the radial tubes sufficiently cool up to 30 mm beneath the back-drilled manifold. We also discovered that flow bypass through the end gap on the tee vane is relatively small and has little effect on cooling of the front cover plate for gap sizes as large as 3 mm.

Introduction

This paper will look at how different geometry flow drivers will affect flow, pressure, and temperature in a 4-channel prototypical model, as shown in Figure 1, representing a subset of an ITER neutron shield module through a computational fluids analysis tool, CFdesign.

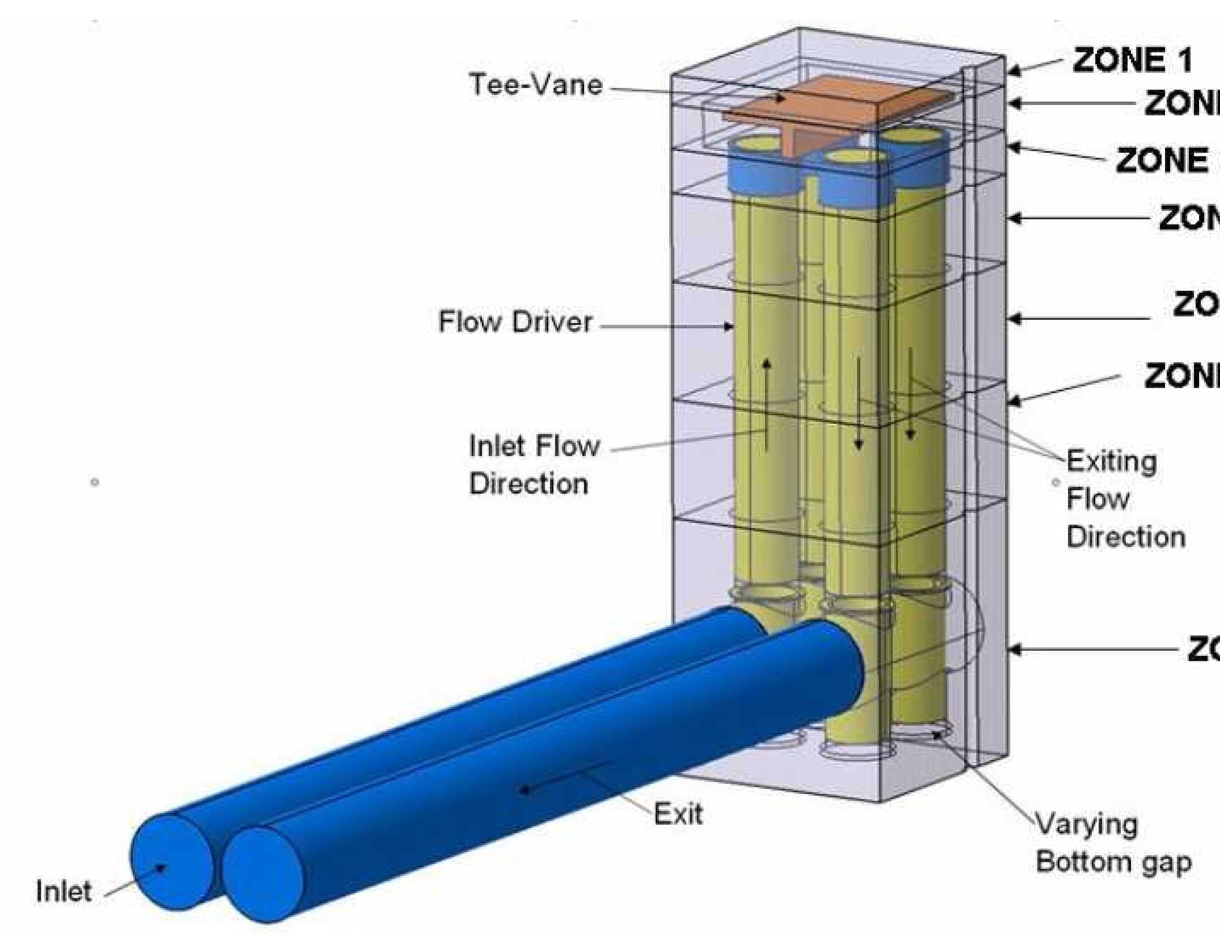

Figure 1. Simplified 4 hole model representation of ITER neutron shield module.

From the analysis results we hope to determine if it might be possible to fabricate a constant 90-mm length flow driver for the majority of the shield module(s) rather than creating various length configurations for each different drilled depth. Figure 2 shows an example of an ITER neutron shield module; the medium sized bored holes (approximately 50-mm in diameter) will be where the flow drives are placed. The flow analysis will be a 2, 3 and 4 mm gap along the upper and lower annuli and 10, 15, 20, 25, and 30 mm depths of the radial channels below the bottom of the lower flow drivers.

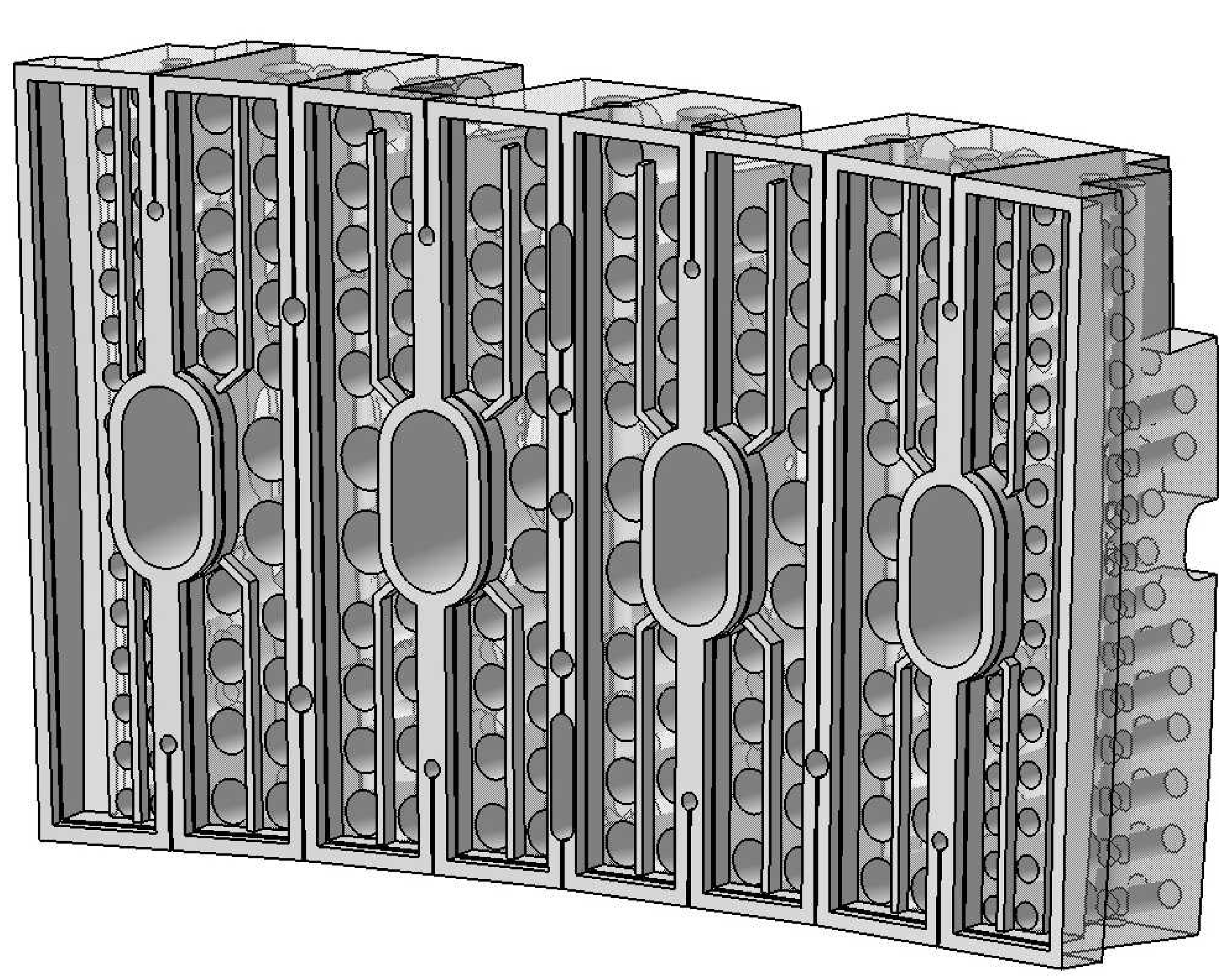

Figure 2. An example of an ITER neutron shield module.

