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The Effect of Fuel Injector Spacing, Angle, and Blowing Ratio on the Fuel Air Mixing Performance of a Scramjet Engine

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The Effect of Fuel Injector Spacing, Angle, and Blowing Ratio on the Fuel Air Mixing Performance of a Scramjet Engine

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in Mechanical Engineering

By

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Under the mentorship of Dr. Marcel Ilie

ABSTRACT

In the operation of a Scramjet engine, which operates at hypersonic velocities, one of the most important factors is mixing the fuel and air before the high velocity air stream through the engine blows the mixture out of the engine before it could burn. Because of the importance of rapidly mixing fuel and air within a Scramjet engine, there are multiple design elements used to increase mixing. One of which is called a flame holder cavity, which is usually located behind fuel injectors, and designed with an open (length to depth ratio is less than 10) geometry to promote recirculation of the fuel and air. Additional factors which may affect the mixing within the engine are the spacing between fuel injectors, the angle of the fuel injectors, and the blowing ratio of the fuel injectors which is the ratio of fluid entering through the fuel injectors to fluid entering the engines main inlet. These three factors based around the fuel injectors are studied utilizing multiple models of as base scramjet, with modified fuel injectors to test each of these variables. Utilizing the scramjet models prepared in Solidworks, Ansys CFX could then be used to test how the modifications preformed. These tests allow the optimal combination of fuel injector spacing, angle, and blowing ratio to be found.

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I owe thanks to my mechanical engineering friends Kyle Combs and James O'Hara for standing in my corner as they too worked through their own set of research obstacles. Their contributions to my research efforts cannot be overlooked. Other friends in my corner include Justin McCorkle, Jonathan Descarse, and Mason Pryor who were always there when I needed a break or motivation.

Finally, I owe much of my gratitude to my family. My mother, father, and sister have been there for me since day one, and I can say with utmost certainty that this would not have been possible without their undying love and support.

Thank you all.

Introduction

A scramjet is a variant of the jet engine that has no moving parts, and operates at supersonic, and hypersonic velocities. In a scramjet engine the fuel must be injected in a manner that causes it to mix rapidly with the supersonic airstream, or risk blowing unburnt fuel out of the engine. This need for rapid mixing of fuel and air within the engine is important because the dwell time of air within the engine's combustion chamber is short, usually only measurable in milliseconds or smaller units. One design that can help increase the speed of mixing of fuel and air is by using multiple parallel fuel injectors. An additional design element that can improve the mixing performance of a scramjet is by adding a flame holder cavity. A flame holder can be classified as open or closed, with an open flame holder having a length to death ratio of seven to ten, while a closed flame holder has a length to death ratio of ten to thirteen. An open flame holder cavity combined with flush mounted fuel injectors can improve the mixing performance of a scramjet, which will increase the overall performance of the jet engine. In scramjets where multiple fuel injectors were utilized the spacing of the fuel injectors can impact the mixing performance, in a test between injectors spaced 18mm center to center and 54mm center to center, resulted in finding that the further spaced jets lead to better mixing characteristics for the fuel and air mixture. [1]

An additional part of the design of a scramjet that can be varied to increase the amount of mixing between the mainstream through the center of the jet, and the fuel being injected is by varying the blowing ratio. The blowing ratio is the ratio between the velocity of the mainstream to the velocity of the stream from the fuel injectors. A study of the effects of changing the blowing ratio of a scramjet by changing fuel pressure found that as the pressure increased, the mixing increased, but the mixture had a lower dwell time within the engine, indicating that there is a blowing ratio that strikes a balance between mixing of the fuel and air, and the dwell time of the mixture. [2]

An additional modification that can be made to a scramjet engine is a ramp at the rear of the flame holder. The addition of a ramp at the rear of a flame holder cavity can affect how the fluid recirculates within the cavity. Additionally, a flame holder cavity can experience velocity fluctuations near the bottom of the cavity, and vertical fluctuations near the rear of the cavity, both of which can be reduced via the addition of a ramp at the rear of the cavity. This reduction in velocity fluctuations means that a ramp at the rear of a scramjet flame holder creates a smoother flow within the cavity when compared to a cavity without a ramp. A ramp at the rear of the flame holder cavity can also increase the efficiency of a scramjet engine by reducing pressure drag that a flame holder can induce. [3]

An additional modification that can be made to a scramjet flame holder cavity is its dimensions, making it either opened or closed. The classification of a flame holder cavity is based on the ratio of its length to its depth. An open flame holder is defined by having a length over depth ratio less than 10, while a closed flame holder has a length to depth ratio greater than 14. A flame holder cavity length to depth ratio of 7 can be considered to be a transitional flame holder. In an experiment comparing open, closed, and transitional flame holder cavities found that a transitional flame holder cavity with a length to depth ratio of 7 to be the most effective at reducing shockwaves within the cavity. [4]

An additional variable that can affect the efficacy of a scramjet engine is the angle of attack, which is the angle between the jet engine and the flow of air. The angle of attack can change how a flame holder cavity behaves, changing it from behaving like an open flame holder to behaving like a closed flame holder. The difference in flame holder behavior is that the fluid recirculates in an open flame holder, while in a closed flame holder, the fluid will enter and exit without recirculation. In a study that tested a flame holder cavity that would be classified as open at zero angle of attack, operating with a hypersonic flow, found that at -10° of angle of attack the flame holder still behaved as an open flame holder, but when the angle of attack was changed to -15°the flow behavior within the flame holder changed top that of a closed flame holder. [5]

A scramjet engine can also be influenced by the implementation of a shock generator. A shock generator is a geometric feature within the engine that is designed to create a shockwave then the engine is operating. The location of the shock generator, and the resulting shock wave can influence the flow within the scramjet engine. In a study that focused on shock waves from shock generators, it was found that if the shockwave was close to the fuel injector jet, then the strength of the flame holder vortex would be reduced. While the shock does reduce the strength of the flame holder vortex, it also increases turbulent mixing within the engine by causing more area of the flame holder to have turbulent flow within it. [6]

Another concern in the operation of a Scramjet engine is how to ignite the fuel air mixture. In an experiment that tested a dual flame holder scramjet, with one flame holder behind the other, and fuel injectors above and below the front of each flame holder found that the front flame holder could be partially covered to provide more suitable conditions for ignition. The issue that comes from this configuration if the partially covered flame holder could affect combustion once the engine has been ignited. The effect on combustion could be mitigated by making the baffle of a material with a low melting point that will melt away leaving o normal flame holder once ignition has occurred to stabilize combustion. [7]

Compared to gaseous fuels such as hydrogen, liquid fuels such as kerosene are desirable for usage in scramjets, but poses many challenges that are unique to liquid fuel. One of the main challenges in the usage of liquid fuel is the ignition of the engine. In order to ignite a liquid fueled scramjet, the igniter must be placed where the fuel will be, so the fuel distribution of a scramjet with a flow through it at Mach 5.5 was used to test this. The experimental scramjet was constructed with 4 fuel injectors placed in front of a pair of in line flame holders. The experiment found that the front of the flame holders was fuel lean, and the rear was fuel rich making the midpoint an ideal area for an igniter, the kerosene fuel enters the cavity through a sheer layer at a predictable angle, and that as fuel injector pressure increases it penetrates higher into the airstream through the engine but less fuel enters the flame holder. [8]

In the operation of a scramjet engine with a flame holder cavity combustion oscillation may occur. In a study of these oscillations there were multiple causes found. The first cause of combustion oscillations was found to be an unsteady spread of the flame from the flame holder cavity to the main stream through the engine, which produced low frequency oscillations. The second cause of the oscillations is auto ignition of packets of jet fuel that form, and are accompanied by hairpin vortices, which produces high frequency oscillations. [9]

In addition to a traditional flame holder, a scramjet can be designed with a rear wall expansion chamber, which typically includes a ramp at the rear of the flame holder, and then a slight angle of the outlet starting from the flame holder going backwards, leading to a larger engine outlet. An engine with this modification was studied to see how well the flame would stabilize with thew addition of the rear wall expansion cavity. The study found that the most intense heat release from the combustion was close to the flame holder cavity rear wall, and that if the equivalence ratio of the fuel or the rear wall height was lowered, then the most concentrated area of heat release would move further from the rear wall of the engine, towards the exhaust. Additionally, it was found that the addition of a rear wall expansion cavity would prevent thermal choking in the combustor. [10]

The distance between the fuel injectors and the front of a flame holder cavity can have a large impact on the performance of a scramjet engine. An experiment was conducted involving the fuel injector placement from the flame holder, with a freestream velocity of Mach 1.9, and fuel injectors placed .1L, .5L, and 1L, with L being the length of the flame holder. The experiment found that the injector being placed at .1L lead to enhanced mixing within the flame holder. [11]

Experimental Setup

This experiment was performed using computer simulations, utilizing Solidworks and Ansys. Solidworks was used to model 12 variants of a scramjet. All the models had an inlet and outlet that was 100x100mm, and each jet was 1.25mm long. Additionally, each model had a pair of fuel injectors with a diameter of 13.2mm, and a rectangular open flame holder with a height of 20mm, and length of 100mm. Each fuel injector was spaced 10mm form the flame holder to the center of the fuel injector. There were only two variables that were changed in the models. The first variable that was changed was the distance between the fuel injectors, which was 18mm, 54mm, or 82mm. The second variable that was changed was the angle of the fuel injector, which was 90°, 60°, 45°, and 30°. These variants allowed the effects of nozzle spacing and nozzle angle on the mixing of fuel and air within the engine.

After each variant of the scramjet was modeled, it was saved and imported into an Ansys CFX simulation. In the setup of the CFX simulation a speed of 10m/s as the inlet was set, with no flow restriction at the outlet, and smooth walls. The flow entering the fuel injectors is the third variable which was changed. The velocity of the flow into the injectors was set to four different values for each variant of the scramjet. The four velocities of the flow through the fuel injectors were set at 10m/s, 20m/s, 30m/s, and 40m/s. The various velocities of the fuel injection allowed for the study of the blowing ratio on the mixing of fuel and air within the engine. The blowing ratio is the ratio of fuel injected to the air entering through the engine inlet.

After each successful run of the simulation data was collected by placing a YZ plane centered on a fuel injector in the scramjet engine. This plane could be used to study the flow from the inlet of the engine to the fuel injector, through the flame holder, and out the outlet. Additionally, three XY planes were placed in the flame holder cavity to visualize the flow across the entire width of the cavity, at the front middle and back. The positions of the XY planes were at the center of the flame holder, .04mm towards the rear of the flame holder, and .04mm towards the front of the flame holder. The planes were created to provide the locations for contour vector plots that would show the flow within the engine. For each plane, three contour plots, and one vector plot were created to visualize the flow. The first contour plot created for each plane was a pressure contour, with a scale of 0-75 [Pa]. The second contour plot that was created for each plane was turbulence kinetic energy, with a scale of 0-1 $m^2 s^2$. The third contour plot that was created shows the velocity with a scale of 0-40 m/s. Each contour plot was created with 30 contours. The vector plots for each plane showed the velocity, using the equally spaced sampling method, with 5000 points, and used tangential projection.

Results

Figures 1, 2, 3, and 4 show the side view of the velocity vector plot of the scramjet with injectors spaced at 18mm, and the angle of the injectors is 90^0. The pictures can be used to compare the results of changing the blowing ratio on the turbulent mixing occurring in the engine. Figure 1 has a fuel injector inlet velocity of 10 m/s, in figure 2 it is 20m/s, in figure 3 it is 30m/s, and in figure 4 it is 40 m/s. In these figures, there is a small area of recirculation above the flame holder, that raises higher above the flame holder as the blowing ratio increases. In all scenarios where an engine with a fuel injector spacing of 18mm was tested the area of recirculation never touches the bottom of the flame holder, or even occurs within the flame holder, which is where recirculation is desired. In the engine with fuel injectors spaced at 18mm the highest mixing performance was seen at the lowest blowing ratio, with a fuel injector velocity of 10m/s, and the lowest mixing performance at the highest blowing ratio, with a fuel injector velocity of 40m/s.

