Effects of Upstream Nozzle Geometry on Downstream Liquid Metal Flow

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PROBLEM

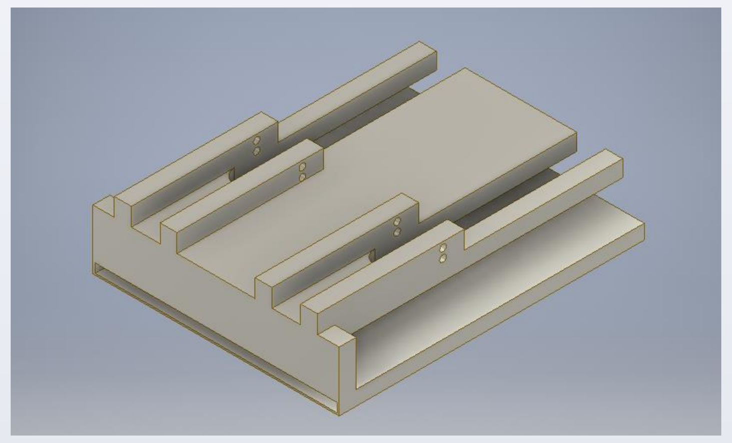
The divertor region in a tokamak is exposed to a high heat flux. High Z materials, such as tungsten, are known to have destabilizing effects on the core plasma since bremsstrahlung power losses scale like $\sim Z^4$. In the divertor region, the tungsten plates that are used need to be replaced readily as they completely erode from the heat flux and this is not economical. Fast flowing low Z Liquid Metal (LM), such as liquid lithium, would provide an effective way to remove heat through convection without destabilizing the core plasma. If used to coat the entire wall, LM could also prove to be a "self-healing" wall eliminating instabilities resulting from thermal gradients at the edge. However, fast flowing LM face instability issues such as hydraulic jumps which result in a slower thicker flow. In the Liquid Metal Experiment (LMX) channel, other issues like flow-wall separation are also of concern for fast flows. Various nozzles were designed, built (3-D printed)* and implemented in the LMX to attempt to tackle these problems.