After the flow results are analyzed we will focus on how these changes will effect of the cooling the simplified model. The ideal result for each analysis would be a balanced flow system to provide optimal cooling to the outer surface of the manifold. The concern for cooling is due to the high neutronic heating, the approximate value is 5 MW/m^3, seen at the shield module. We were also concerned about the end conditions of the tee-vane due to the high mechanical stress. In order to reduce the stress, small gaps were added on each end. The concerns were the effects of the flow over, under, and around the tee vane and how the change would effect the cooling in the tee-vane region.

Results

From the results it could be determined that the overall ideal situation for flow would be the 2-mm gap and 15-mm bottom gap case because this gives an even velocity flow exiting the upper annuli into the lower flow drivers and fairly good flow distribution in the 15-mm bottom gap as shown in Figure 3 and referring to Figure 4 the velocity values show an almost constant flow 5-mm below the flow driver and the highest flow values for all the cases. To reduce the stagnations in the corners chamfers or radii could be added. Also by adding radii to the lower flow drivers could aide in allowing for a smoother transition from the exit of the upper annuli flow.

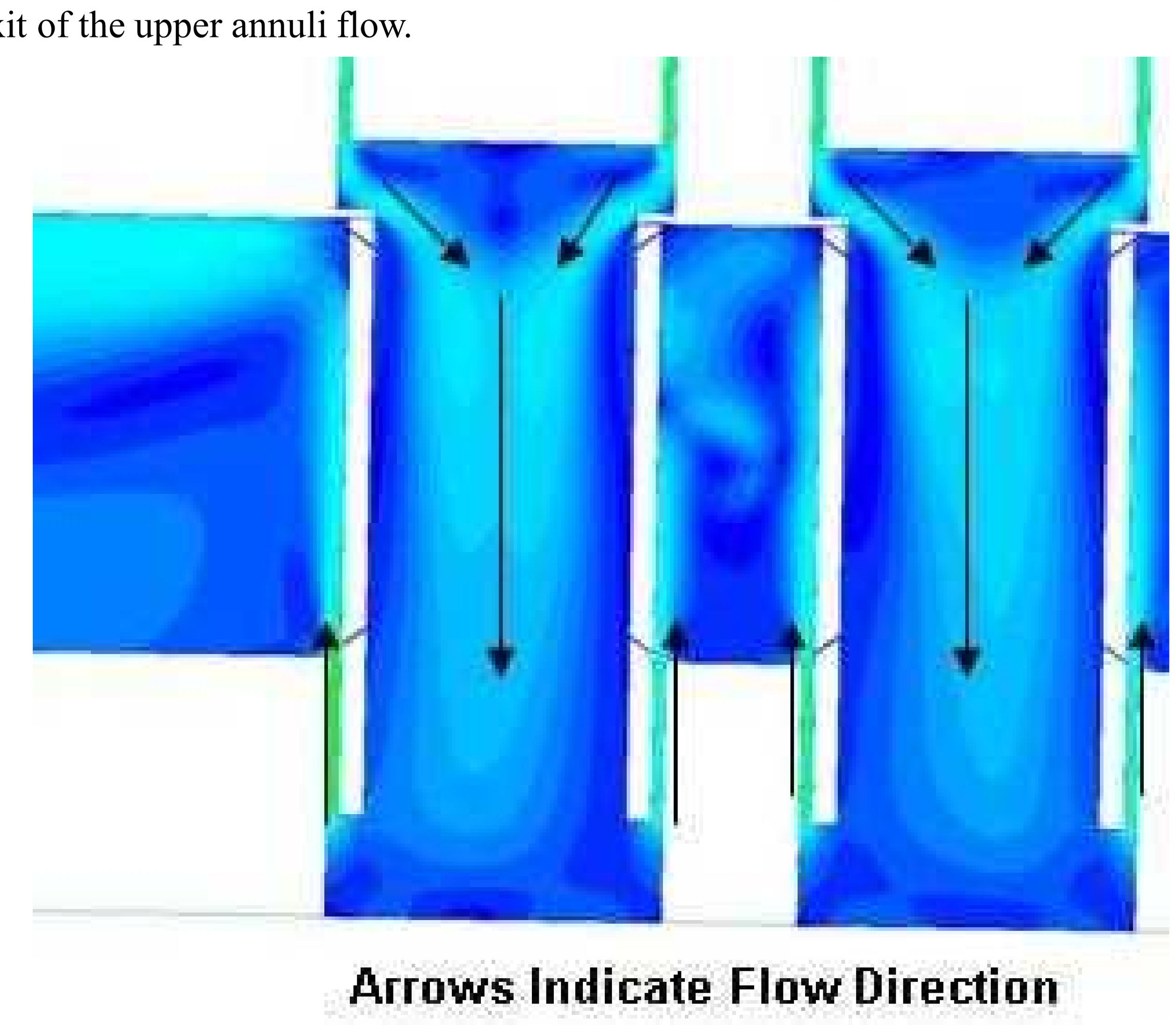

Figure 3. 2-mm gap (46-mm diameter flow driver) and a 15- mm bottom gap for the exit flow side.