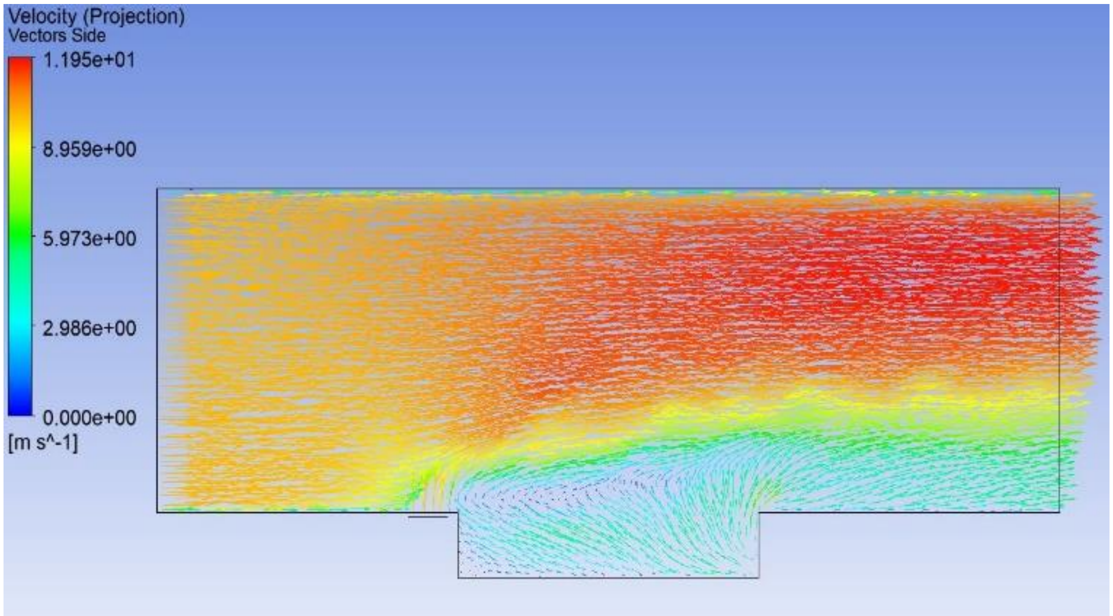

Figure 1. Side view of vectors, 18 mm injector spacing, 90° injector angle, and 10 m/s injector inlet velocity.

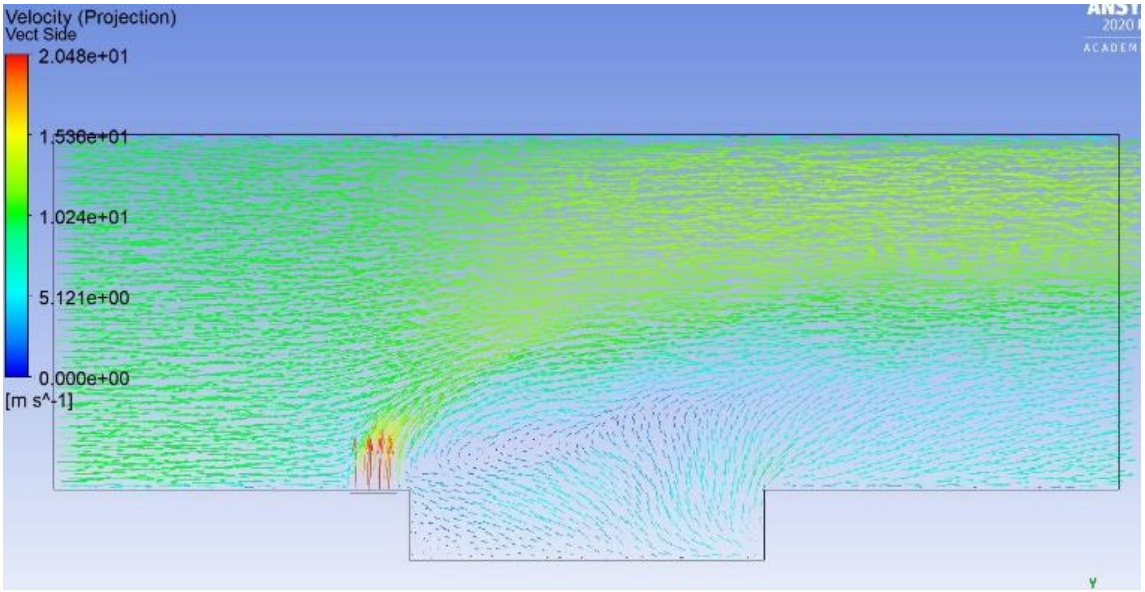

Figure 2. Side view of vectors, 18 mm injector spacing, 90° injector angle, and 20 m/s injector inlet velocity.

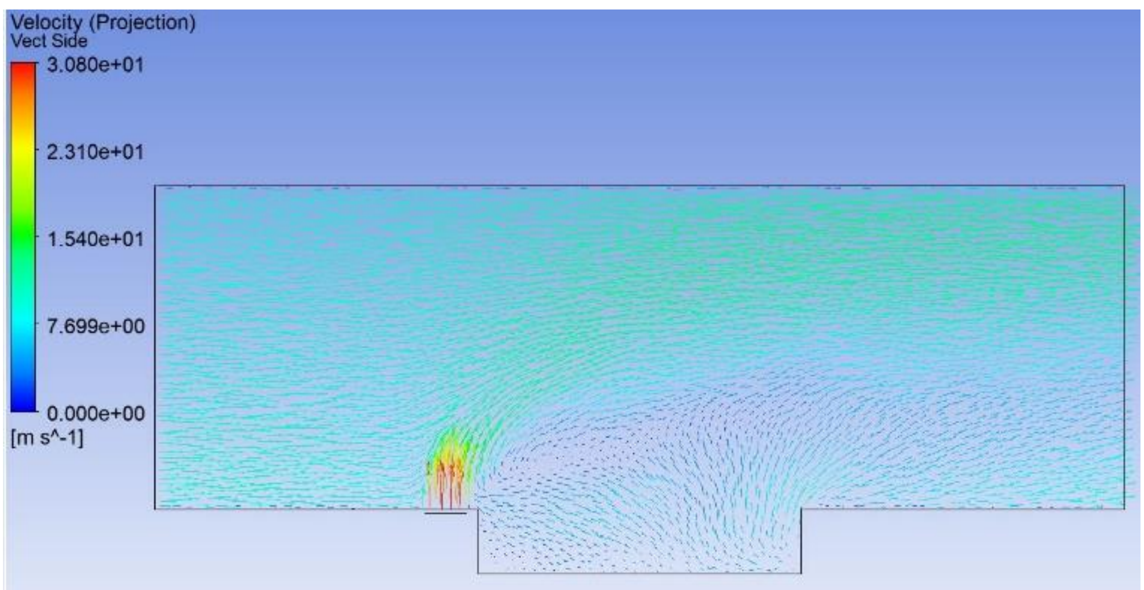

Figure 3. Side view of vectors, 18 mm injector spacing, 90° injector angle, and 30 m/s injector inlet velocity.

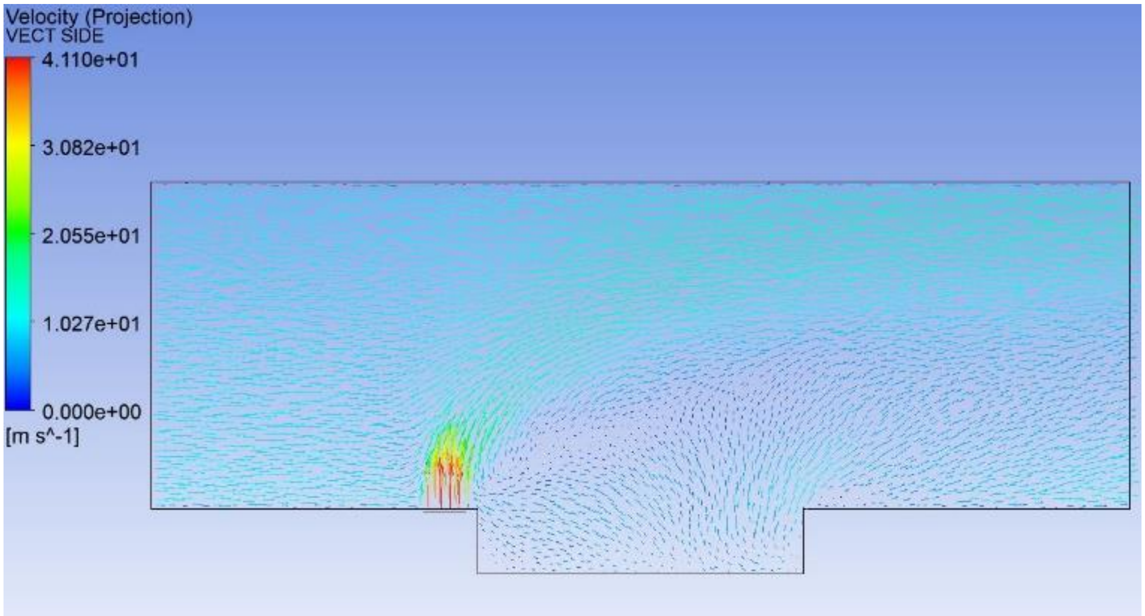

Figure 4. Side view of vectors, 18 mm injector spacing, 90° injector angle, and 40 m/s injector inlet velocity.

Figures 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 are the side view of vector plots like the previous figures, and have the same 18mm injector spacing, and same velocities at the fuel injectors, but the fuel injectors are now at the angles of 60°, 45°, and 30 °. This will allow the effect of the angle of the fuel injector to be studied compared to the 90° angled injectors from figures 1-4, and how changing the blowing ratio affects angled fuel injectors. The injectors in figures 5-8 are angled at 60°, in figures 8-12 the angle is 45° and in figures 13-16 the angle is 30°. The velocity through the fuel injectors in figures 5, 9, and 13 is 10 m/s; 20 m/s in figures 6, 10, and 14; 30 m/s in figures 7, 11, and 15; and 40 m/s in figures 8, 12, and 16. These figures are similar to figures 1-4, all showing an area of recirculation above the flame holder, that raises higher above the flame holder as blowing ratio increases. Additionally, the angle does not seem to impact the recirculation.

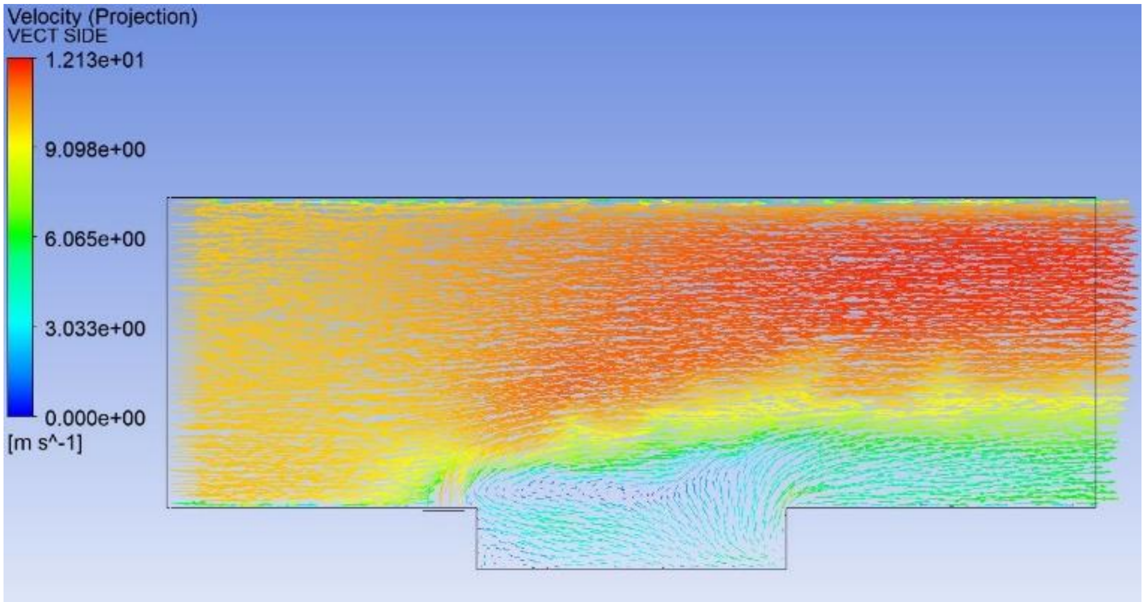

Figure 5. Side view of vectors, 18 mm injector spacing, 60° injector angle, and 10 m/s injector inlet velocity.