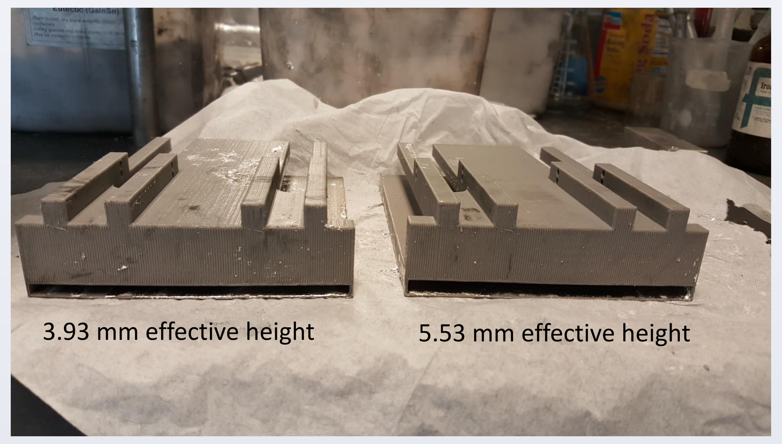
BACKGROUND

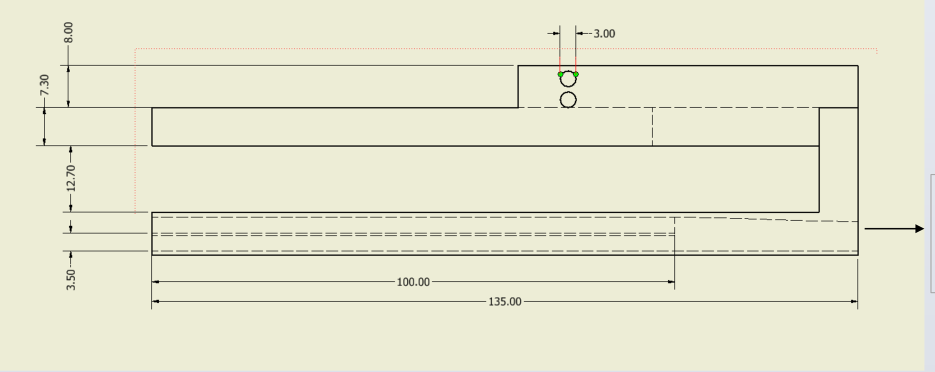
- The Reynolds number, $Re = \frac{\rho u L}{\mu}$, is a ratio of inertial forces to viscous forces in a fluid and is often used to characterize a flow as laminar versus turbulent
- The Froude number, $Fr = \frac{u_0}{\sqrt{g h_0}}$, of a flow of height h_0 is the ratio of the average flow velocity u_0 to the velocity of wave propagation in the flow in the shallow depth limit.
- $Fr > 1$ represents a supercritical flow which is susceptible to a hydraulic jump where a flow experiences a sudden rapid change in height as well as a drop in velocity. Flow downstream of the jump is said to be subcritical ($Fr < 1$).
- For LM flows the Hartmann number, $Ha = Ba\sqrt{\frac{\sigma}{\mu}}$, defines a ratio of the magnetic forces to the viscous forces.
- A transverse B-field is known to damp turbulence intensity and relaminarize flows which roughly satisfy the condition $\frac{Re}{Ha} < 30$[1].
- Turbulence in flows can also be reduced by passing the flow through a honeycomb. Large scale eddies are eliminated but small scales eddies are introduced for which turbulence intensity decays like $\sim \left(\frac{1}{x}\right)^{\frac{1}{2}}$ where x is the distance downstream from honeycomb exit [2].

DESIGN & CONSIDERATIONS

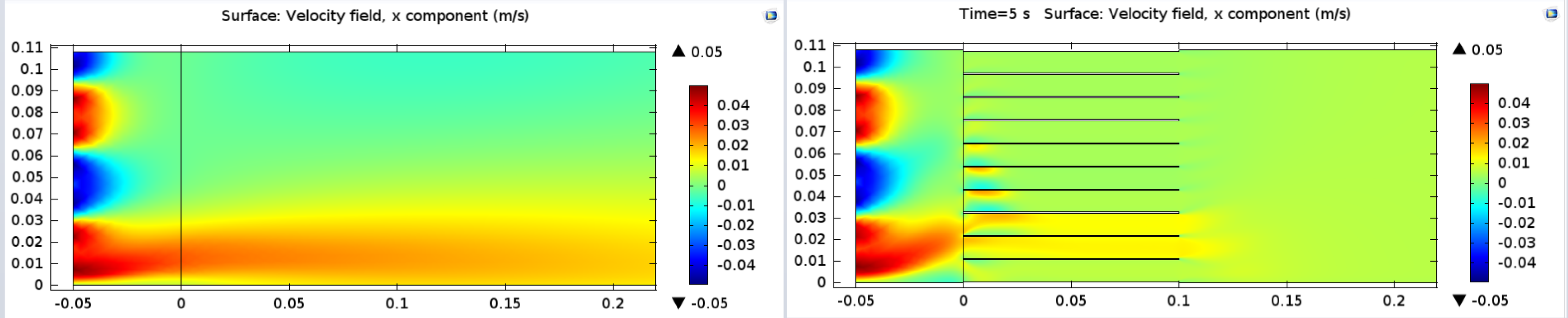
- $\frac{L}{M} > 10$, where L is the honeycomb length and M is the mesh size, used to effectively remove large scale turbulence[3].
- At the honeycomb exit, a 3cm closed duct was added to allow streams to recombine. Distance determined via COMSOL Multiphysics simulations.
- Upon exiting from the honeycomb, flow was converged to the equivalent effective area using a 3rd order curve to minimize adverse pressure gradients in the duct[4].