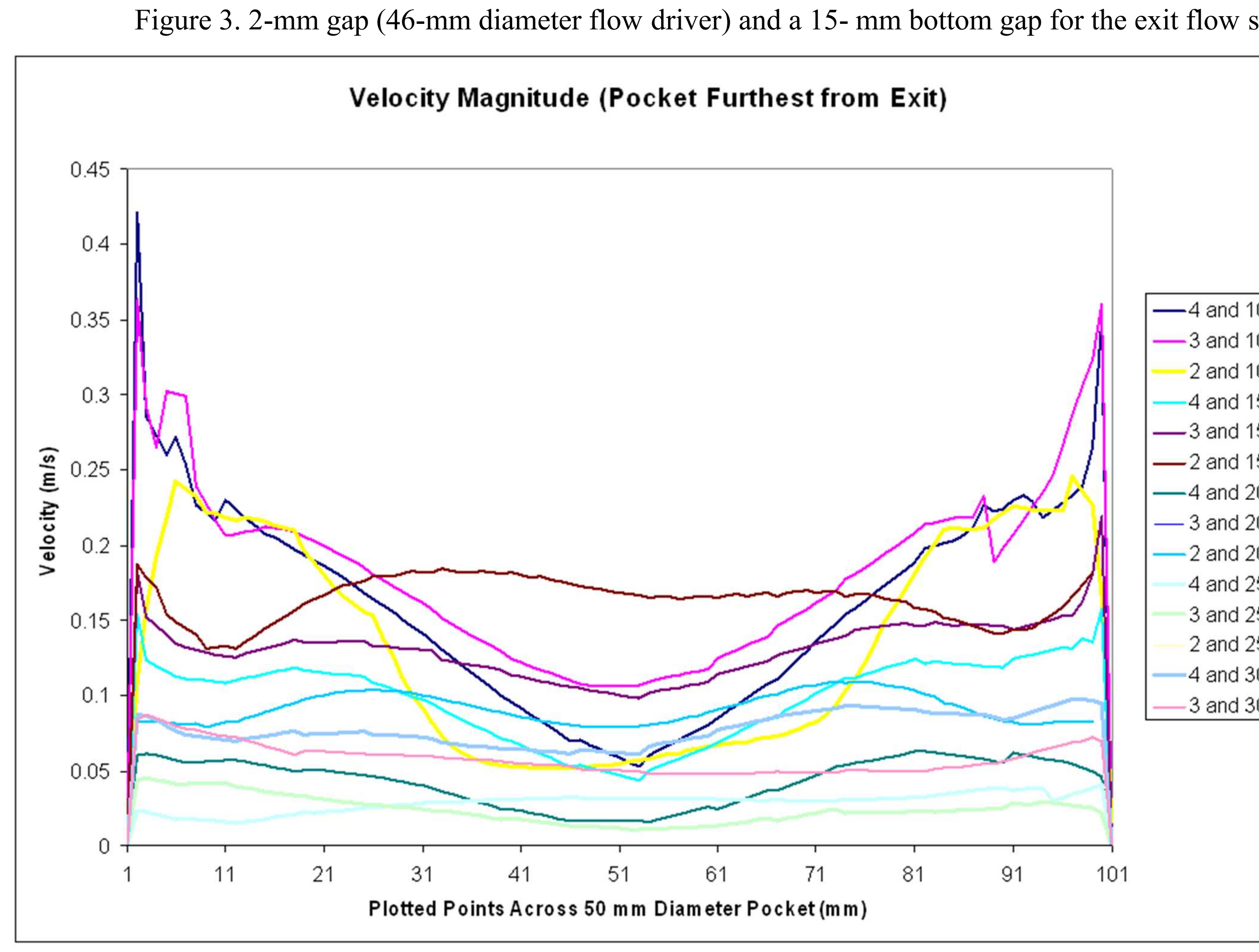

Figure 4. The figure shows the velocities 5 mm below the flow drivers with 100 linear plotted points.

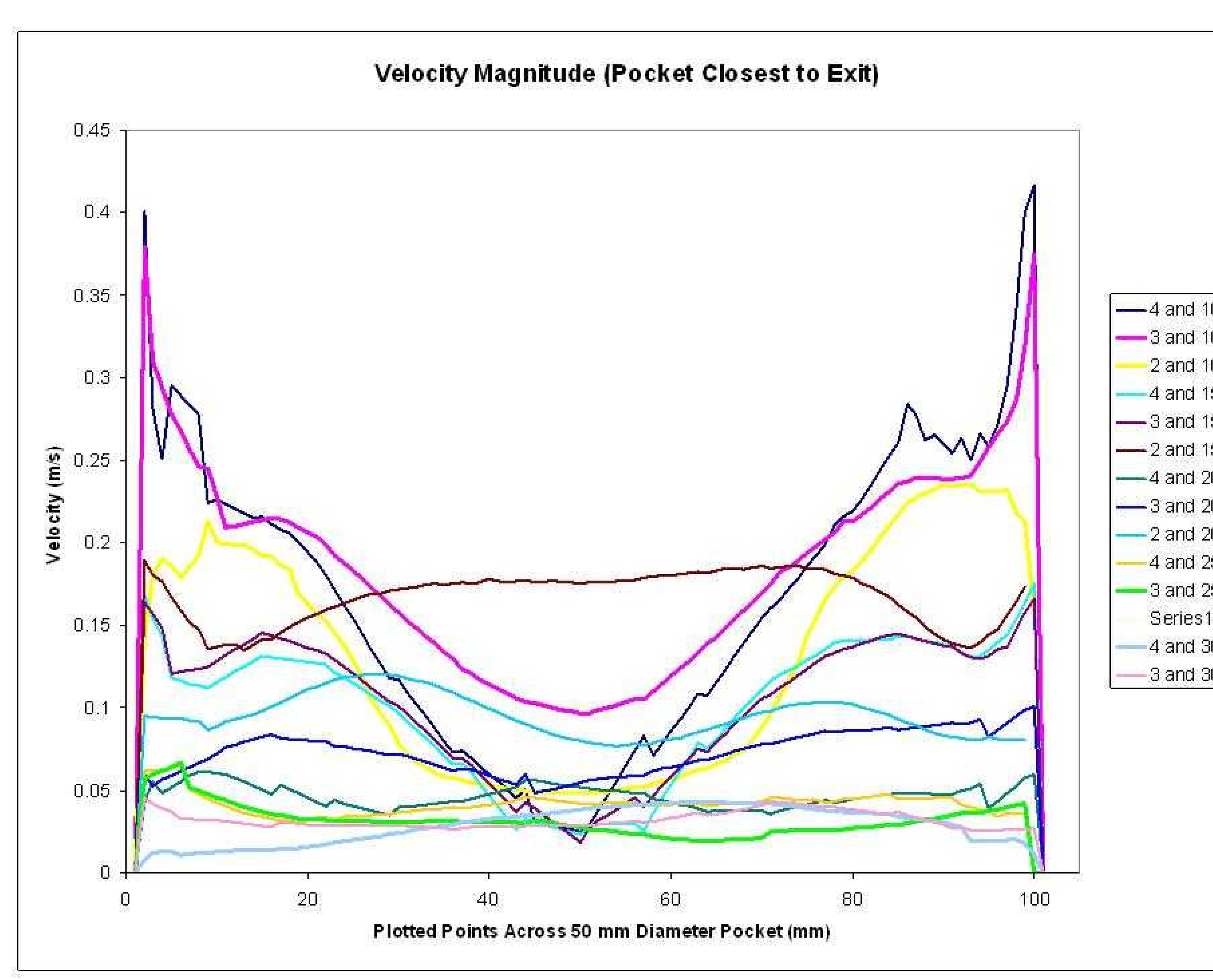

Figure 5. The figure shows the velocities 5 mm below the flow drivers with 100 linear plotted points but for a different flow driver and pocket.

Figure 4 and 5 shows the majority of the flow rate cases analyzed. The velocities were taken 5-mm below the lower flow driver in a linear plot parallel to the inlet and exit flow tubes axis. The majority of the flow velocities fell within the range of 0 to 0.15 m/s for the pocket furthest from the exit and 0 to 0.1 m/s for the pocket and flow drivers closet to the exit.

From the velocity profile of the 4-mm gap case with the same 30-mm bottom gap it appears that this was not the most ideal flow scenario. The flow shows almost not flow in the lower portion of the gap. This would result in pooling of water which in turn could cause unnecessary heating in these regions.