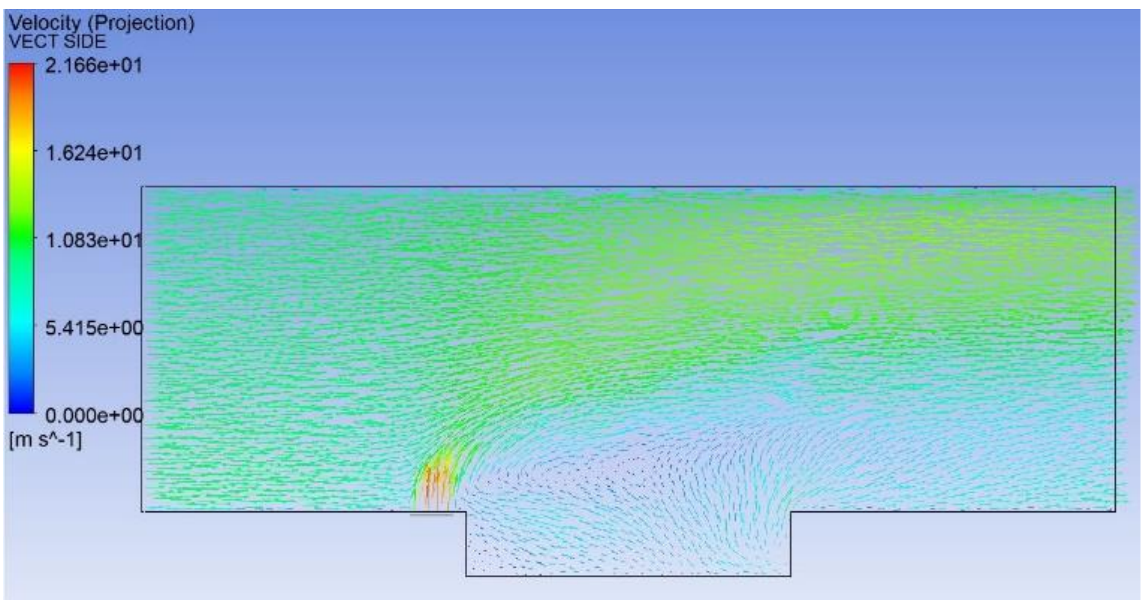

Figure 6. Side view of vectors, 18 mm injector spacing, 60° injector angle, and 20 m/s injector inlet velocity.

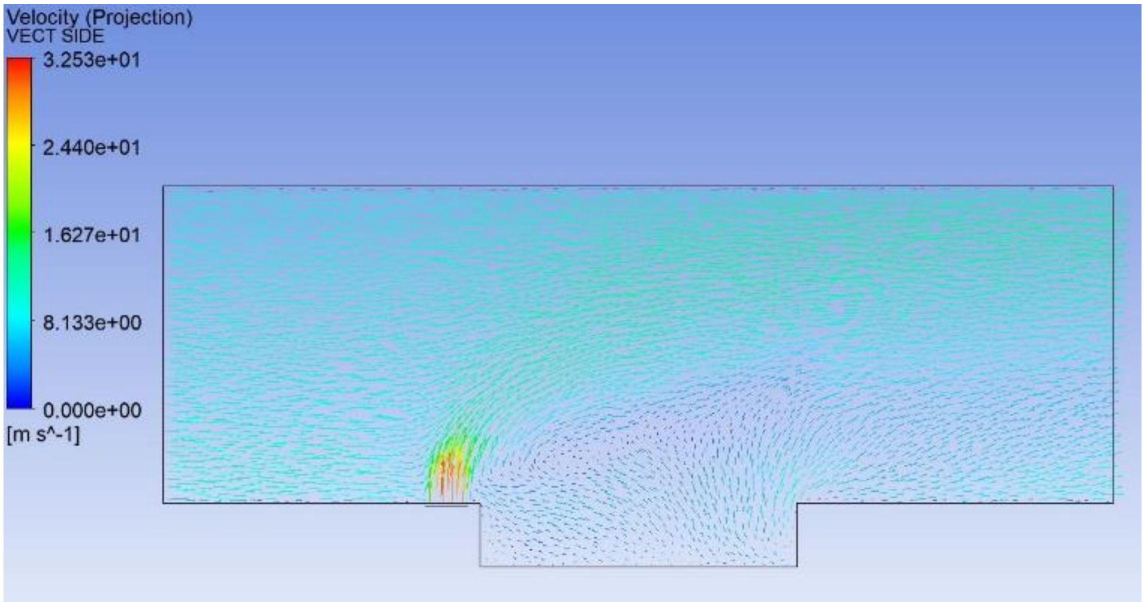

Figure 7. Side view of vectors, 18 mm injector spacing, 60° injector angle, and 30 m/s injector inlet velocity.

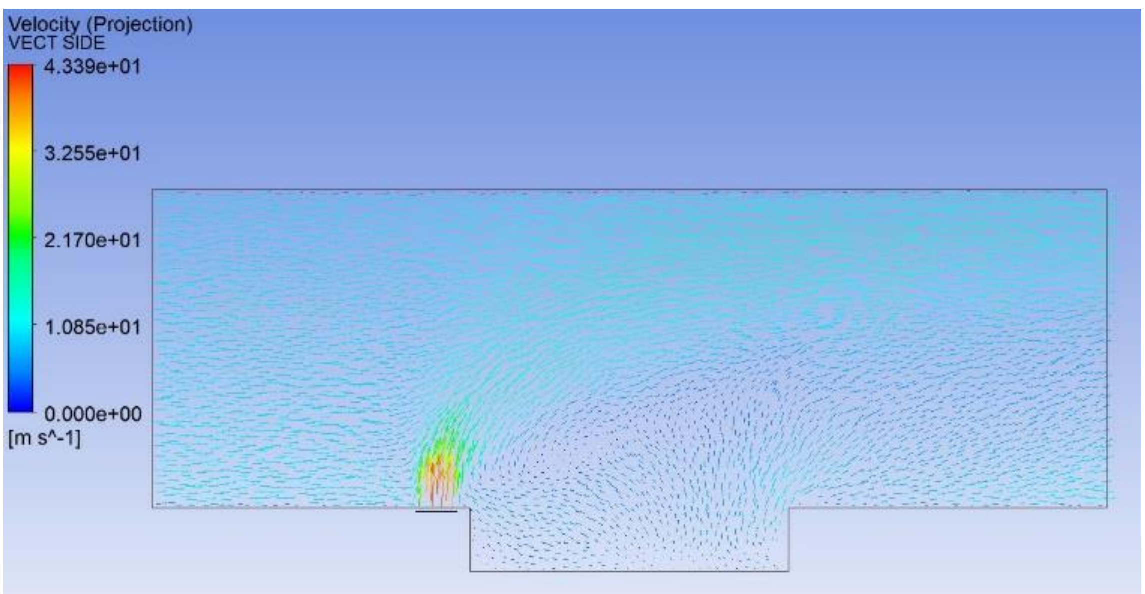

Figure 8. Side view of vectors, 18 mm injector spacing, 60° injector angle, and 40 m/s injector inlet velocity.

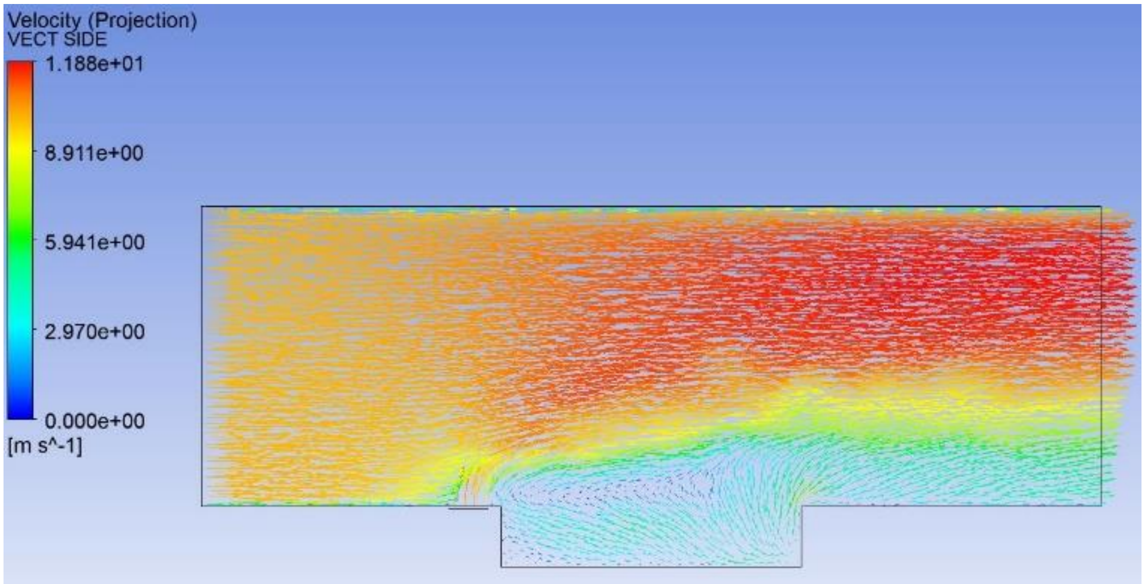

Figure 9. Side view of vectors, 18 mm injector spacing, 45° injector angle, and 10 m/s injector inlet velocity.

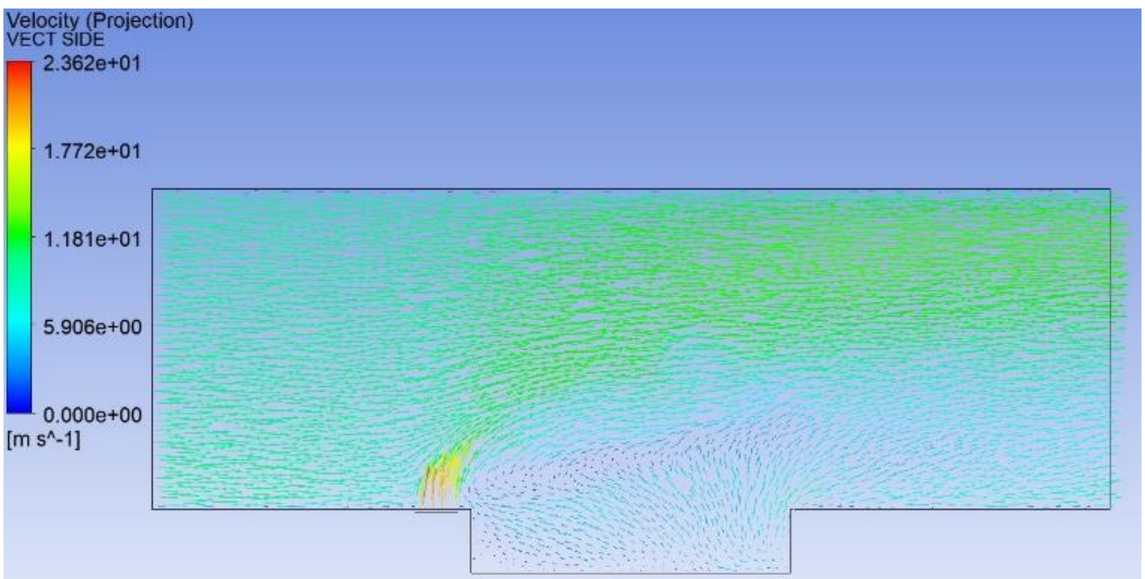

Figure 10. Side view of vectors, 18 mm injector spacing, 45° injector angle, and 20 m/s injector inlet velocity.

