SUMMARY DOCUMENT

Poreh's Radial Jet Correlations as Applied to a Pulse Jet Mixing Process

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Introduction

Currently, there are 53 million gallons of high level waste (HLW) being stored inside tanks located at the Hanford Site. The Department of Energy's (DOE) main objective is to immobilize, treat and store the waste in order to prevent contamination to the environment. The planned solution for this objective is to have the radioactive waste undergo separation and vitrification, which converts the waste into glass for permanent storage. The waste needs to have particular rheological properties before it goes through this process, including density, viscosity, porosity, etc. The HLW separates itself into multiple layers, referred to as salt cake, sludge and supernatant, due to density differences. This gives rise for the need to properly mix the HLW inside the storage tanks prior to treatment.

Pulse jet mixing (PJM) is one of the methods used at Hanford site to mix the HLW slurry prior to the vitrification process. This method involves suctioning a portion of the waste in the tank into a pressurized vessel which then injects it back into the tank creating a round jet. This round jet impinges on the bottom of the tank resulting in radial wall jets. These radial wall jets then collide against each other at the center of the tank creating an up wash region which promotes mixing of the waste. This process is repeated over a number of cycles until desired mixing is achieved [1].

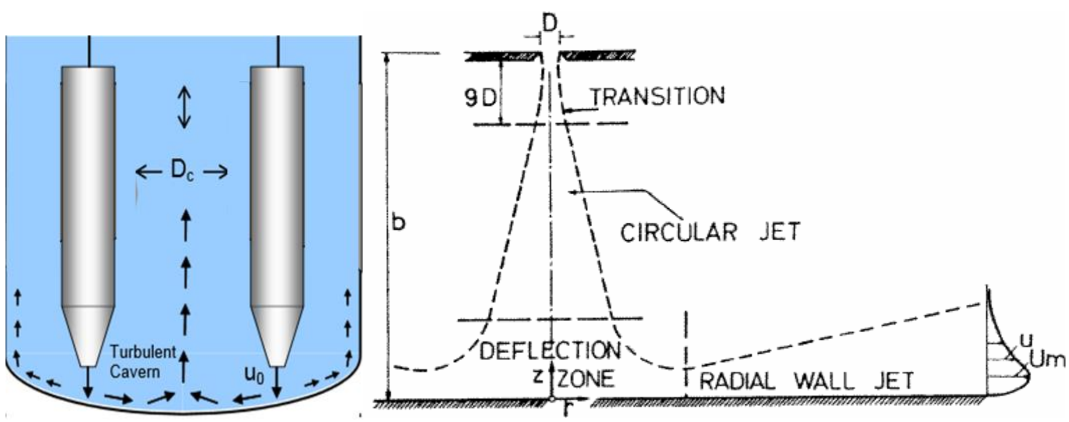


Figure 1. Pulse jet mixer diagram and Poreh's descripion of single jet impingement.

In the analytical assessment of the PJMs, the radial wall jet is described by correlations developed by Poreh's paper, "Investigation of a turbulent radial wall jet." His experiment predicts two characteristic velocity profile values after jet impingement. These values describe the maximum velocity and the thickness of the radial jet which can be attained at different radial locations along the radial wall jet. The correlations are defined below as follows:

$$\delta = b * .098 * \left(\frac{r}{b}\right)^{.9} \quad (1)$$

$$U_m = \frac{\sqrt[2]{K}}{b} * 1.32 \left(\frac{r}{b}\right)^{-1.1} \quad (2)$$

Poreh's experiment, studies the situation where a round jet of air is impinged on a flat perpendicular surface. The correlations are based off a non-dimensional number that takes into account the ratio of the initial jet diameter and the distance from the nozzle to the impingement surface. However, the non-dimensional characteristic ratio that pertains to the PJMs is about 1.5, while the value tested by Poreh is 8 at the lowest. At this low characteristic ratio, the circular jet is not given enough time to become fully developed, as is the case in Poreh's experiment. In addition, Poreh's experiment didn't take into account curvature of the impingement surface which is part of the PJM geometry. How well the correlations maintain accuracy with the characteristic ratio that pertains to the PJMs geometry will be analyzed in this research effort. This will be achieved using computational fluid dynamic (CFD) analysis with the Star-CCM+ software. First, a simulation of Poreh's original experiment is run in order to establish that the model is able to predict experimental data. That same simulation is then run using the r/b ratio of the PJMs in order to predict how a low b/D ratio affects the accuracy of Poreh's correlation. A final simulation is then run using a scaled down version of a PJM vessel in order predict the correlations accuracy on a curved impingement surface.