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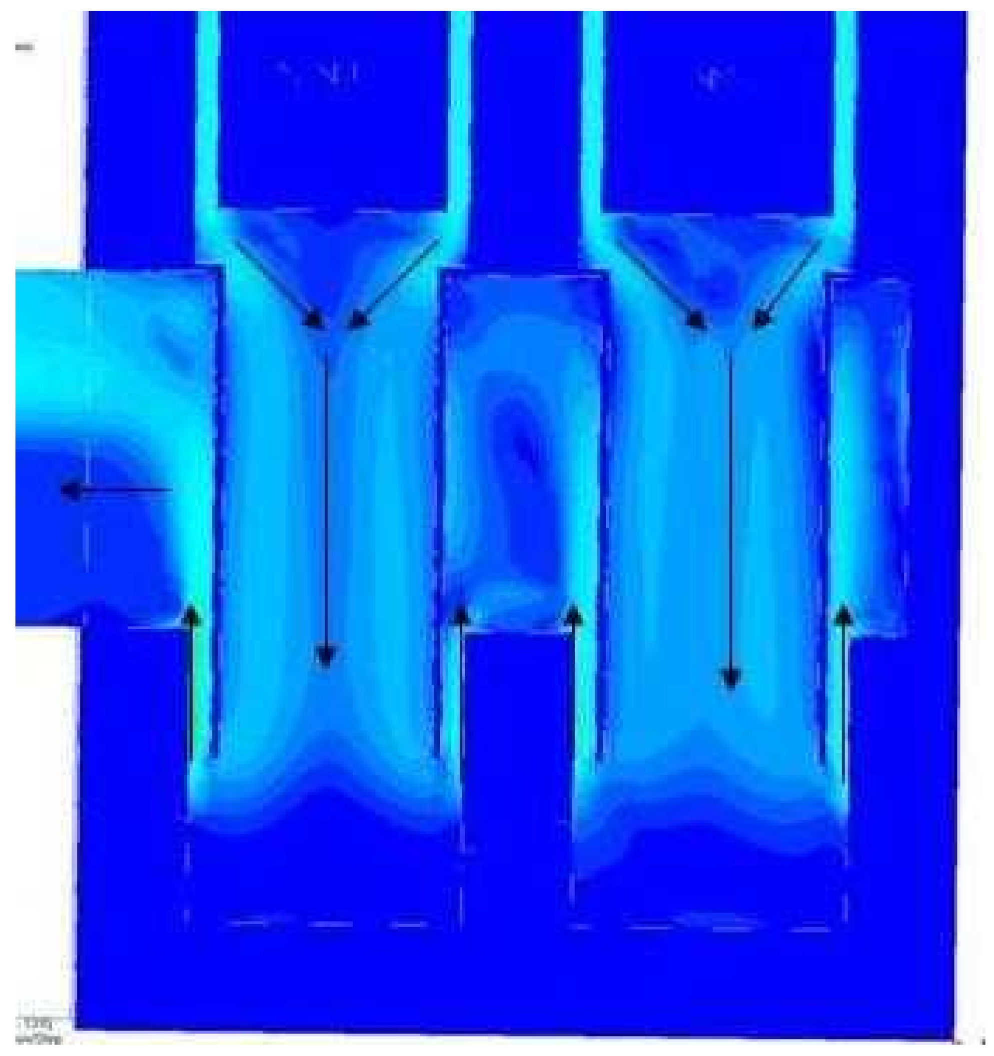

Figure 6. 4 mm gap (42 mm diameter flow driver) and a 30 mm bottom gap for the exit flow side an d as indicated in Figure 5 the arrows show the flow direction.

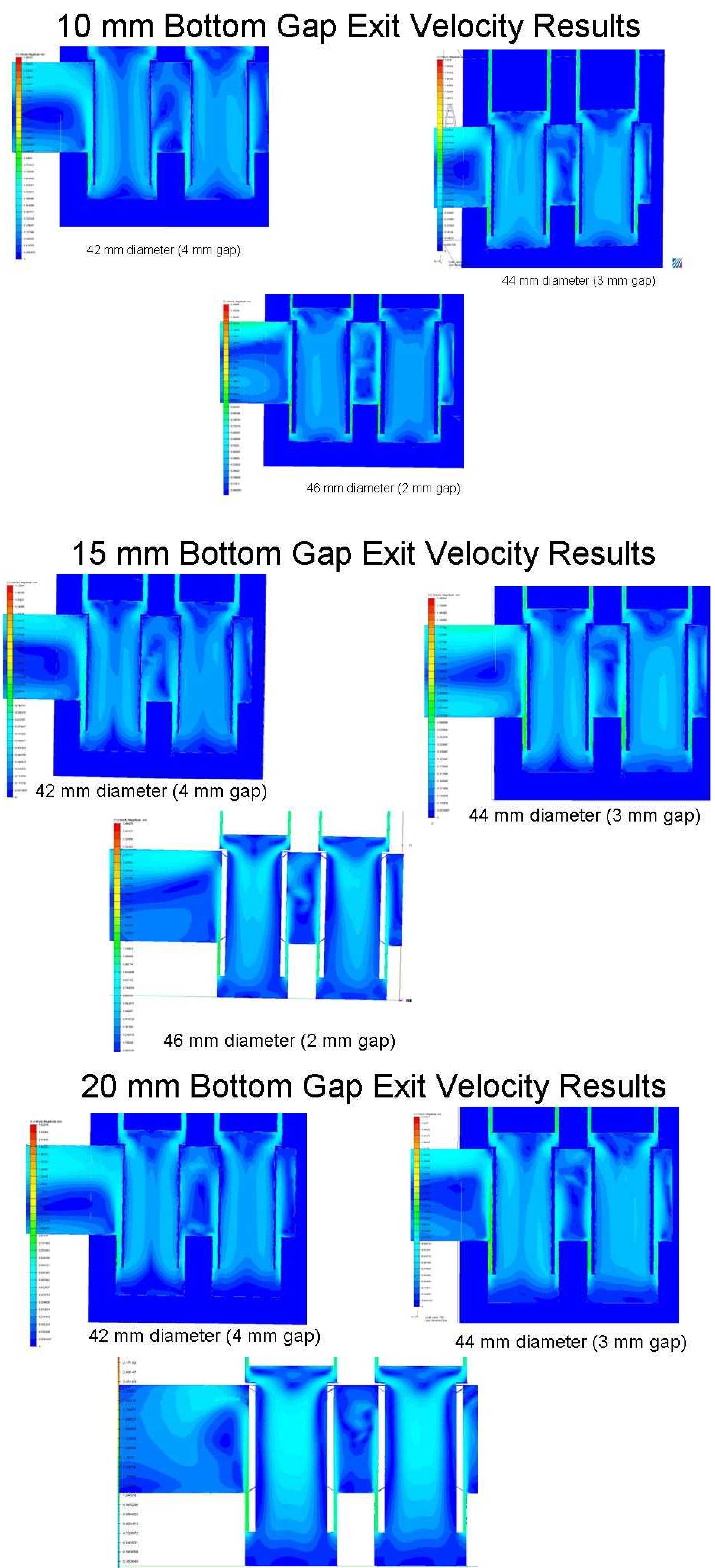

Figure 8. These are few of the velocity flow results for the 10, 15, and 20 mm bottom gap cases.

Although the small annuli give us better flow they do introduce other concerns. These new concerns would be the amount of pressure these higher velocities would create. Figure 9 demonstrates the pressure values for each analyzed case. The previously mentioned flow analysis, the 2-mm and 20-mm gap case, which was a well balanced, but when compared to the other cases it caused the highest pressure and when combined with thermal stress, could cause the material, when mechanical analyzed, not to meet the safety factor criteria for its specified material properties.