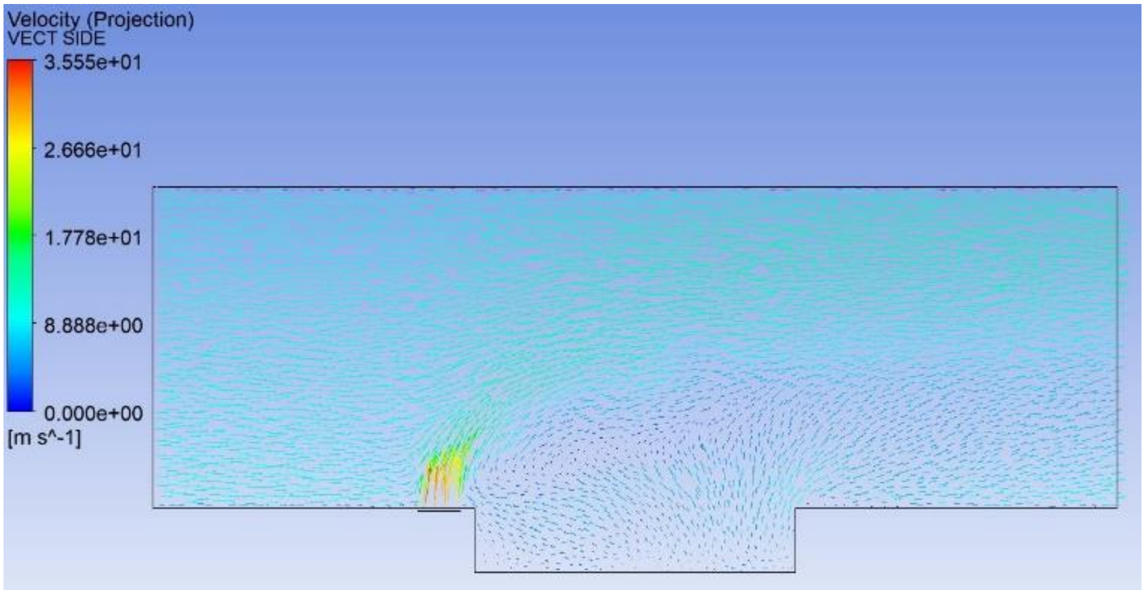

Figure 11. Side view of vectors, 18 mm injector spacing, 45° injector angle, and 30 m/s injector inlet velocity.

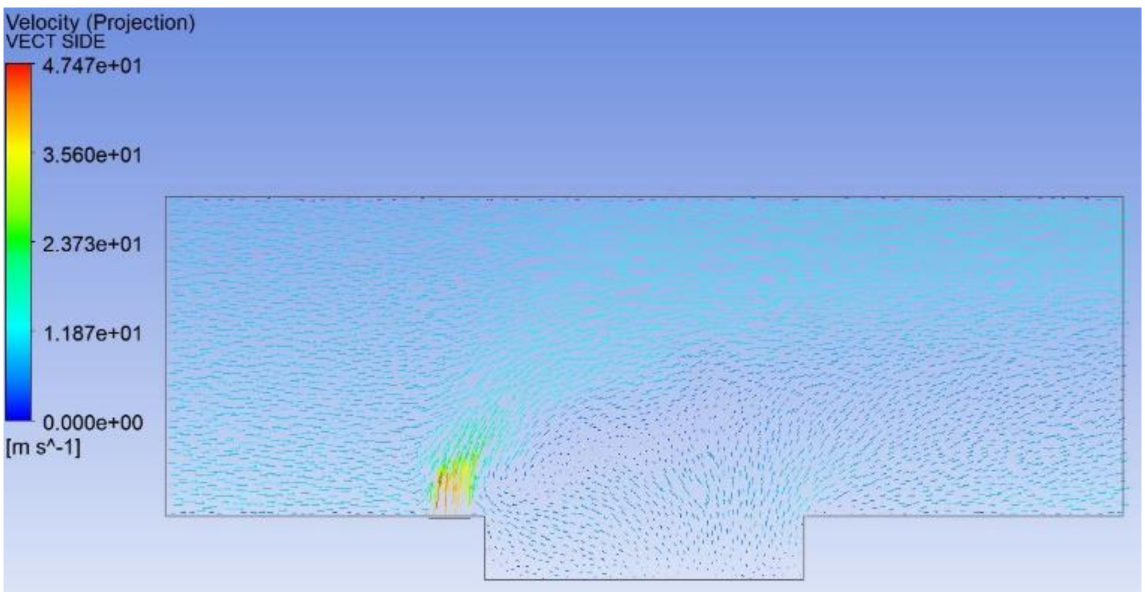

Figure 12. Side view of vectors, 18 mm injector spacing, 45° injector angle, and 40 m/s injector inlet velocity.

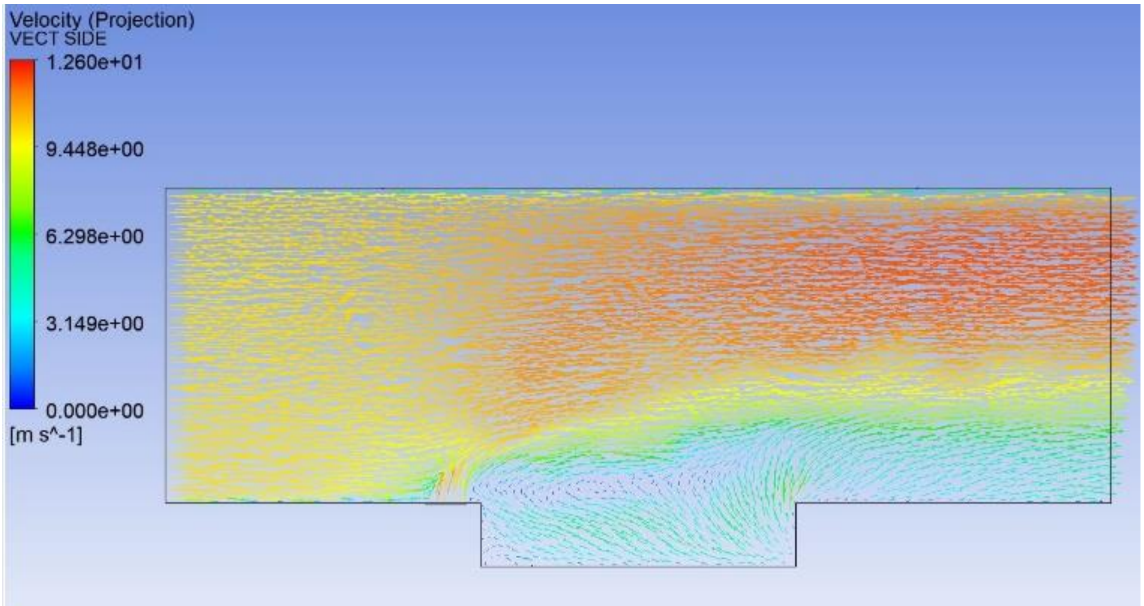

Figure 13. Side view of vectors, 18 mm injector spacing, 30° injector angle, and 10 m/s injector inlet velocity.

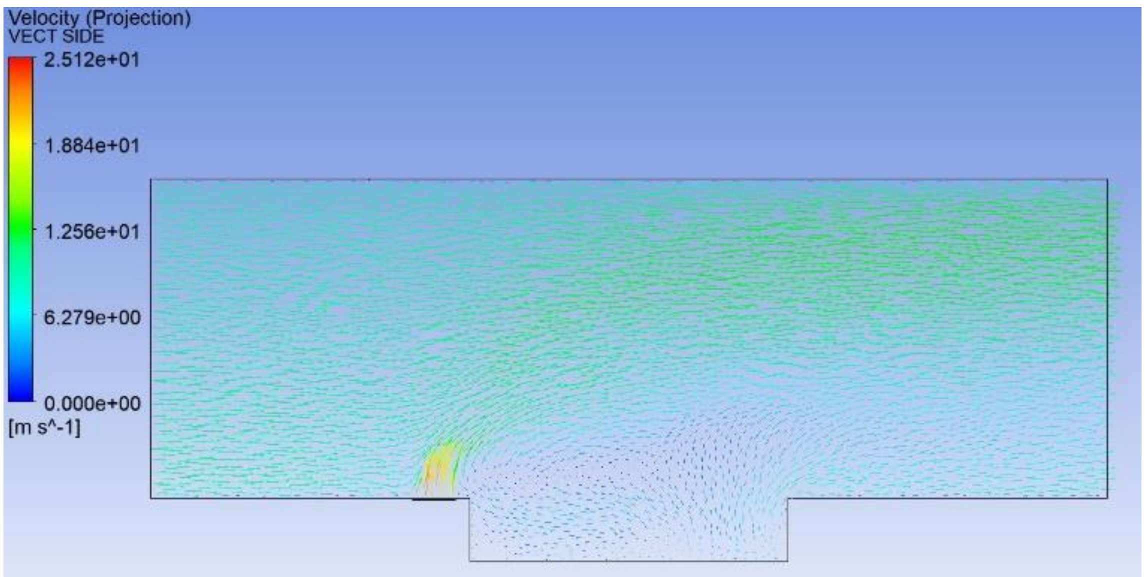

Figure 14. Side view of vectors, 18 mm injector spacing, 30° injector angle, and 20 m/s injector inlet velocity.

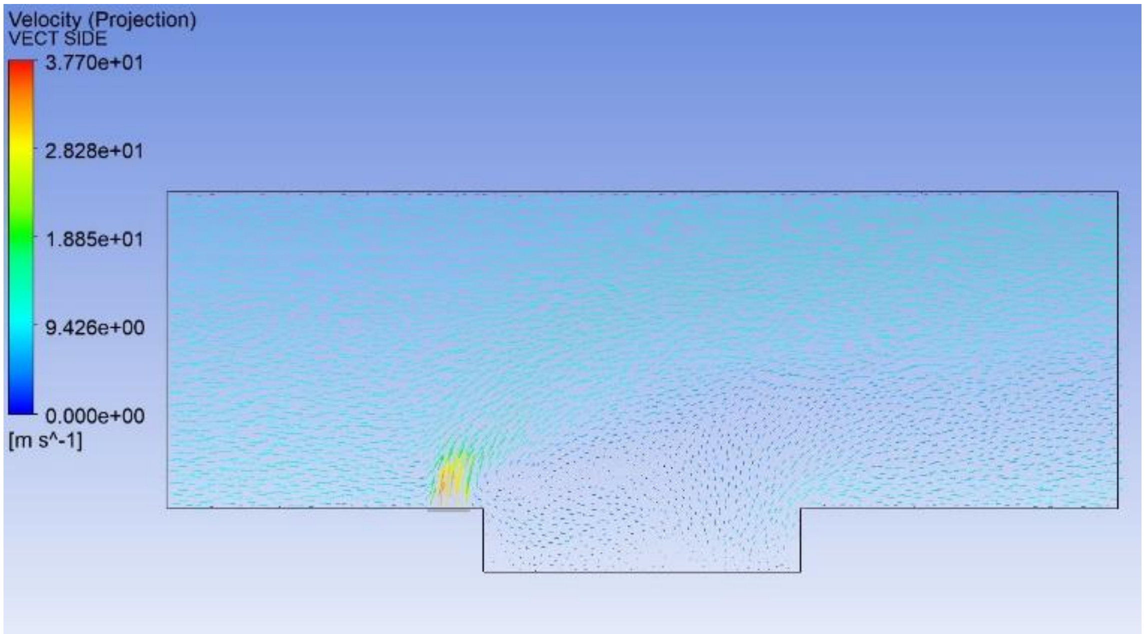

Figure 15. Side view of vectors, 18 mm injector spacing, 30° injector angle, and 30 m/s injector inlet velocity.

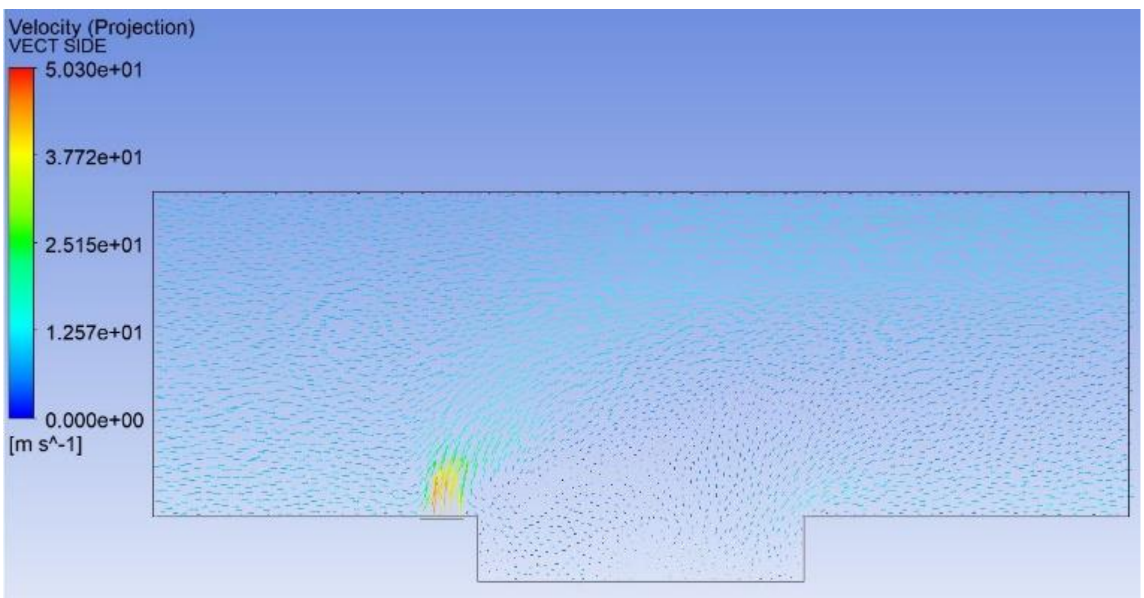

Figure 16. Side view of vectors, 18 mm injector spacing, 30° injector angle, and 40 m/s injector inlet velocity.