Simulation Verification

In order to shed light on whether Poreh's correlations are appropriate for the PJM configuration, a simulation of one of Poreh's original experiments was replicated in order to show that the model of choice can correctly capture experimental data. An axisymmetric 2-D domain using a standard-k-ε two-layer model was used. The figure below depicts the boundary conditions of the geometric domain:

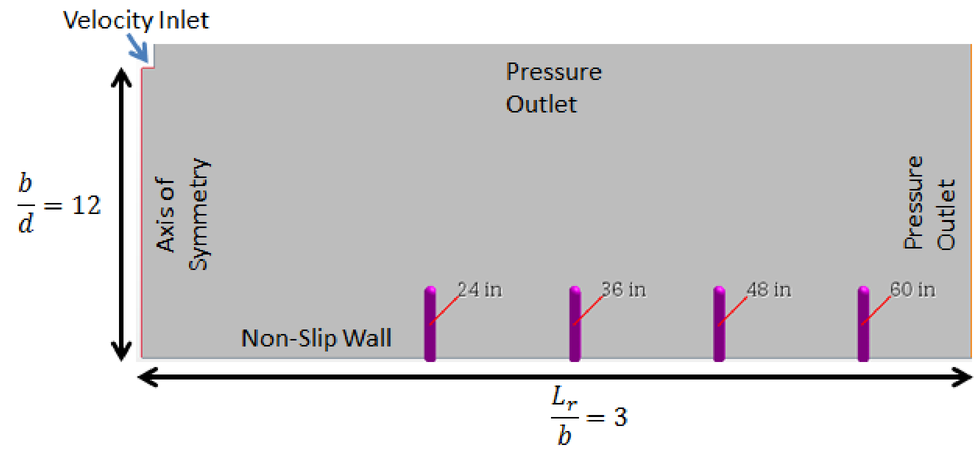


Figure 2. Geometric domain with boundary conditions and line probe locations.

A velocity inlet is used to represent the nozzle. The impingement wall was modeled by a non-slip wall boundary condition. An axis of symmetry was defined as shown in Figure 2. All other boundaries were set as pressure outlets. If the domain were to be revolved by the symmetry axis, a cylindrical volume with a circular jet at the top middle would result. This accurately depicts the experimental set up laid out by Poreh's experiment.

The fluid utilized in Poreh's experiment was air. It has a density of $0.0621 \frac{\text{lb}}{\text{ft}^3}$ and a kinematic viscosity of $2 \text{ x } 10^{-4} \frac{\text{ft}^2}{\text{s}} * 0.0621 \frac{\text{lb}}{\text{ft}^3}$. The nozzle jet velocity was $340 \frac{\text{f}}{\text{s}}$ yielding a Reynolds number of $1.9 \text{ x } 10^5$. This velocity is in part due to what is referred to as a vena contracta. In this particular case, it results in a reduction of total area due to the inability of the fluid to instantly turn at the edges of the jet orifice diameter. This effect cannot be captured by the proposed simulation; therefore, an effective kinematic flux was calculated. The kinematic flux in the experiment was K = $1540\ \frac{\mathrm{ft}^4}{\mathrm{s}^2}$. Poreh defines kinematic flux as:

$$\mathrm{K} = \frac{\pi}{4}\mathrm{D}^2\mathrm{U}_\mathrm{o}^2 \qquad (3)$$

It follows that for the simulation:

$$\mathrm{U_o} = \sqrt{\frac{\mathrm{K}}{.153\pi\mathrm{D}^2}} = \sqrt{\frac{1540 * 4}{\pi.166^2}} = 265\frac{\mathrm{ft}}{\mathrm{s}}$$

This effective velocity was the utilized in the simulations. The inlet was further described by specifying a turbulent intensity as well as a turbulent length scale. The length scale was based on the radius of the jet which was 0.1 inches. The turbulent intensity was then decided by an accepted inlet intensity equation for turbulent pipe flow:

$$I = .016\mathrm{R_e}^{-\frac{1}{8}} \qquad (4)$$

$$= .016(1.96 \times 10^5)^{-\frac{1}{8}} = 3\%$$

The table below summarizes the physics models used in Star-CCM+.

Table 1. Physics Models Applied

Physics Model	Justification
Axisymmetric	Poreh experimentally determined that the velocity profile was axisymmetric about the center of impingement
Gas	Fluid under consideration is air
Constant Density	No significant temperature or pressure changes to affect density
Turbulent	Reynolds number of $1.96*10^5$
RANS	Computationally efficient, expected behavior is known
Standard K-Epsilon two-layer	High computationally efficiency
Segregated Flow	Low Mach number and pressure, computationally efficient
Steady	Unsteady state results are not of interest
Two-Layer All Y+ Wall Treatment	Meshing refinement zones will be best resolved by an all Y+ treatment
Segregated Fluid Isothermal	Temperature changes are negligible