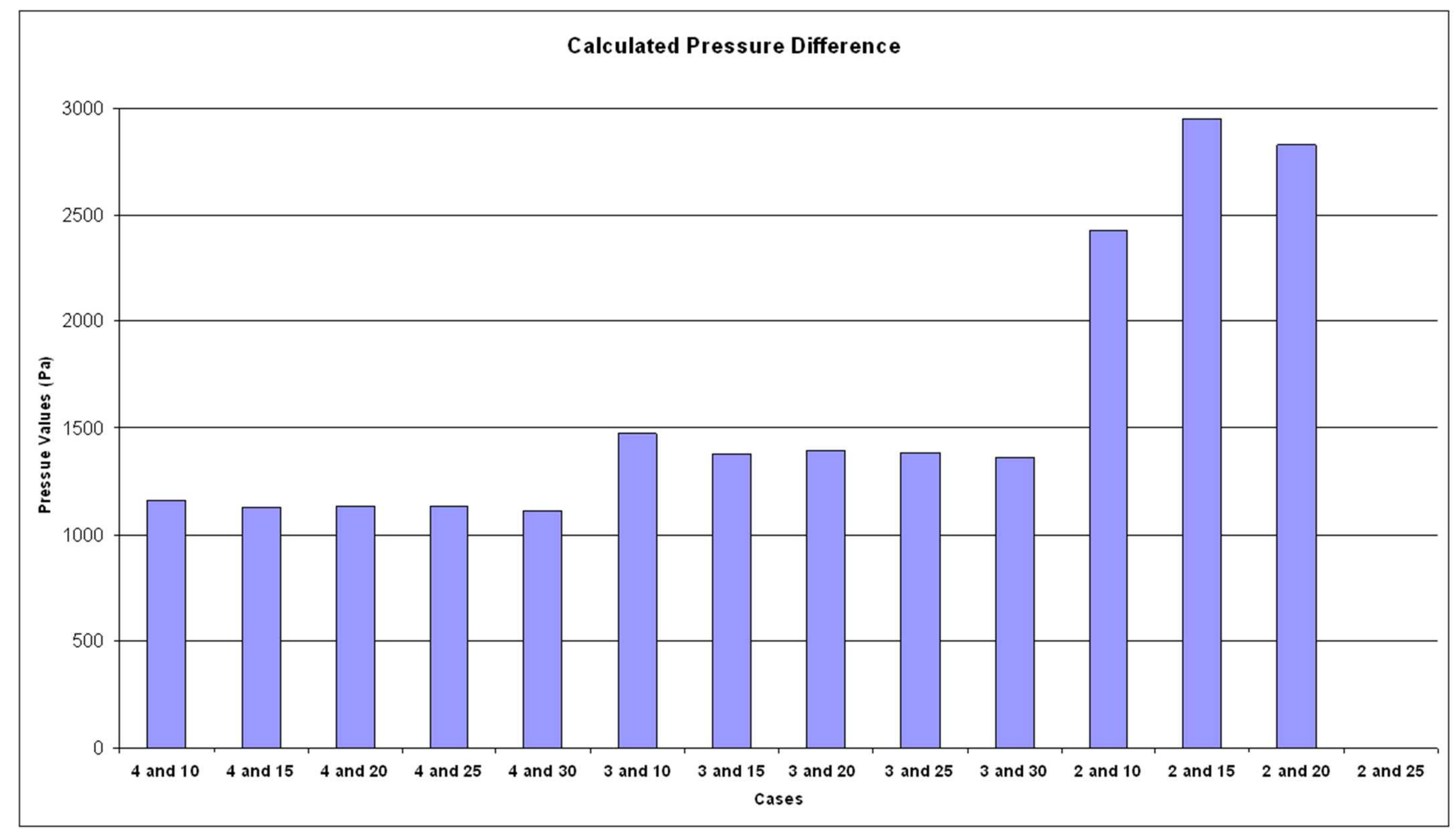

Figure 9. These are the calculated pressure drops in the system for each analyzed case.

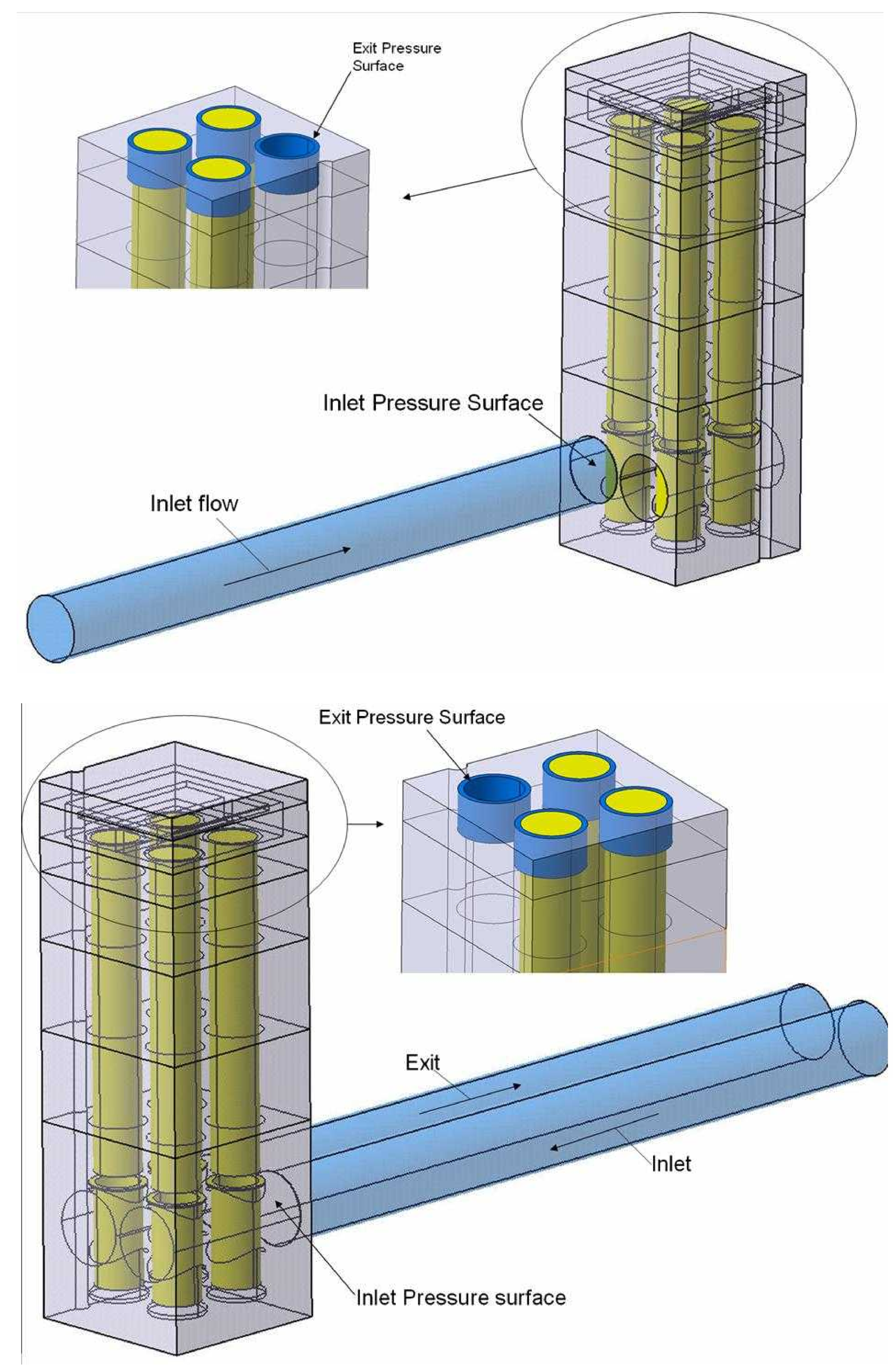

Figure 10. These figures show where the calculated pressure drop values came from.