Figures 17-20 show the side vector plots of the Scramjet engine with fuel injectors spaced at 54mm, and with a fuel injector angle of 90°. The velocity through the fuel injector in figure 17 was 10 m/s, in figure 18 it is 20 m/s, in figure 19 it is 30 m/s, and in figure 20 it is 40 m/s. These figures show a large area of recirculation within the flame holder, that increases in size as the blowing ratio increases. This is the opposite effect from what increasing the blowing ratio of the engine with 18mm injector spacing experienced. Rather than lifting far above the flame holder, the area of recirculation reached the bottom of the flame holder in all cases, and increasing the blowing ratio, even to the maximum ratio with a fuel injector inlet velocity of 40m/s, only expanded the area of recirculation. This means that the engine with 54mm injector spacing experiences an increase in mixing performance with a higher blowing ratio, with a fuel injector velocity of 40m/s, compared to the lowest blowing ratio with a fuel injector velocity of 10m/s.

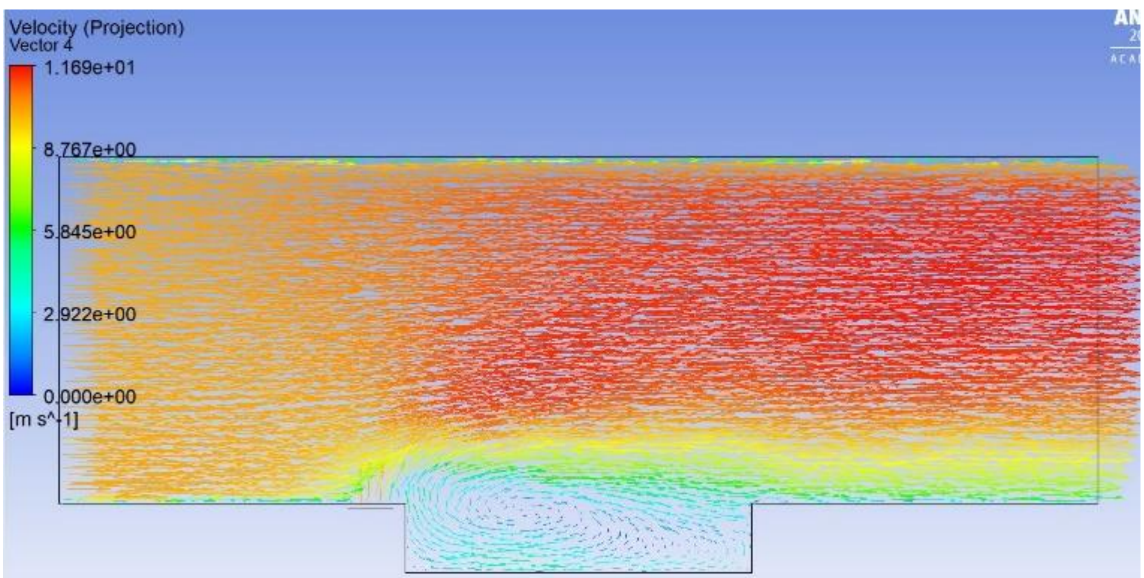

Figure 17. Side view of vectors, 54 mm injector spacing, 90° injector angle, and 10 m/s injector inlet velocity.

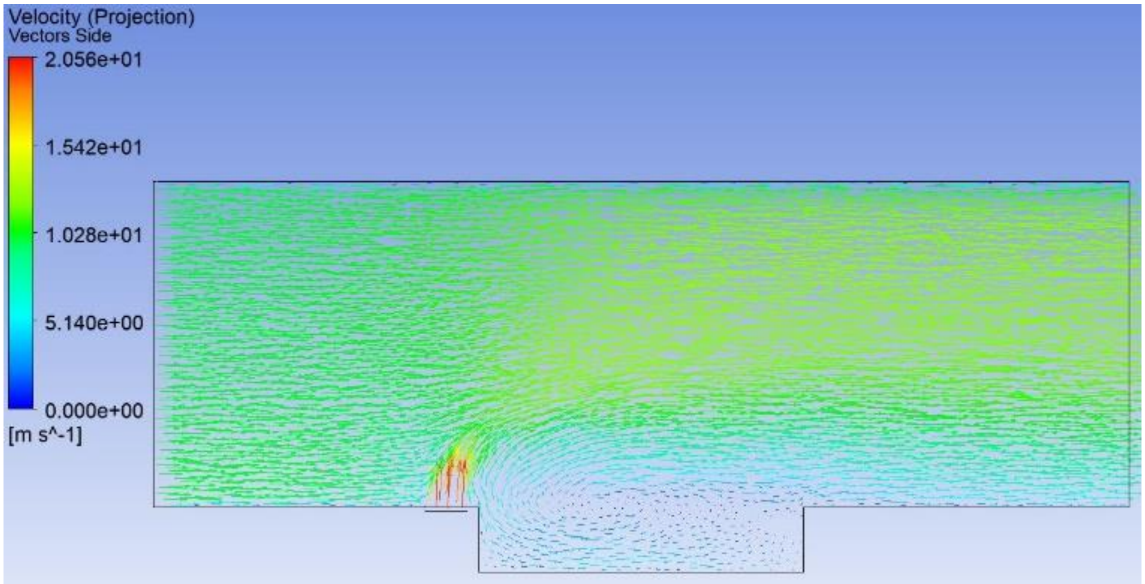

Figure 18. Side view of vectors, 54 mm injector spacing, 90° injector angle, and 20 m/s injector inlet velocity.

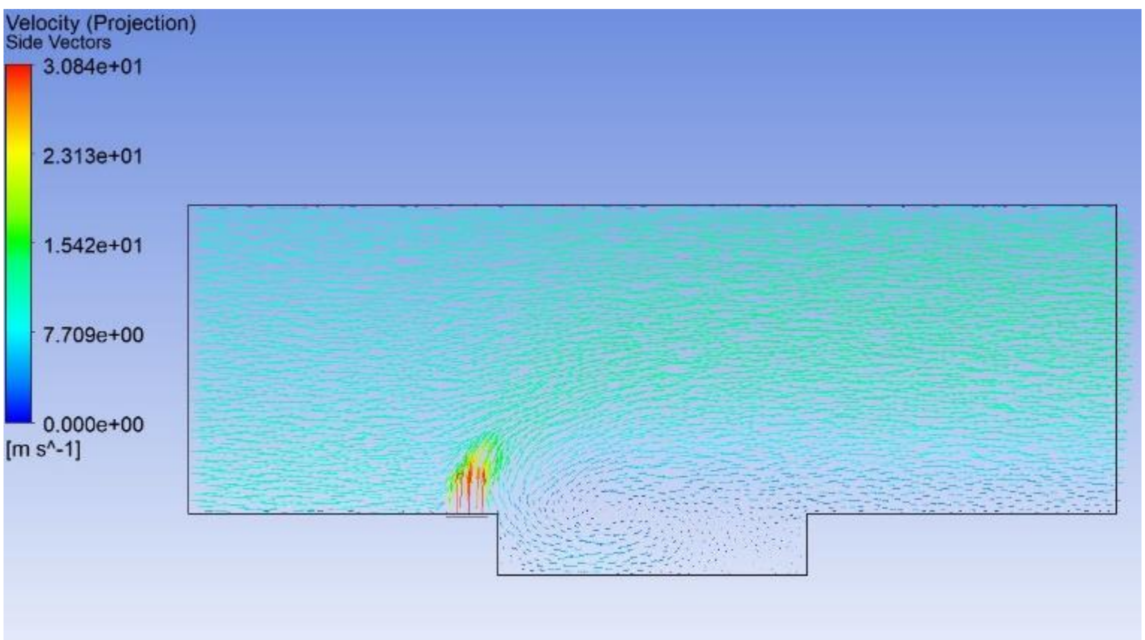

Figure 19. Side view of vectors, 54 mm injector spacing, 90° injector angle, and 30 m/s injector inlet velocity.

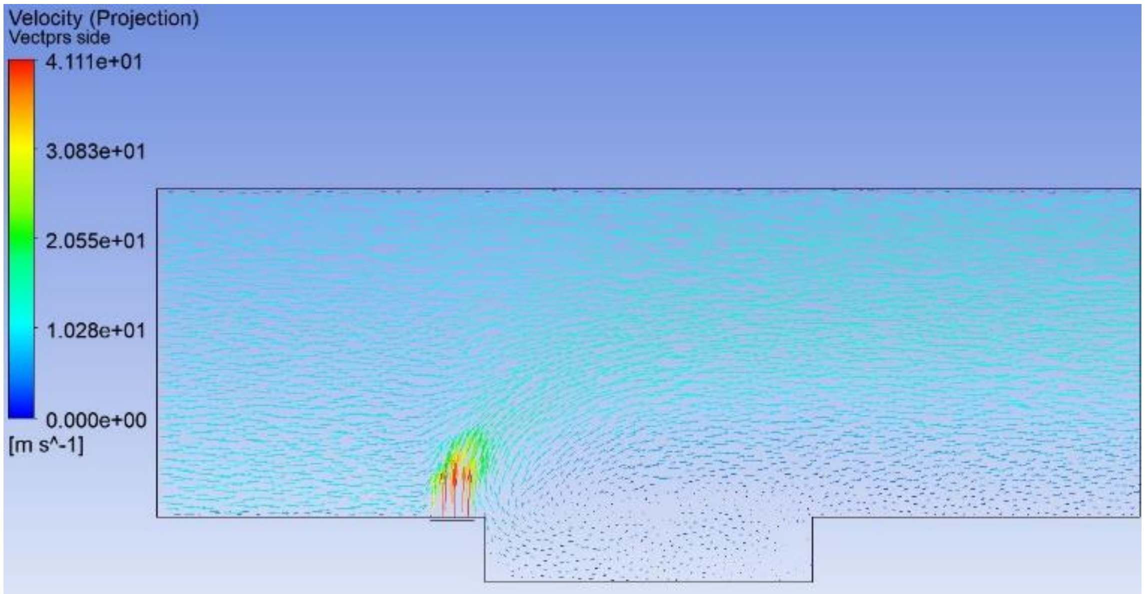

Figure 20. Side view of vectors, 54 mm injector spacing, 90° injector angle, and 40 m/s injector inlet velocity.

Figures 21-32 show the side vector plot of the scramjet with 54 mm spacing between the fuel injectors. Figures 21-24 show the fuel injectors at a 60° angle, figures 25-28 show the fuel injectors at a 45° angle, and figures 29-32 show the fuel injectors at a 30° angle. Figures 21, 25, and 29 have a velocity of 10 m/s through the fuel injectors; the velocity through the fuel injectors is 20 m/s in figures 22, 26, and 30; the velocity through the fuel injectors is 30 m/s in figures 23, 27, and 31; and the velocity through the fuel injectors is 40 m/s in figures 24, 28, and 32. These figures are similar to figures 17-20, with a large area of recirculation within the flame holder cavity, that increases in size with increases in blowing ratio. The angles did not seem to affect the size of the recirculation area.