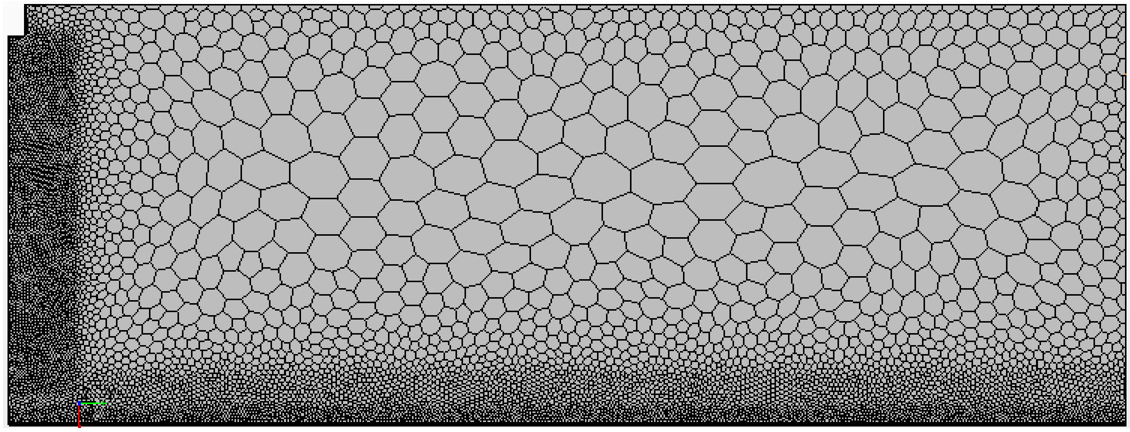
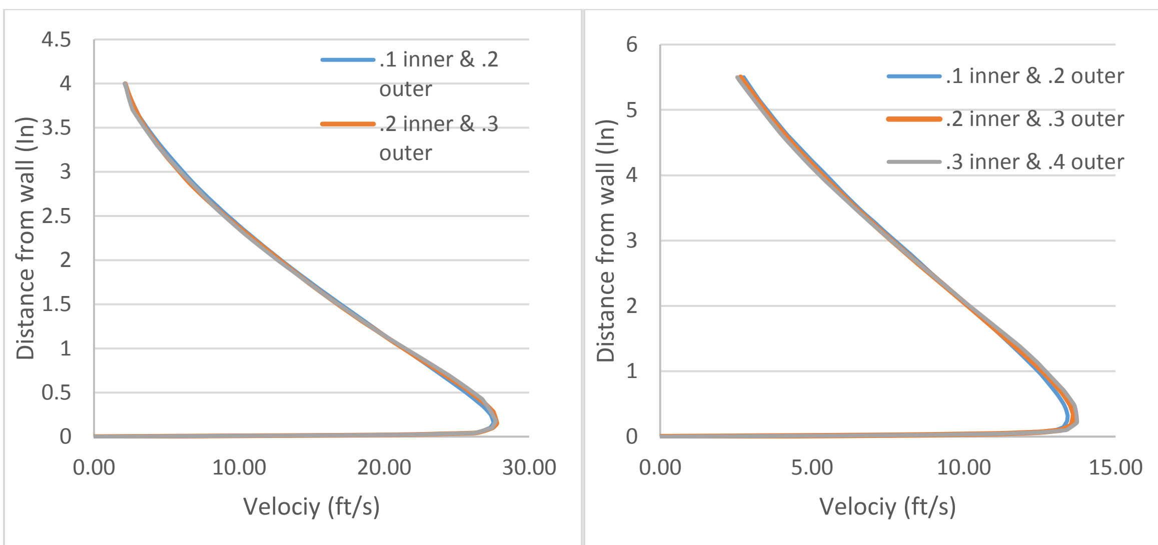
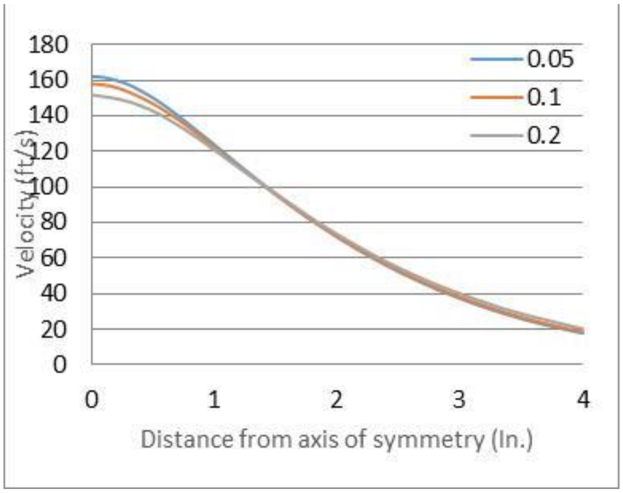


Figure 3. Computational mesh.

For the simulations, an octahedral mesh was used to generate the computational domain with a total of 10K cells. The base mesh size was set proportional to that of the jet inlet radius and was 1 inch. The circular jet, inner radial wall jet, and outer radial wall jet regions implemented a mesh refinement zone. The refinement zones ranged from 20% to 30% of the base size. Four prism layers were used on wall boundary conditions with a total thickness of about 10% of the base mesh size. Mesh sensitivity analysis was performed on both the circular jet and the radial wall jet in order to assure mesh independence.



(a) (b)



(c)

Figure 4. Mesh sensitivity based on percentage of base size of radial wall jet measurements at r/b=1 (a), 2 (b), and round jet (c).

It was observed that at 20% of the base mesh size, the fluctuation in resulting velocity profile of the round jet does not change significantly with increasing mesh size. As previously noted, the radial wall jet consists of two refinement areas. The finer mesh pertains to that of the section closest to the impingement wall. It was observed that the result is largely independent of the mesh.