According to the thermal analysis the change in velocities and pressure seem to have negligible effect on the outer surface of the stainless steel volumes. The highest temperature range was from 264 to 265 degrees Celsius for all the studies. Figure 11 shows the temperature profile on the outer surface of the stainless steel. The heat generation rates for the model were provided by University of Wisconsin-Madison. The heat generation rates are 5.14, 5.03, 4.09, 1.89, 0.68, 0.22, 0.054 W/cm3 for zone 1, 2, 3, 4, 5, 6, and 7, respectively, as shown in Figure 1. The tee-vane was giving a value of 5.03 W/cm3, the upper flow drivers have a value of 0.68 W/cm3, and the lower flow drivers were 0.054 W/cm3. Lastly, the water section was broken into three sections; there was a small section at the top of the flow driver that separated the tee-vane water section, a small section which fit in Zone 2's layer, and a section for the lower flow drives. The values for the tee-vane section 5.03 W/cm3, small water section 4.09 W/cm3, and the lower section 0.68 W/cm3.

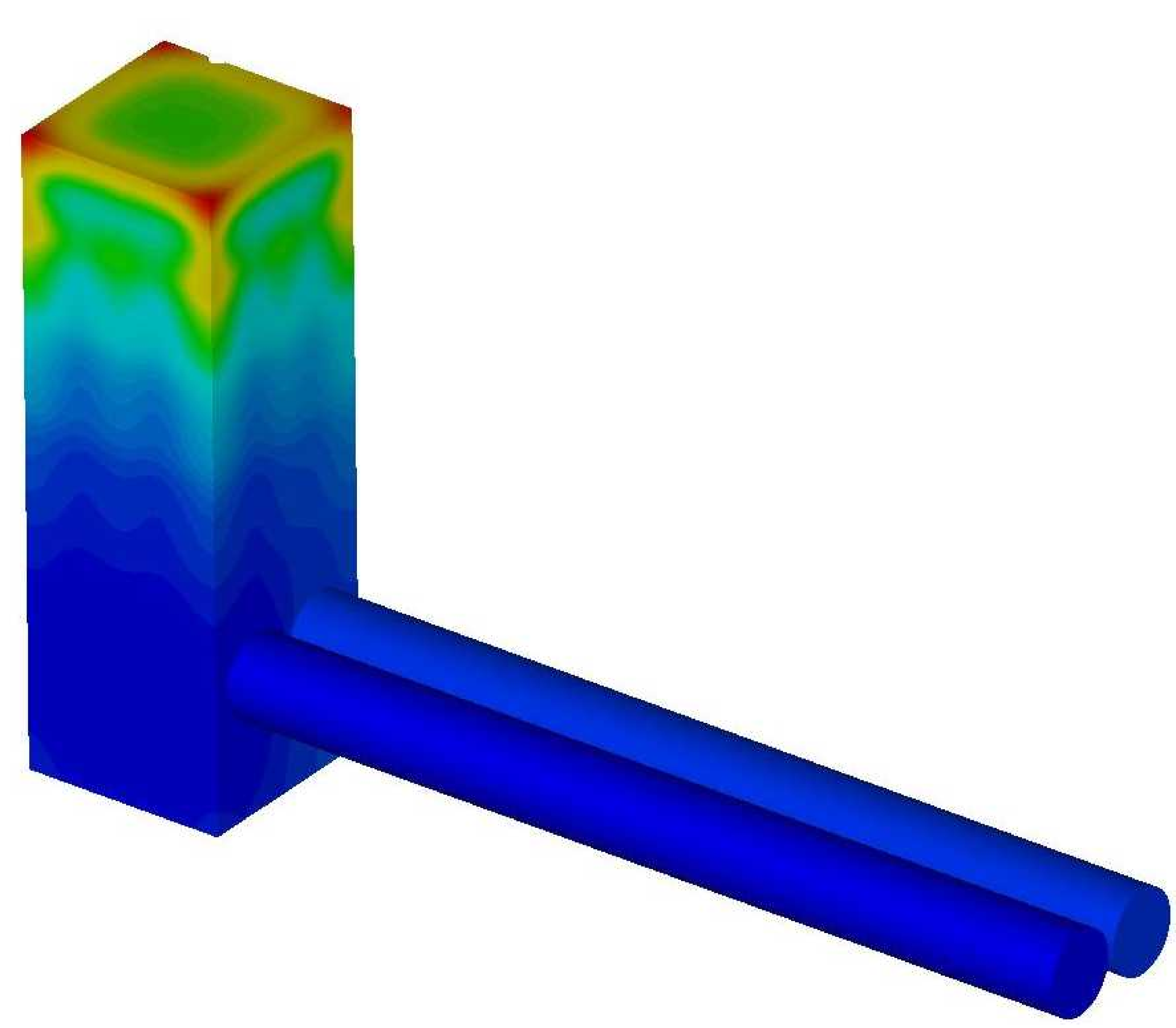

Figure 11. 4 mm annuli gap and 30 mm bottom gap heat profile for the outer surface.

Results from a previous pressure analysis on one of the actual ITER neutron shield modules revealed high stress locations along the intersection of the tee-vane and inner module wall(s) [4]. This required a design slight modification to the tee-vane to accommodate the high stress. The design change required a gap between the tee-vane and wall(s). Due to change in design there was concern that the change might have some effect on the flow velocity which in turn could have an impact on the cooling in these locations. In order to have a better understanding how the gaps will affect the flow three cases of 1, 2, and 3 mm were analyzed. Figure 4 shows a top view of the 1-mm gap case, there is also another 1-mm gap on the opposite side. Changing the gap on the ends had a negligible effect on the velocity on the underside and on the top of the tee-vane, but the velocity did increase through the gap. Figure 12 shows the velocity profile of the flow through the tee-vane gap 0.1 mm from the wall.