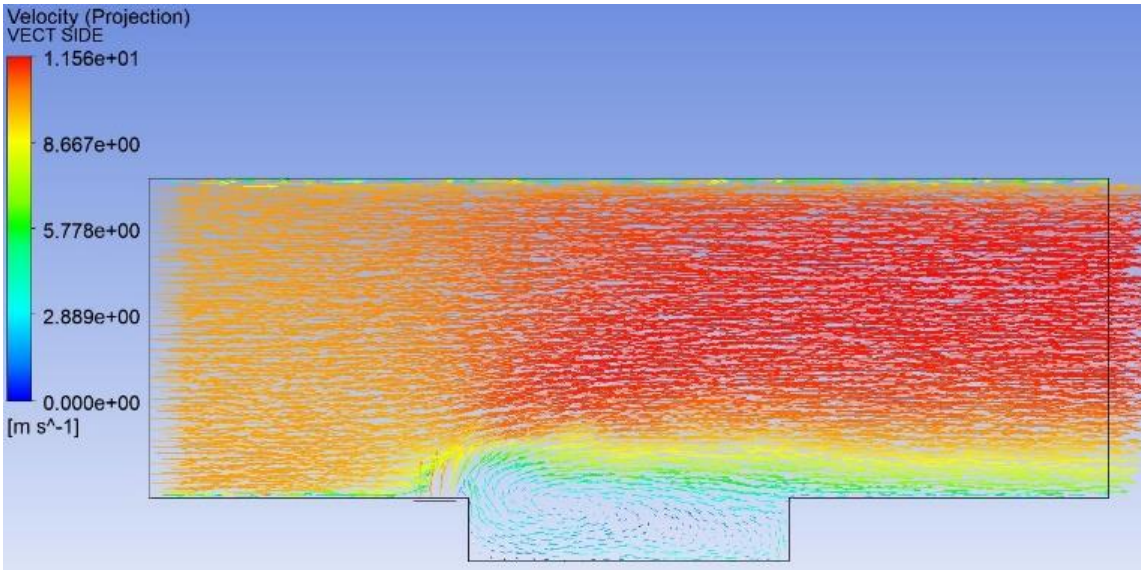

Figure 21. Side view of vectors, 54 mm injector spacing, 60° injector angle, and 10 m/s injector inlet velocity.

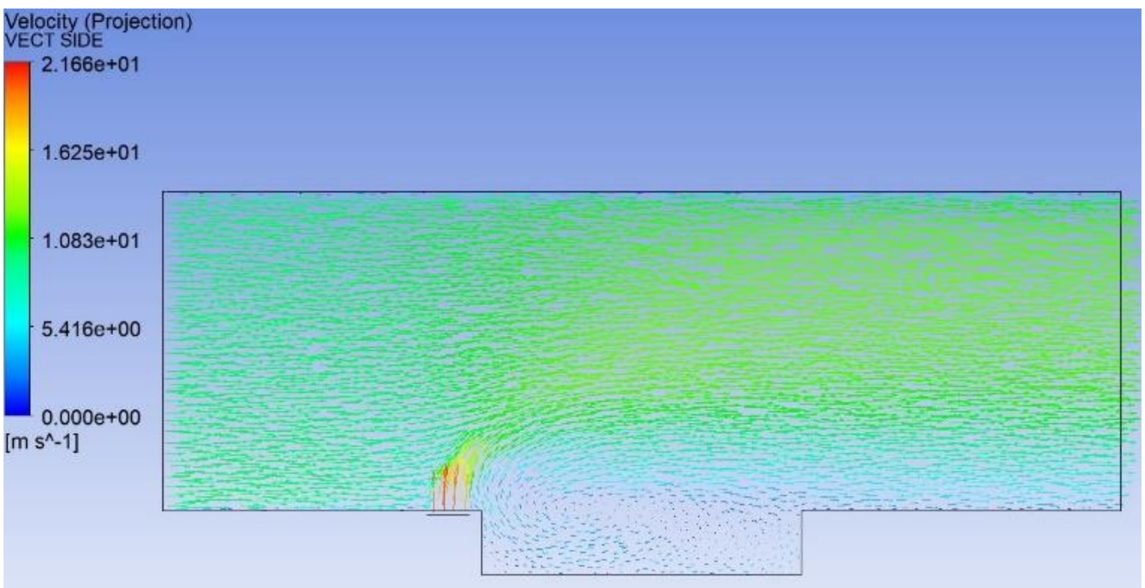

Figure 22. Side view of vectors, 54 mm injector spacing, 60° injector angle, and 20 m/s injector inlet velocity.

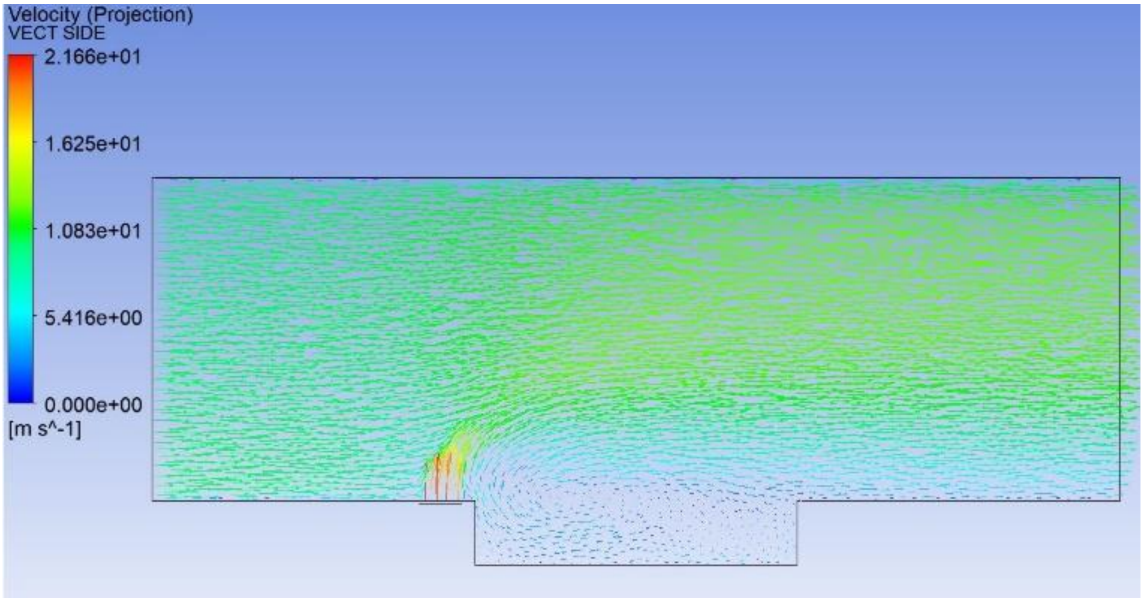

Figure 23. Side view of vectors, 54 mm injector spacing, 60° injector angle, and 30 m/s injector inlet velocity.

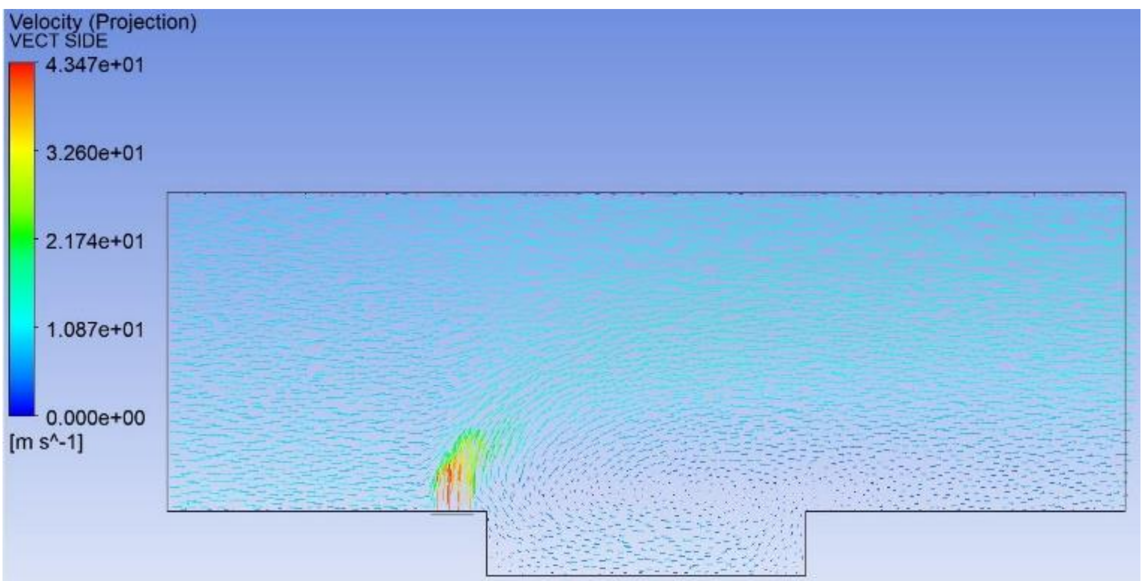

Figure 24. Side view of vectors, 54 mm injector spacing, 60° injector angle, and 40 m/s injector inlet velocity.

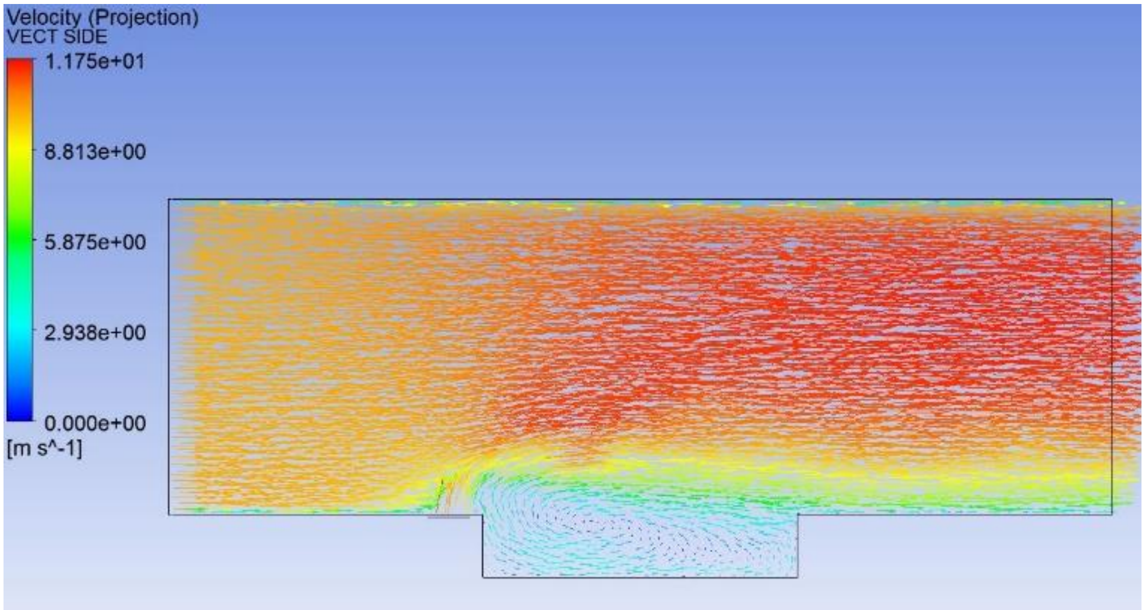

Figure 25. Side view of vectors, 54 mm injector spacing, 45° injector angle, and 10 m/s injector inlet velocity.

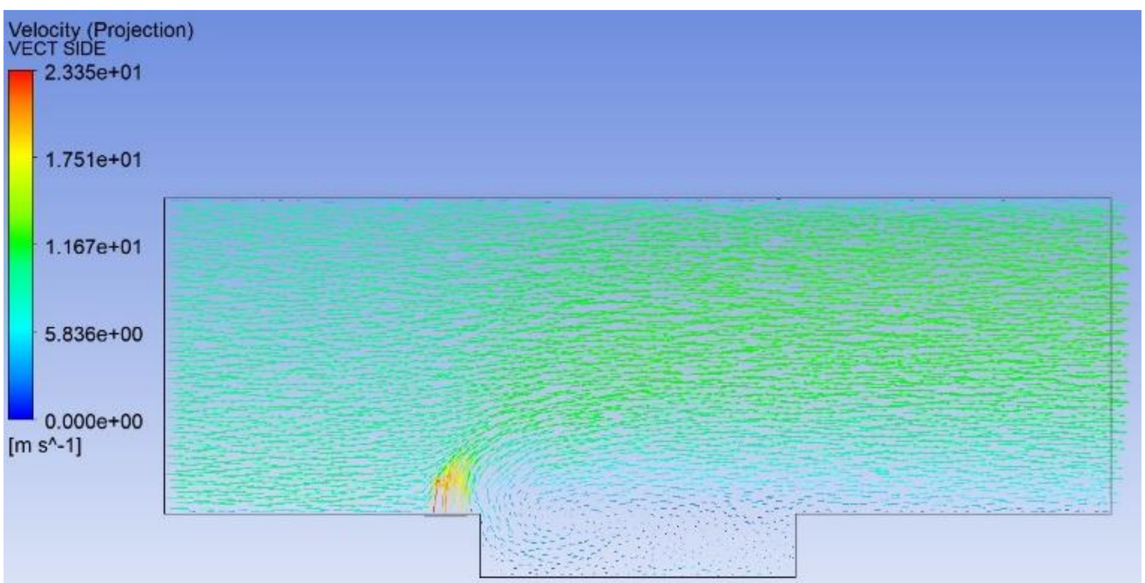

Figure 26. Side view of vectors, 54 mm injector spacing, 45° injector angle, and 20 m/s injector inlet velocity.