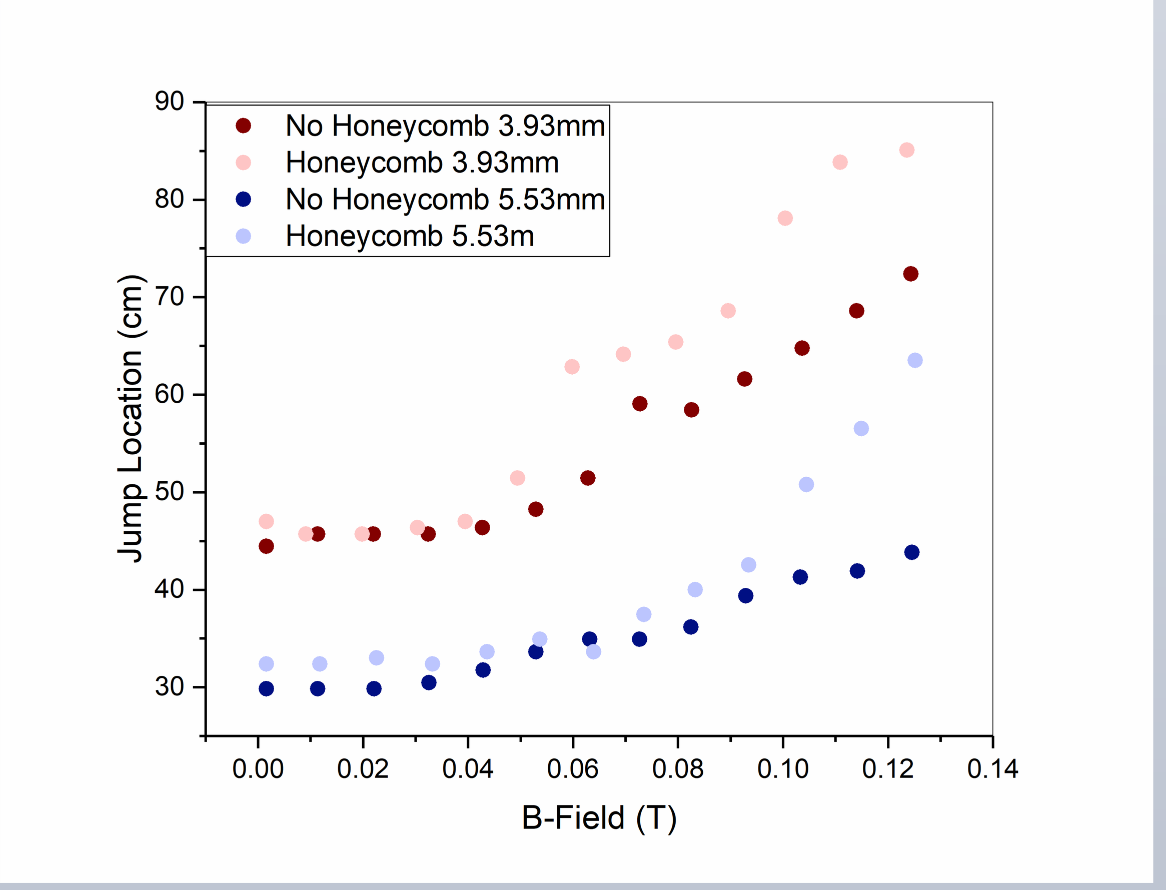


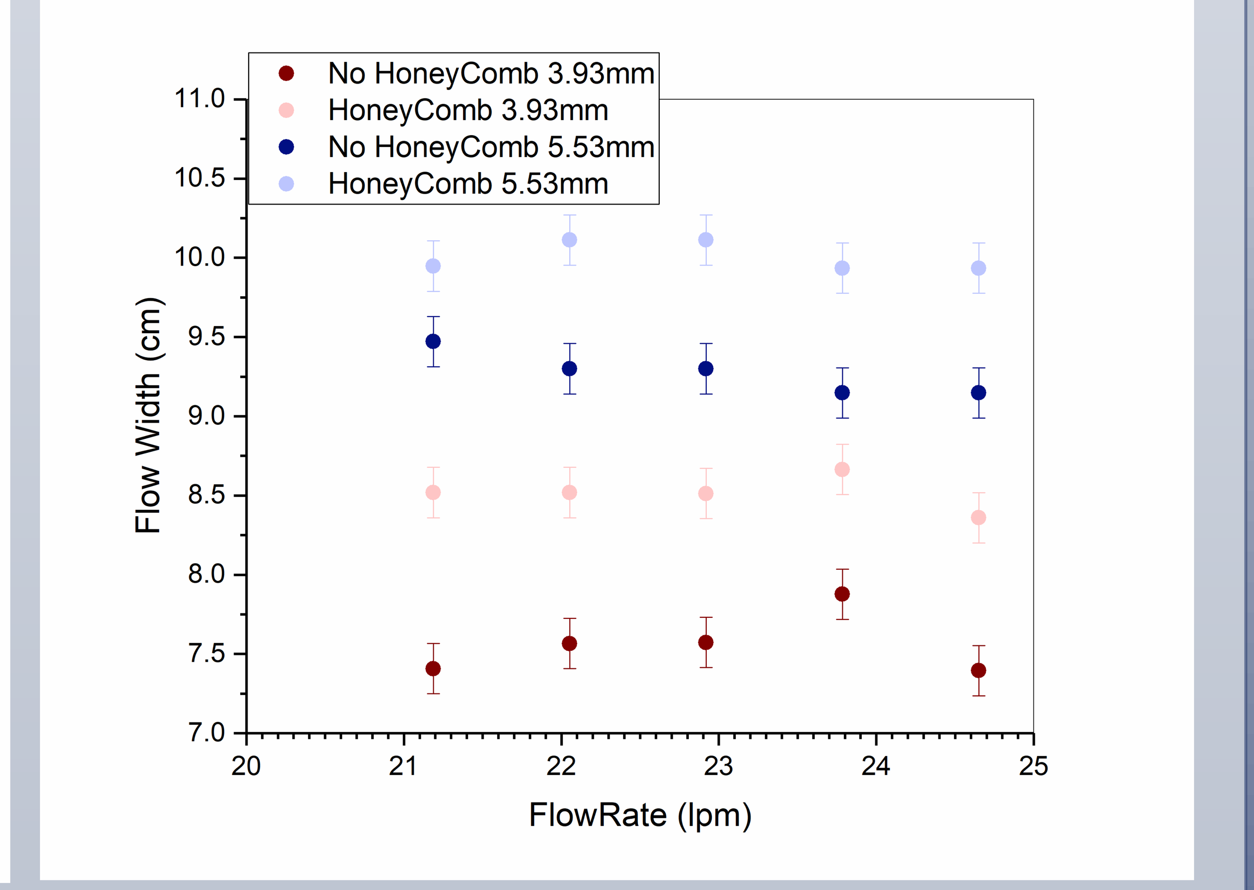


$$y = \frac{D_i}{2} - \frac{3}{2}(D_i - D_0)\left(\frac{x}{L}\right)^2 + (D_i - D_0)\left(\frac{x}{L}\right)^3$$



RESULTS





Red. Hydraulic jump location versus magnetic field for honeycomb and no honeycomb flows at $Fr \approx 4.89$
Blue. Hydraulic jump location versus magnetic field for honeycomb and no honeycomb flows at $Fr \approx 2.93$

Red. Width of the LM flow at various flow rates for both the honeycomb and no honeycomb cases at an effective flow height of 3.93mm.
Blue. Width of the LM flow at various flow rates for both the honeycomb and no honeycomb cases at an effective height of 5.53mm

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DISCUSSION

- Hydraulic jump location appears to have a nonlinear relationship with the magnetic field.
- The honeycomb produced a flow with jump location that seemed to have a stronger dependence on the magnetic field than the flow without the honeycomb.
- Since Fr is a function of the average flow velocity which was the same for both honeycomb and no honeycomb cases for each height, jump location may be indicating less turbulent flow for the honeycomb case.
- Measurements of turbulence intensity using thermocouples to measure heat transport in the LM may help better relate jump location and flow turbulence.
- Honeycomb marginally improved the flow-wall separation problem by reducing the separation distance from the wall. Flow-wall separation appears to have had no dependence on the flow rate.
- Flow-wall separation may have other underlying factors such as Galinstan-acrylic wetting issues.

CONCLUSIONS

- The nozzle design that was created using empirical formulations from existing research was able to consistently push jump location further downstream and perhaps create a faster but less turbulent flow.
- Further work will need to be done to determine the exact relationship of turbulence and jump location.
- Flow-wall separation was not wholly alleviated with this nozzle design, however minor improvements were made.

REFERENCES

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