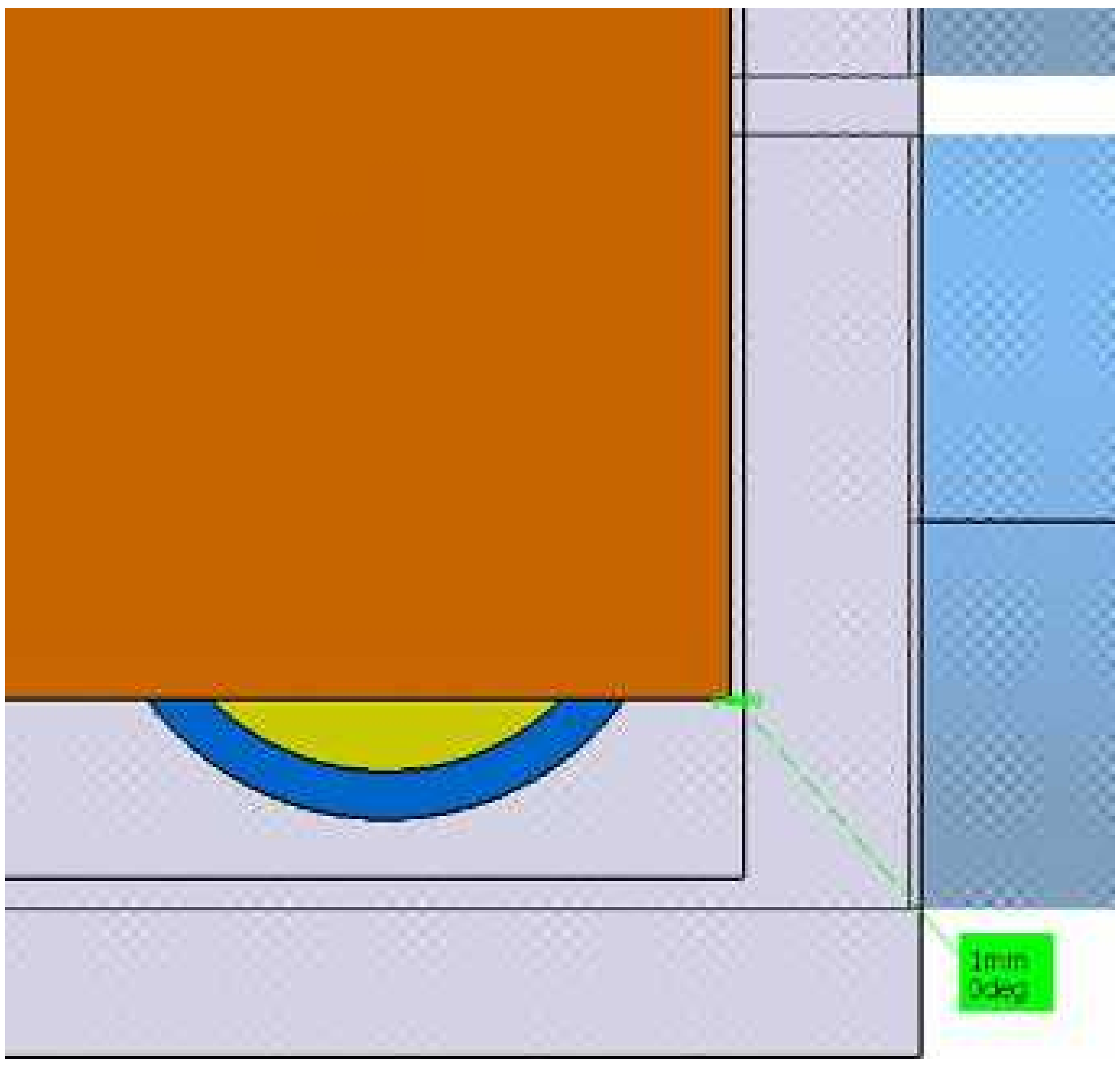

Figure 12. Top view of the tee-vane with a 1mm gap zoomed

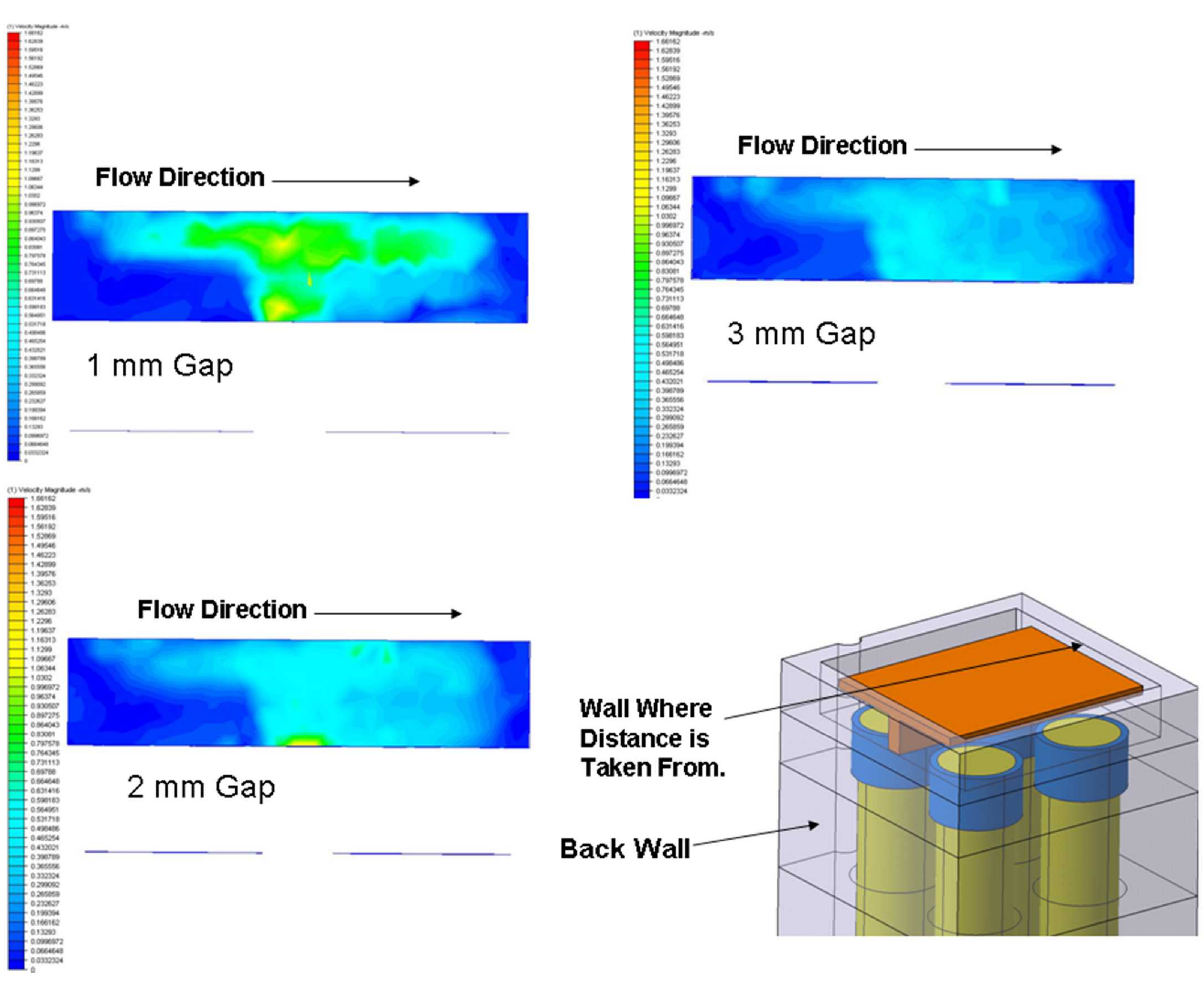

Figure 13. Velocity profiles of the tee-vane for the 1, 2, and 3 mm cases.

As stated previously and shown in Figure 14 and 15 the flow velocity has remained relatively unchanged due to the modified gaps at the tee-vane and wall.