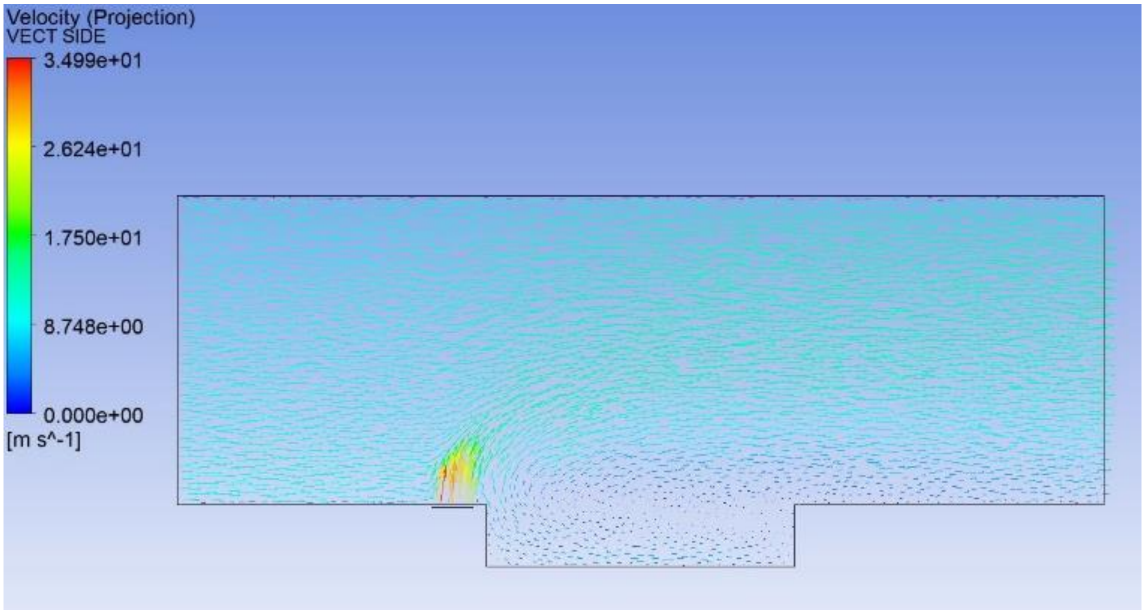

Figure 27. Side view of vectors, 54 mm injector spacing, 45° injector angle, and 30 m/s injector inlet velocity.

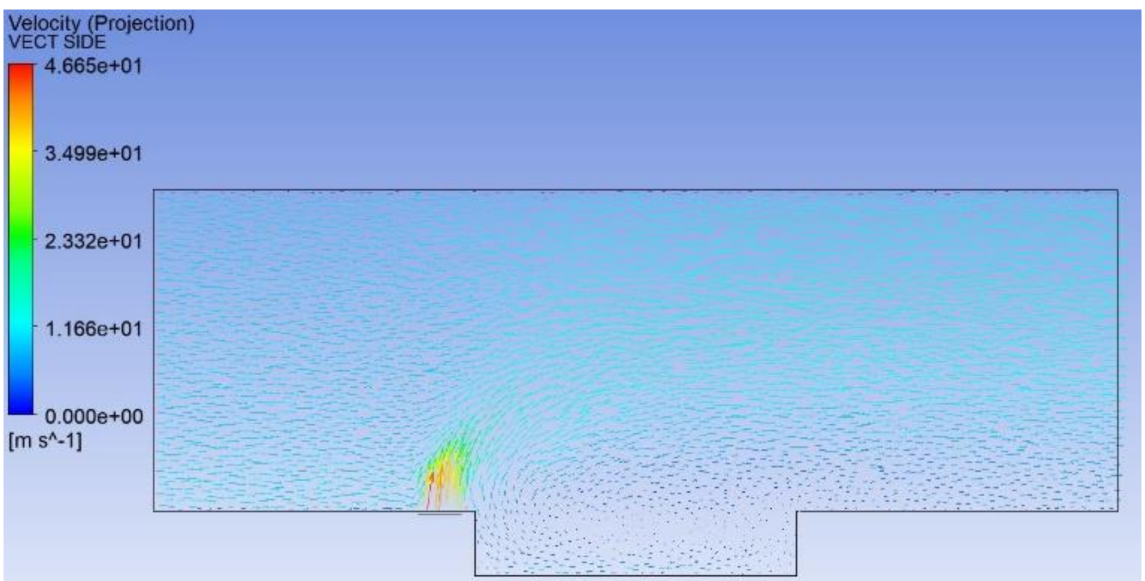

Figure 28. Side view of vectors, 54 mm injector spacing, 45° injector angle, and 40 m/s injector inlet velocity.

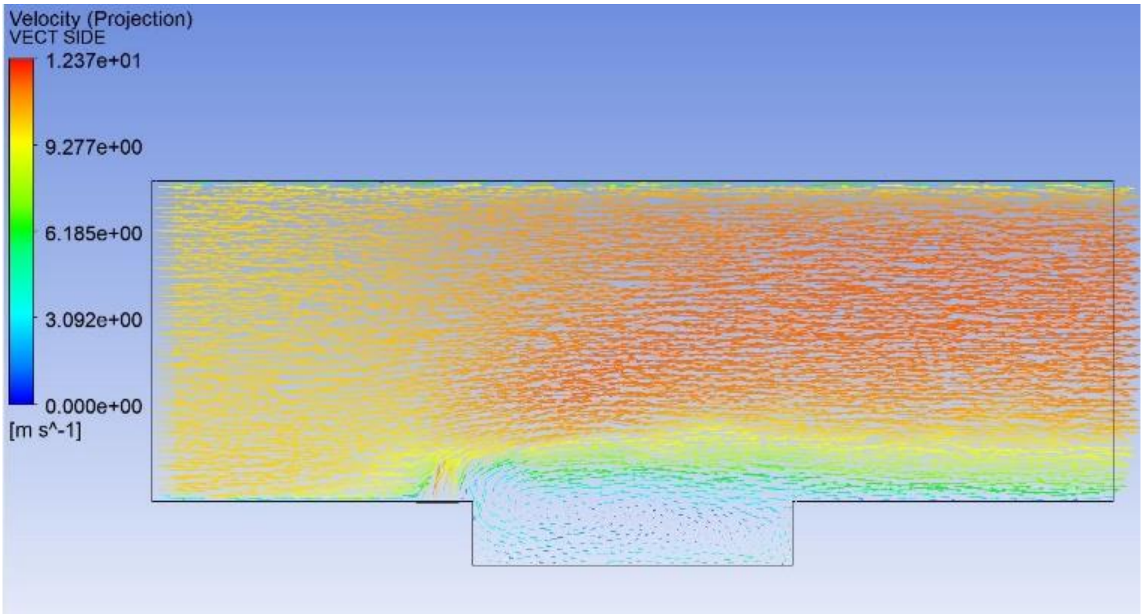

Figure 29. Side view of vectors, 54 mm injector spacing, 30° injector angle, and 10 m/s injector inlet velocity.

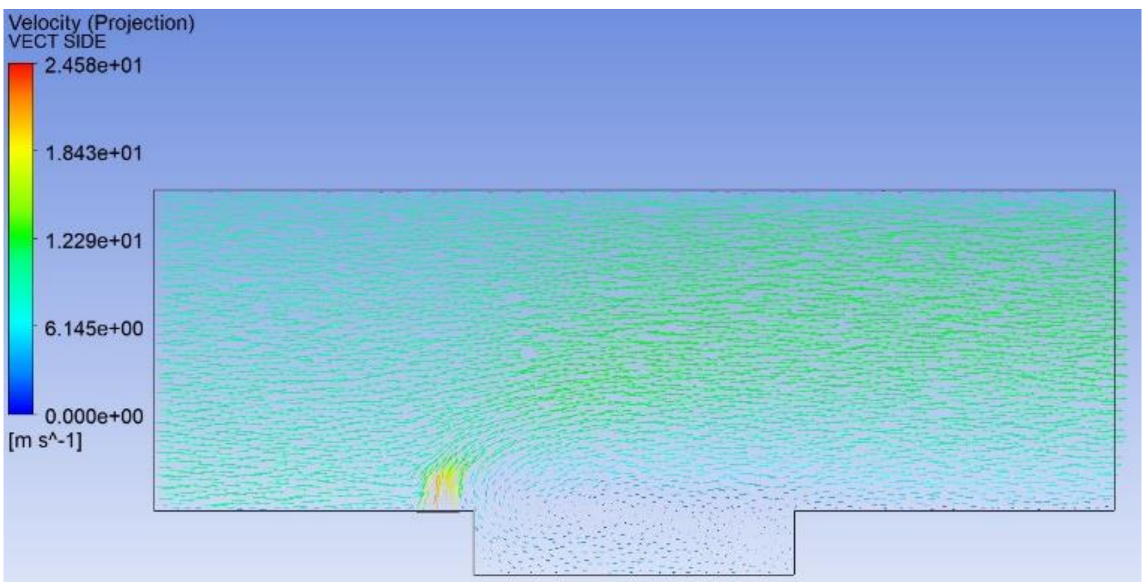

Figure 30. Side view of vectors, 54 mm injector spacing, 30° injector angle, and 20 m/s injector inlet velocity.

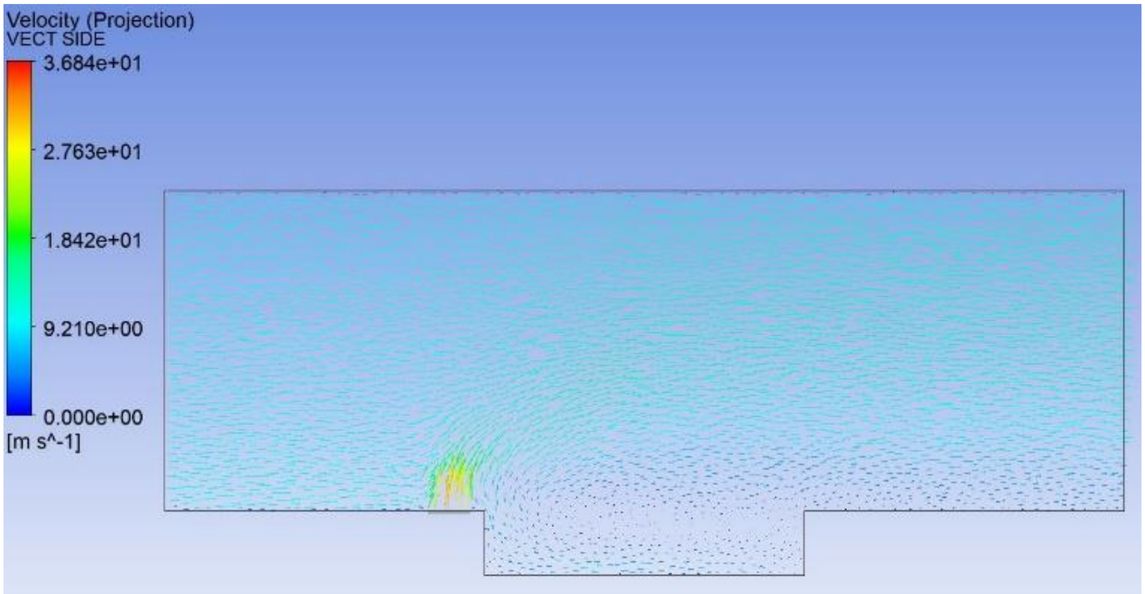

Figure 31. Side view of vectors, 54 mm injector spacing, 30° injector angle, and 30 m/s injector inlet velocity.