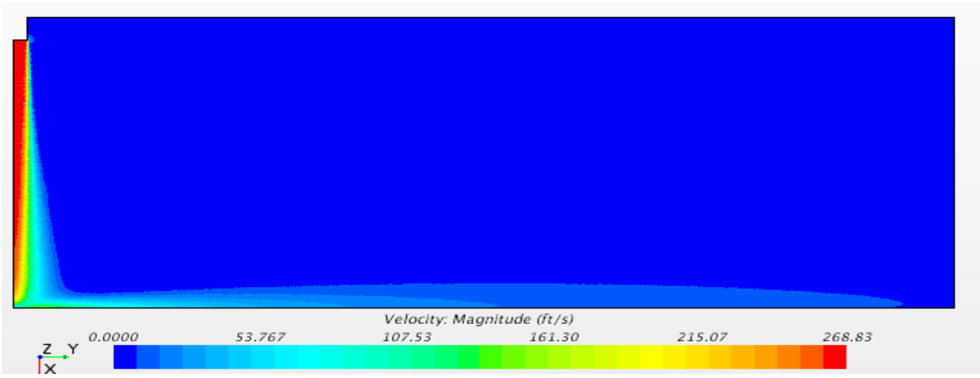
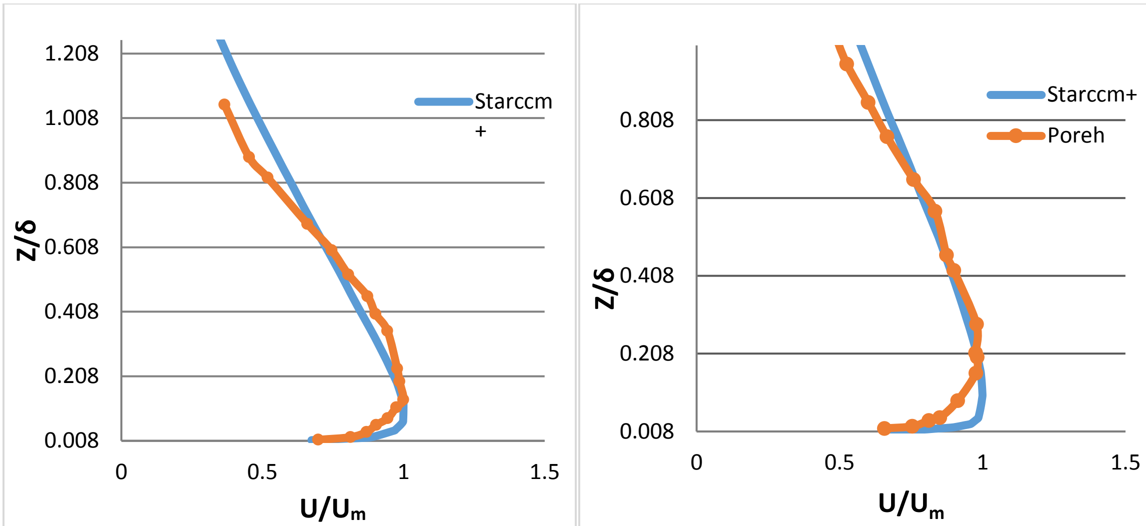


Figure 5. Contour plot of velocity.

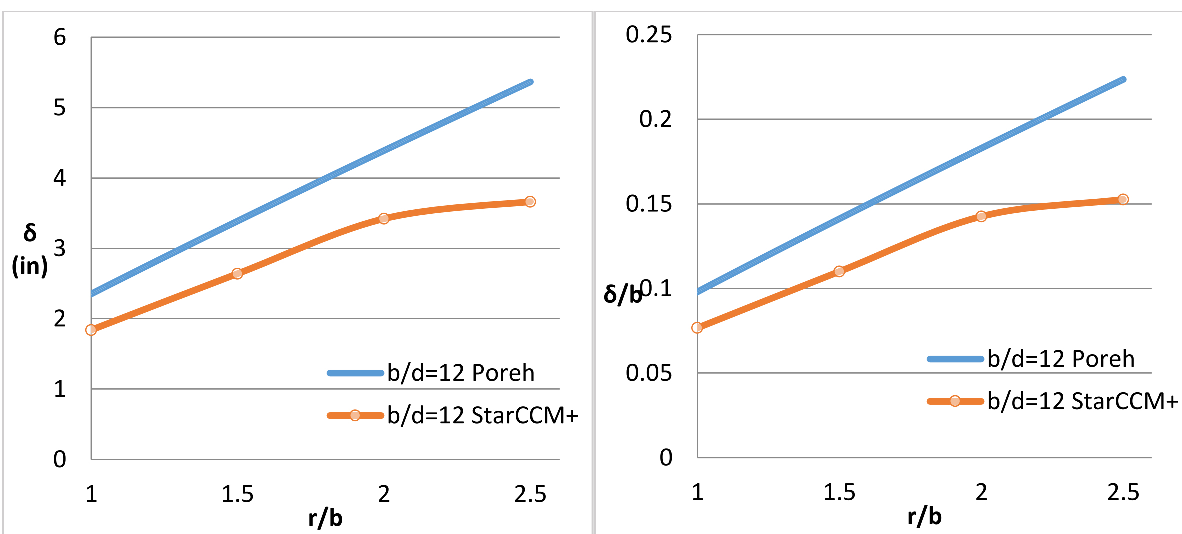
From Figure 5, the fully developed round jet can be observed just prior to impingement. The radial wall jet produced after impingement increases in total thickness as depicted in Figure 1 but does dissipate towards the end of the domain. The agreement between the simulation results and Poreh's correlation are shown below:



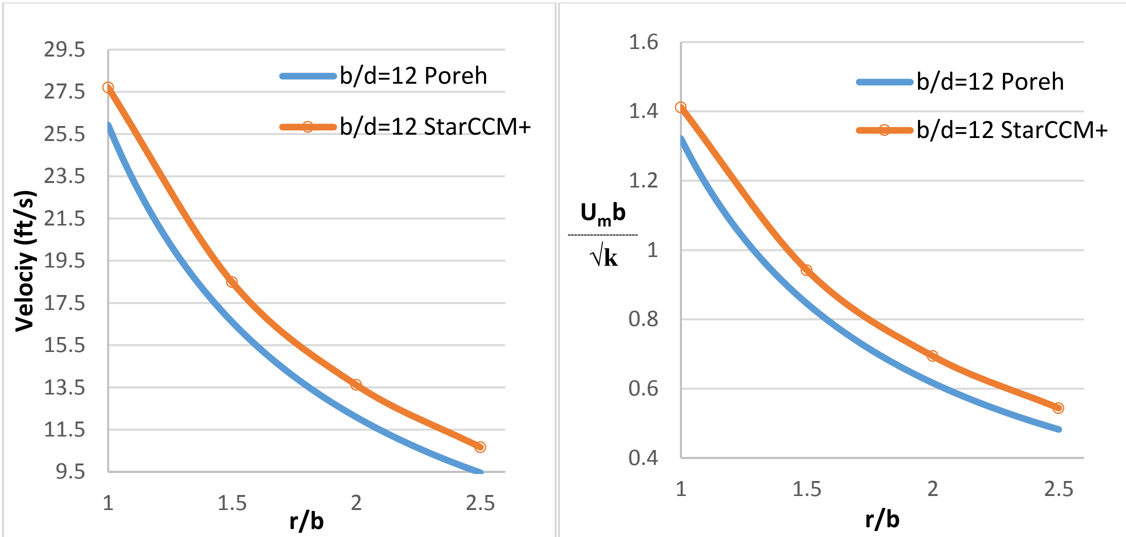
(a) (b)

Figure 6. Non-dimensional comparison of radial jet velocity profile between simulation & experimental data at r/b= 1.5 (a), 2.5 (b).

It can be seen from plots of the radial wall jet velocity profile comparison that the simulation agrees well with the experimental results. It was observed that the experimental results take a longer distance, as measured from the impingement wall, to reach maximum velocity. This can possibly be attributed to the fact that the probes with which the experimental data was taken might have been intrusive in nature. The δ and U_m correlation comparison between the simulation and Poreh's experimental results are shown below:



(a)



(b)

Figure 7. Dimensional (left) and non-dimensional (right) radial jet correlation comparisons of δ (a) and Um (b).

It was observed that the simulation predicts the experimental characteristic correlations within a reasonable degree. The simulations accuracy is suffice enough to be used as a reference for the rest of this study.

Simulation PJM Characteristic b/D Ratio

Given that the simulation gave reasonable results evaluated at one of Poreh's b/D ratios, the distance between the nozzle and the impingement wall of that same simulation was shortened to match the b/D ratio of the PJMs. This is depicted in the resulting velocity profile of the domain:

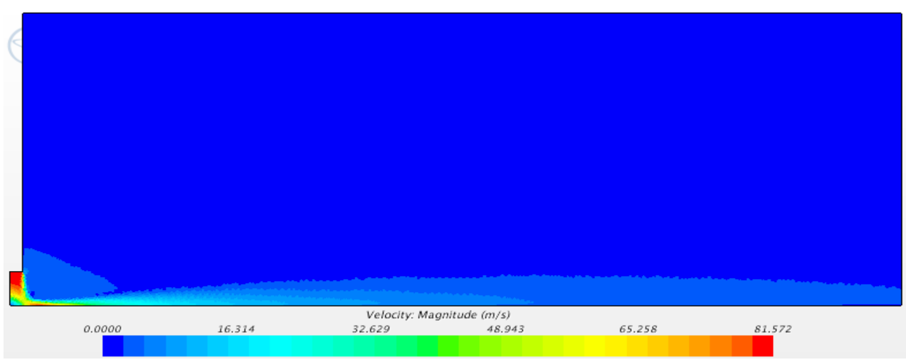
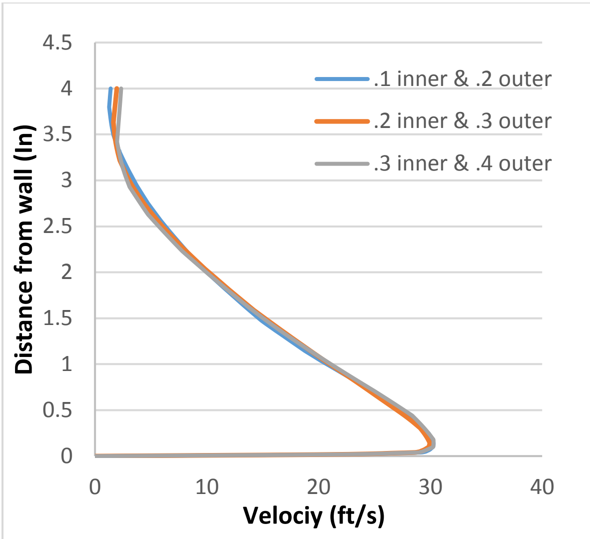
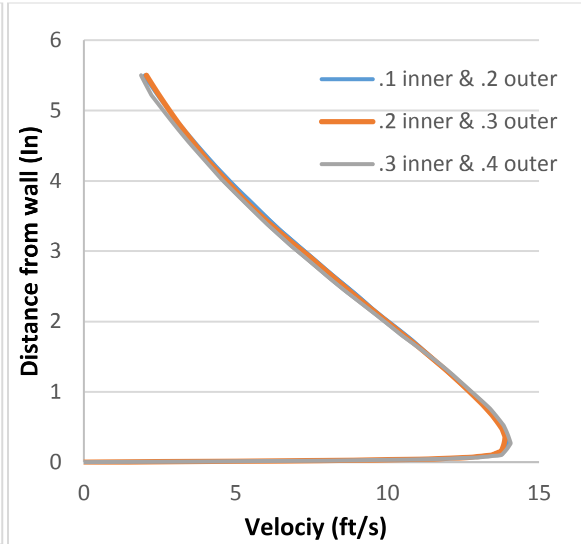


Figure 8. Contour of plot velocity b/D=1.5.