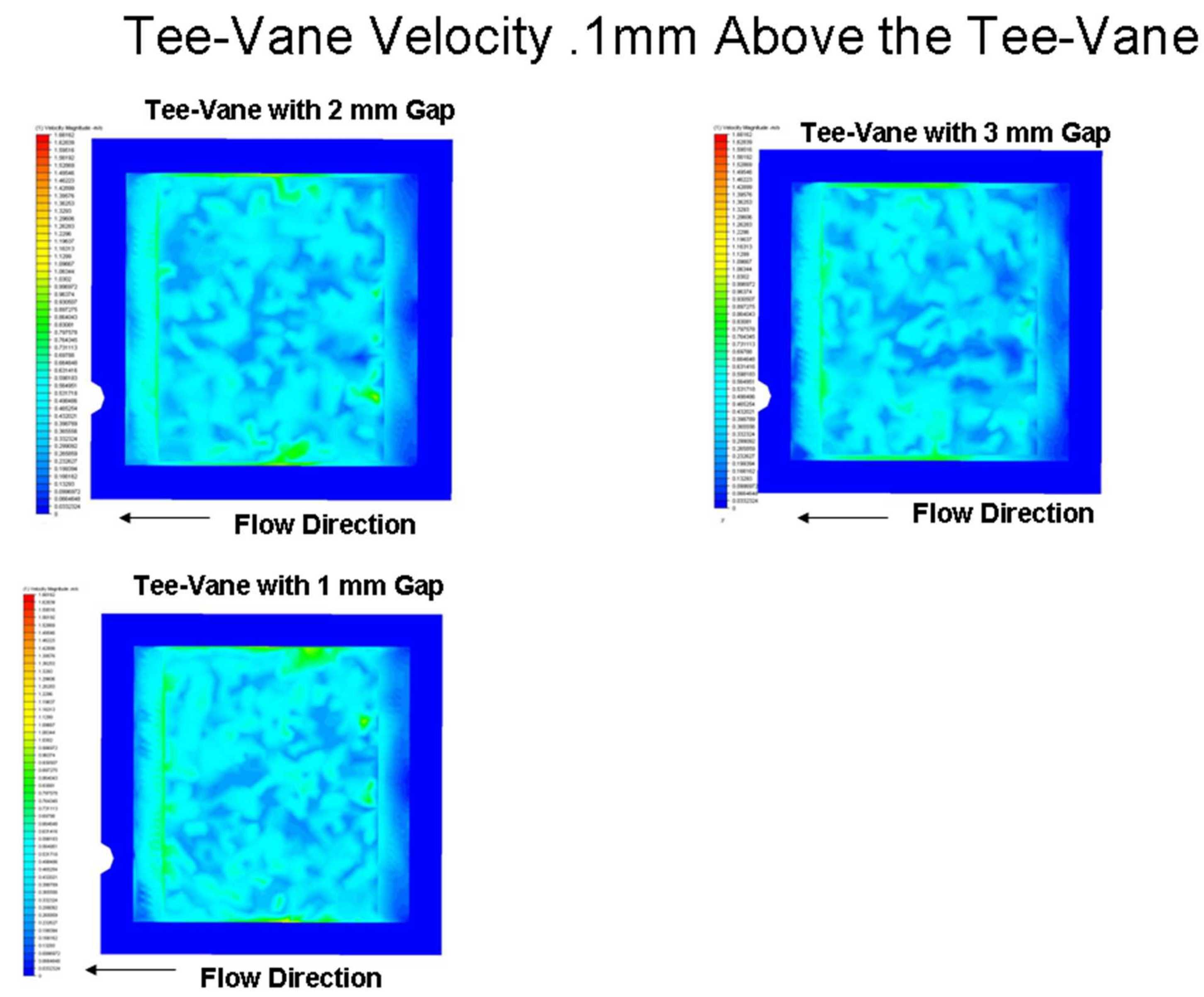

Figure 14. Top view of the velocity profile for the tee-vane cases.

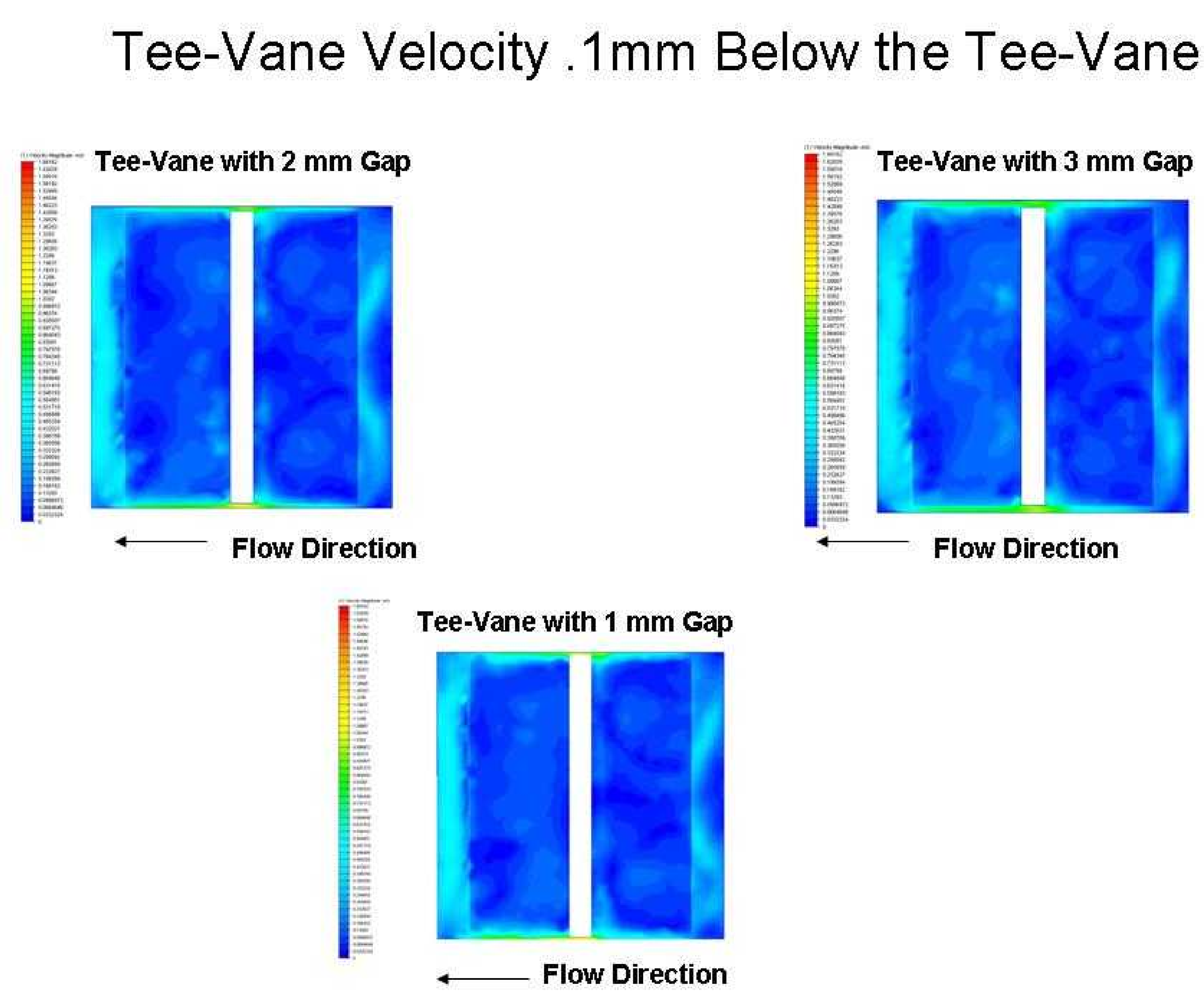

Figure 15. Velocity profile below the tee-vane for the 1, 2, and 3 mm gap cases.

Conclusions

After reviewing all the studies for the gap cases it was shown that the 2-mm annuli gap and 15-mm bottom gap was the ideal flow scenario, but created high pressure results. Higher pressure drops in the modules may be advantageous in providing a more uniform flow distribution between modules. This configuration may produce excessive stress on the modules. In order to determine how these stresses would affect the system, a detailed analysis is required for the actual shield modules to determine if the material would be sufficient to handle such loads. If the thermal stresses are tolerable, the smallest annuli gaps should be chosen. This will allow constant 90-mm long flow drivers to be used everywhere with a depth of 15mm and possibly 2-mm in the bottom gap. It also appeared that small variations in the flow would have little effect on the temperature distribution. The addition of tee-vane gaps also produced little change to the flow or temperature distribution.

Acknowledgments

The authors would like to thank the contributions of J. Bullock for creating the ITER neutron shield module, T. J. Tanaka for the 4-channel prototypical model, and lastly J.M. Garde for the pressure analysis results that demonstrated high stress concerns in the tee-vane region.

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