It can be seen from plots of the radial wall jet velocity profile comparison that the simulation at lower b/D ratios has the same flow structure as the previous simulation. Similar mesh sensitivity analysis was conducted in order to show mesh independence:



(a)



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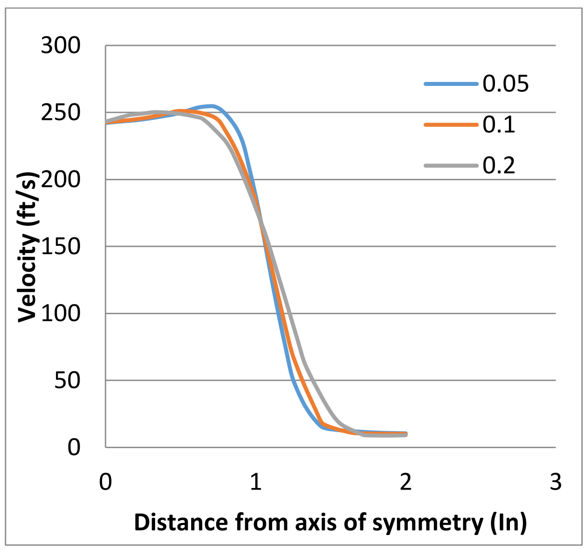
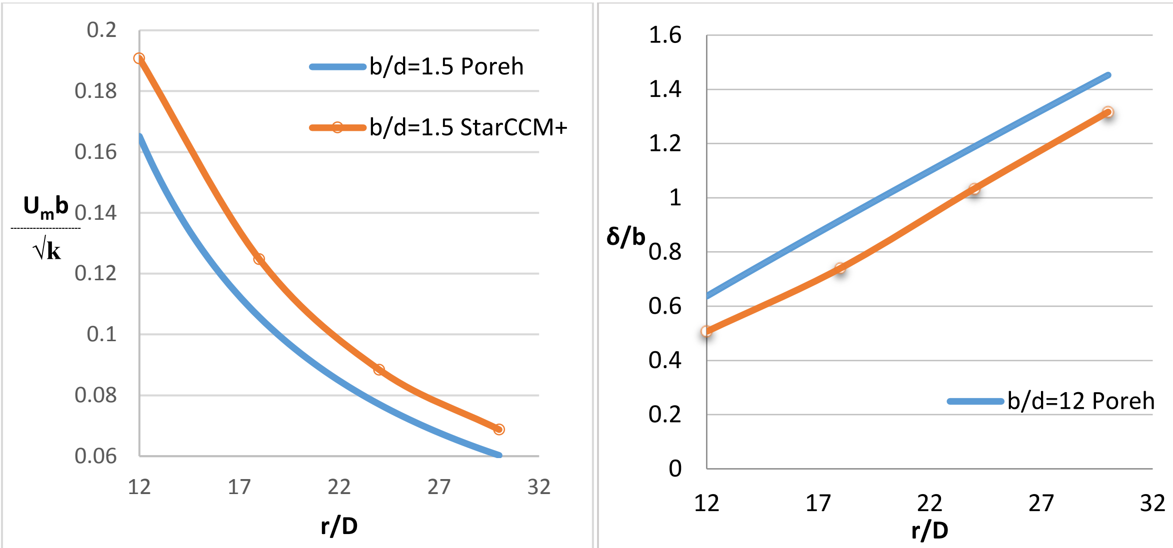


(c)

Figure 9. Mesh sensitivity based on percentage of base size of radial wall jet measurements at r/b=1 (a), 2 (b), and round jet (c) for b/D=1.5.

It was concluded that the same mesh used in the previous simulation is appropriate. It was noted that the radial jet location is now non-dimensionalized with D instead of b; this was done in order to look at the same locations as Poreh’s experiment. The round jet in Figure 8 shows a plug profile for the low b/D ratio right before impingement. This plug profile is the basis for criticism on the use of Poreh’s correlation and is predicted to happen by the simulation at this low b/D ratio. The δ and U_m correlation comparison between the simulation and Poreh’s correlation evaluated at b/D=1.5 are shown below:



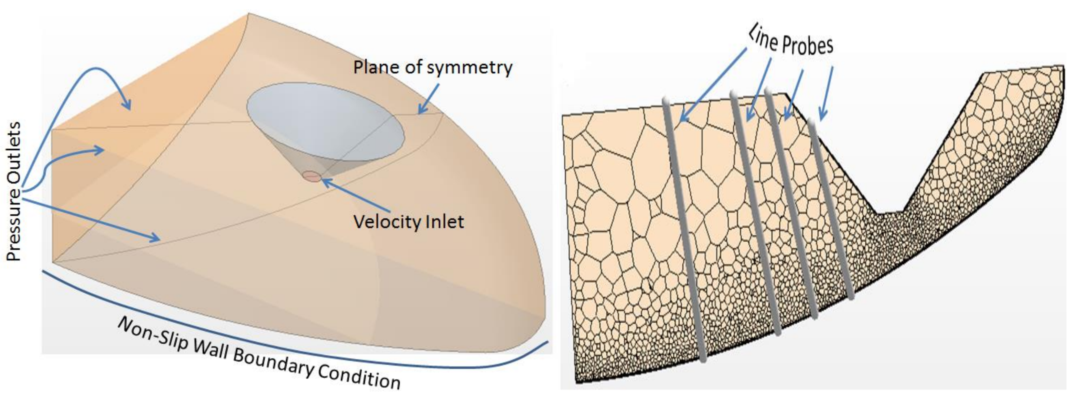
(a) (b)

Figure 10. Non-dimensional radial jet correlation comparisons of Um (a) and δ (b) at b/D=1.5.

Similar agreement between the simulation and Poreh's correlation are observed for both δ and U_m at a low b/D ratio as were seen for the higher b/D ratio. The average discrepancy for both δ and U_m is 15%. This discrepancy is also on the conservative side, providing a factor of safety. For the scope of the PJM process, the plug profile before impingement does not significantly affect the accuracy of Poreh's correlation.

Simulation of PJM Geometry

It was observed that the low b/D ratio of the PJMs did not significantly affect the applicability of Poreh's correlation. The simulations have thus far been conducted using a flat impingement surface, as was Poreh's experimental set up. The effects of a curved impingement on a single jet will be similarly investigated. This is accomplished by looking at a quarter of a scaled down PJM vessel using similar mesh, as shown below:

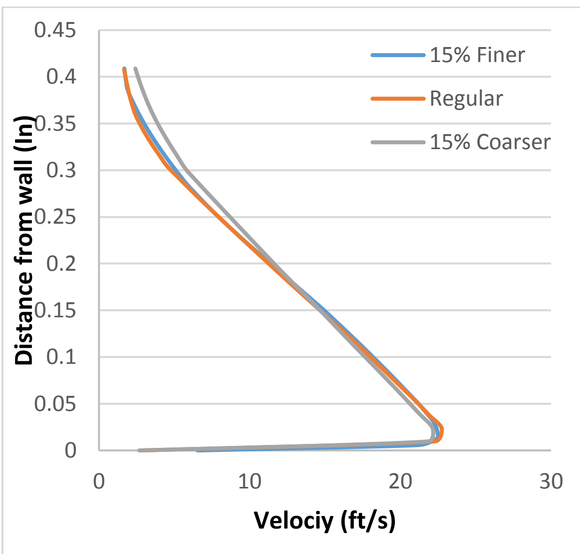


(a) (b)

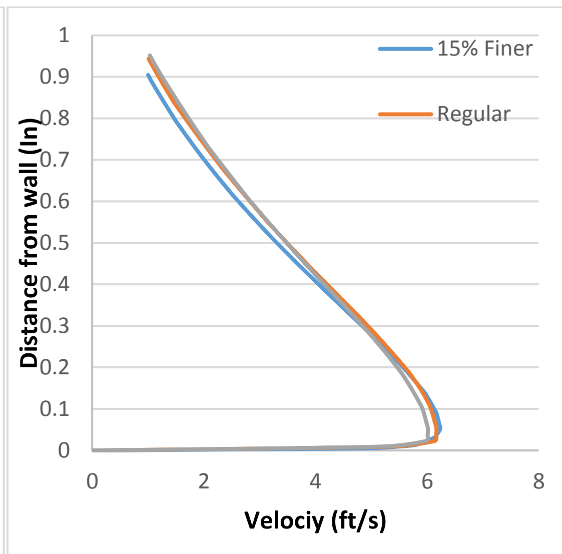
Figure 11. Simulation PJM domain with boundary conditions (a) and mesh (b).

The boundary conditions are similar in nature to that of the axisymmetric simulation. The physics solvers used are all identical to that of the previous simulations with the exception of the axisymmetric boundary condition, the working fluid, and the inlet velocity. The fluid in the PJM was approximated by water and the inlet velocity was set to $8\frac{m}{s}$ giving a new Reynolds number of $1.7 \text{ x } 10^4$.

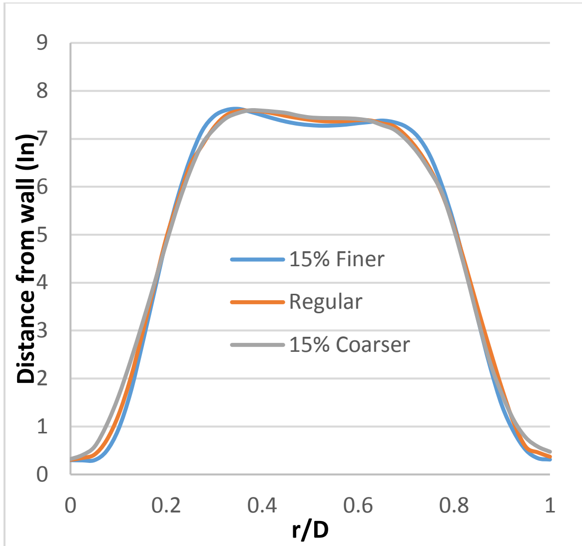
All information obtained from the simulation is from the plane of symmetry which cuts through the center of the nozzle. This plane is depicted on the right of Figure 11 where the line probes and mesh are also displayed. The line probes are created to be perpendicular to the curved surface at all times. Similar octahedral meshing with prism layers was utilized in this simulation. The same three refinement zones were also used: the round jet, the inner, and the outer radial wall jet. A total of 311 thousand cells resulted from the prescribed mesh. Mesh sensitivity of the simulation at two different radial jet locations and round jet are shown below:



(a)



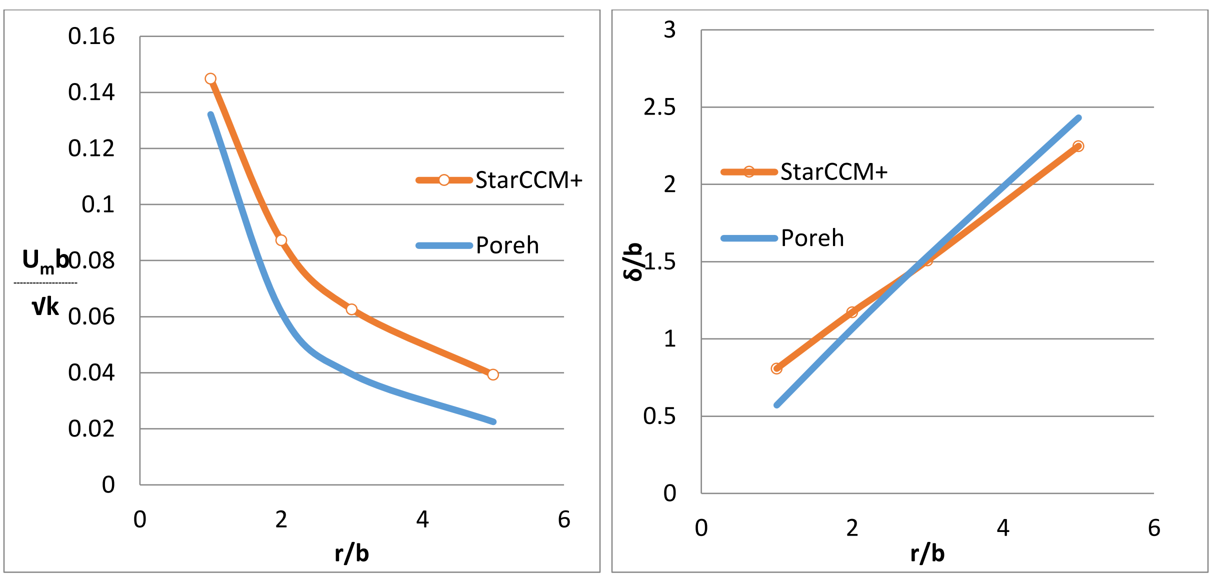
(b)



(c)

Figure 12. Mesh sensitivity based on percentage of base size of radial wall jet measurements at r/b=1 (a), 5 (b), and round jet (c) for PJM geometry.

It was observed that the solution is predominantly independent of the mesh. The characteristic plug profile before impingement of the low b/D ratio can be seen from Figure 12. Below are the comparisons of Poreh's correlation evaluated b/D=1.5 and the curved surface simulation:



(a) (b)

Figure 13. Non-dimensional radial jet correlation comparisons of Um (a) and δ (b) for PJM geometry.

The simulation results indicate that Poreh's correlation for maximum velocity can predict with reasonable accuracy the maximum velocity of the radial wall jet. The trend is with increasing error at a maximum of 40%. The radial wall jet thickness also shows reasonable agreement with Poreh's correlation, with a maximum error of 30%. After an r/b of 5, the PJMs radial wall jets collide with each other, a region in which different physics apply.

Conclusion

A CFD simulation of one of Poreh's original single jet impingement experiments was conducted using the Star-CCM+ software. The radial wall jet velocity profiles between the simulation and Poreh's experiment were seen to have good agreement for both δ and U_m. Once a simulation producing reasonable and physical results was established, the same simulation was run with a b/D ratio pertaining to that of the PJM (i.e., 1.5). The results predicted that the lower b/D ratio did not significantly affect the correlations original accuracy. Although the lower b/D ratio was the main cause of uncertainty in the applicability of the correlations to the PJMs, the comparison was finalized by conducting the same analysis to a scaled down version of the PJM geometry and same Reynolds number.

It was observed that the final PJM simulation predicts that Poreh's correlation is within a reasonable degree of accuracy for the application of pulse jet mixing. For both δ and $U_{m,}$ Poreh's correlation prediction is on the conservative side. It predicts a lower maximum velocity and a smaller characteristic jet thickness. It can therefore be concluded that the use of Poreh's correlation to approximate the characteristic jet thickness and maximum velocity for the radial wall jet of the PJMs is valid.

Path Forward

Further error analysis will be conducted in order to properly quantify the amount of error predicted by the simulations. A study on turbulence modeling will be conducted in order to gain an understanding of its effects to the overall prediction of Poreh's correlation.

Acknowledgements

This research would not have been possible without the collaboration and guidance from Rahul Garg and Pankaj Saha from the NETL stationed in Morgantown, WV. A special thanks to Chris Guenther who helped establish the collaboration between FIU and NETL.

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