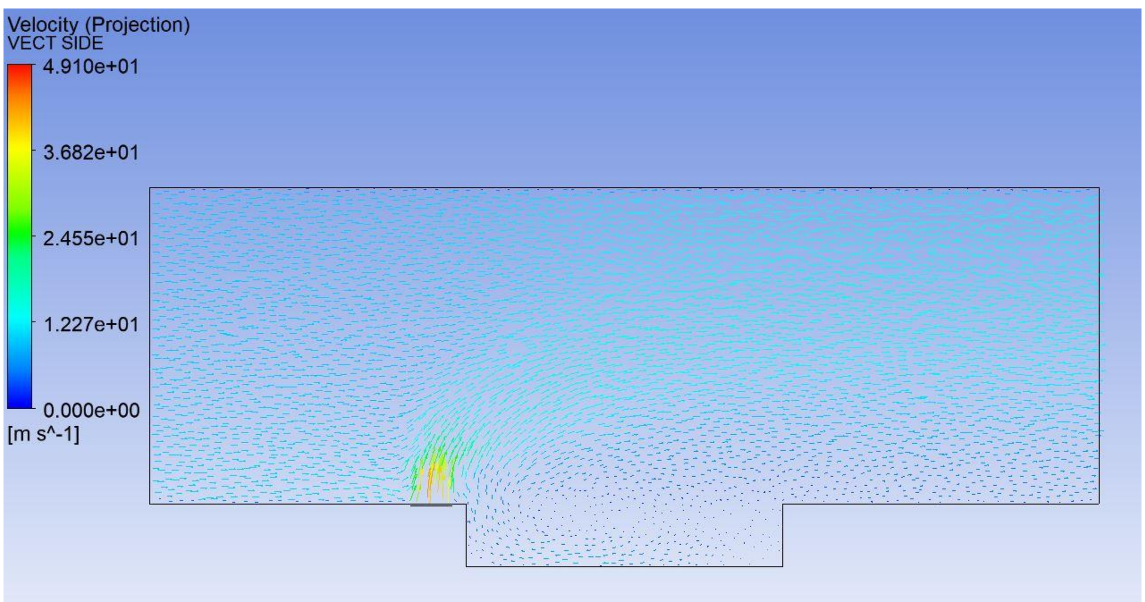

Figure 32. Side view of vectors, 54 mm injector spacing, 30° injector angle, and 40 m/s injector inlet velocity.

Figures 33-36 show the side vector plot of the scramjet with the injectors at an angle of 90°, and with a fuel injector spacing of 82mm. The velocity of the flow through the fuel injector is 10 m/s in figure 33, it is 20 m/s in figure 34, is 30m/s in figure 35, and 40 m/s in figure 36. In these figures a small area of recirculation is present above the flame holder, that shrinks and rises as blowing ratio is increased. At the maximum blowing ratio tested, which was with a fuel injector velocity of 40m/s, the recirculation shrinks to an extremely small area, and raises very high into the engine above the flame holder, causing a decrease in mixing performance compared to the lowest blowing ratio with a fuel injector velocity of 10m/s. This can be observed in all cases with injectors spaced at 82mm, regardless of the injector angle, and is similar to the engine with a fuel injector spacing of 18mm, but to a more extreme degree.

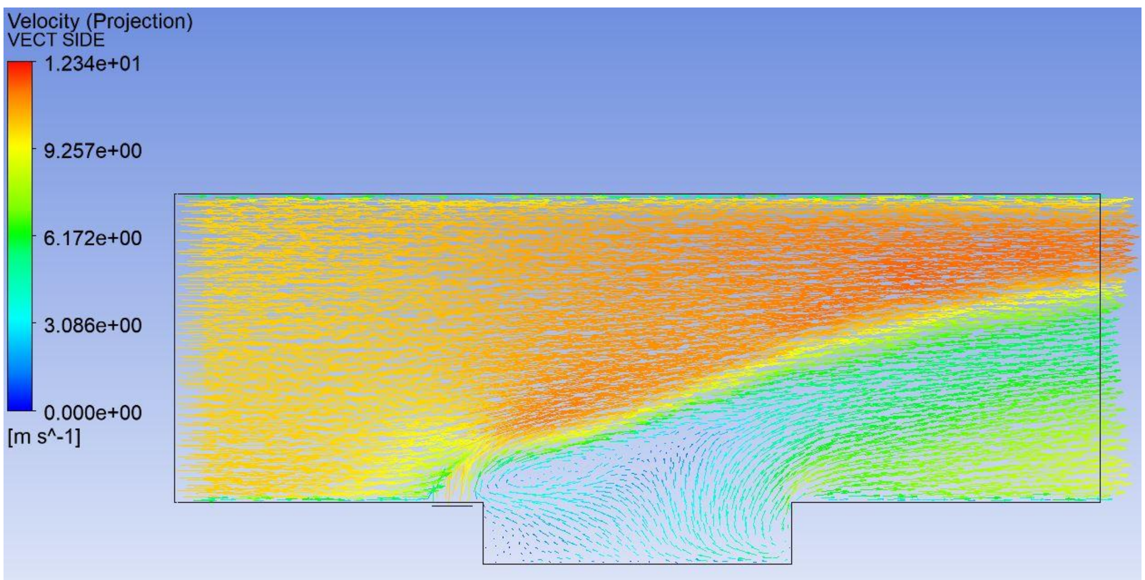

Figure 33. Side view of vectors, 82 mm injector spacing, 90° injector angle, and 10 m/s injector inlet velocity.

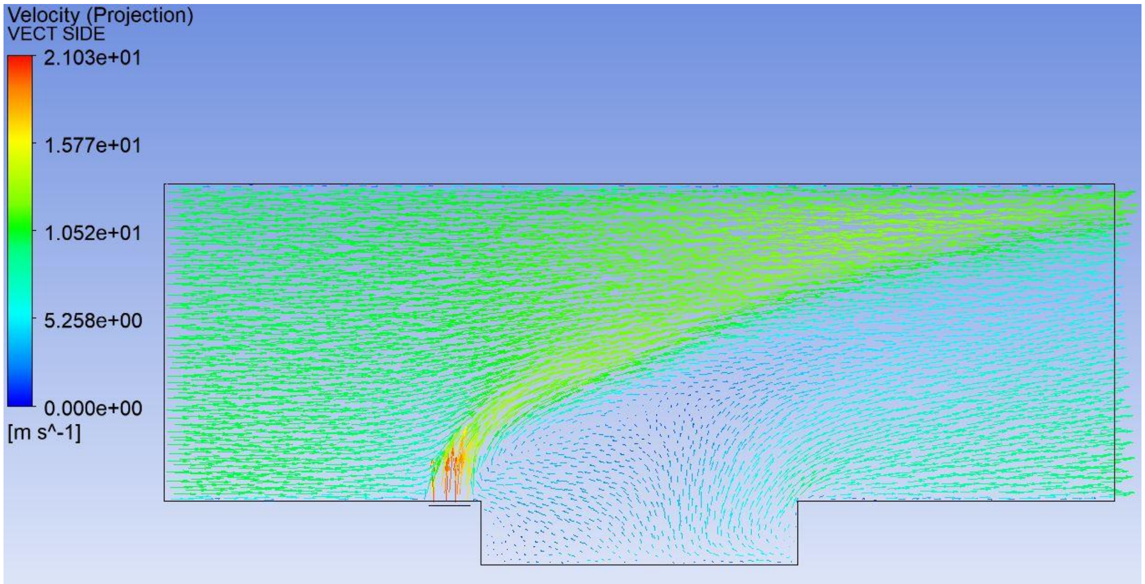

Figure 34. Side view of vectors, 82 mm injector spacing, 90° injector angle, and 20 m/s injector inlet velocity.

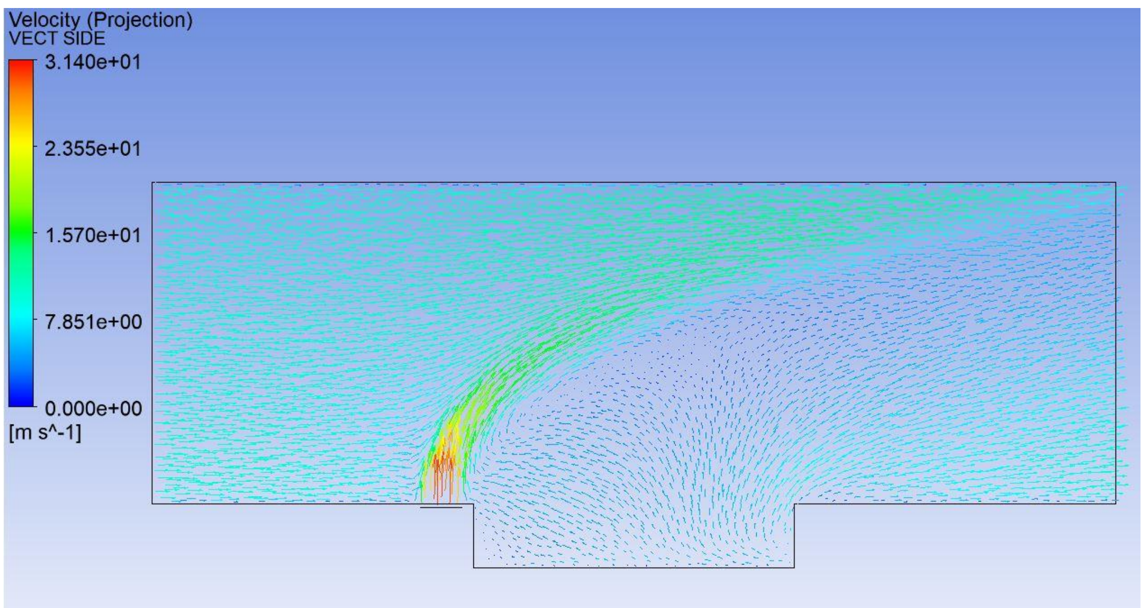

Figure 35. Side view of vectors, 82 mm injector spacing, 90° injector angle, and 30 m/s injector inlet velocity.

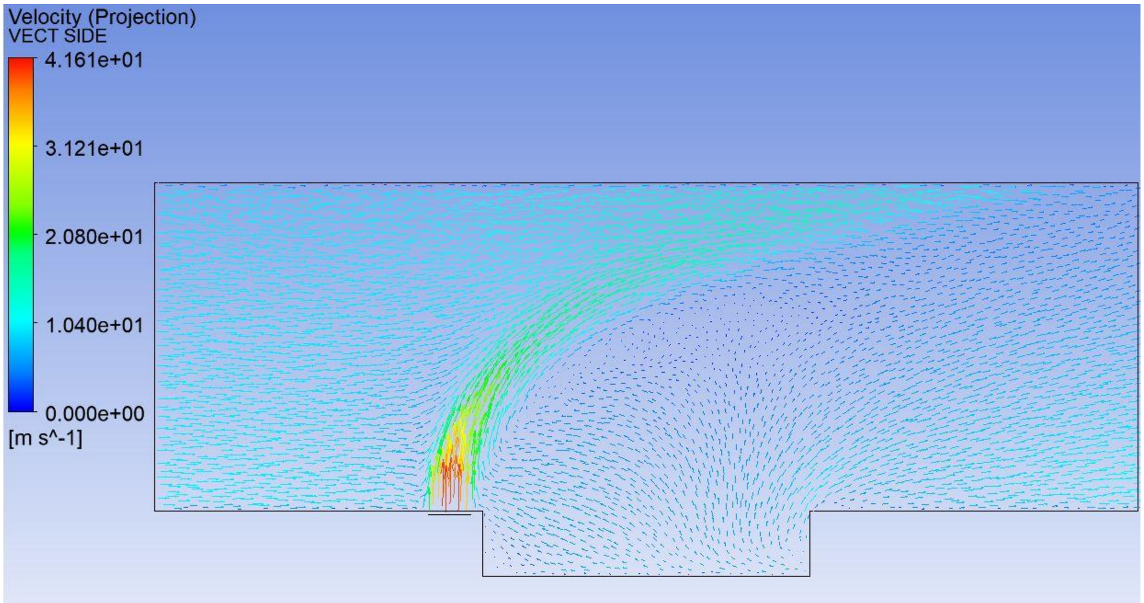

Figure 36. Side view of vectors, 82 mm injector spacing, 90° injector angle, and 40 m/s injector inlet velocity.

Figures 37- 48 have the same fuel injector spacing as figures 33-36, 82mm, and show the side view of the vector plot, but they are at different fuel injector angles. Figures 37-40 are at a 60°, figures 41-44 are at a 45°, and figures 45-48 are at a 30°. The velocity of the flow through the fuel injectors is 10 m/s in figures 37, 41, and 45; is 20 m/s in figures 38, 42, and 45; is 30 m/s in figures 39, 43, and 48; and is 40 m/s in figures 40, 44, and 48. These figures are similar to figures 33-36, with are small area of recirculation above the flame holder that shrinks and raises further above the flame holder as the blowing ratio increases. The area of recirculation in these figures appears to be unaffected by changing the angle of the injectors.

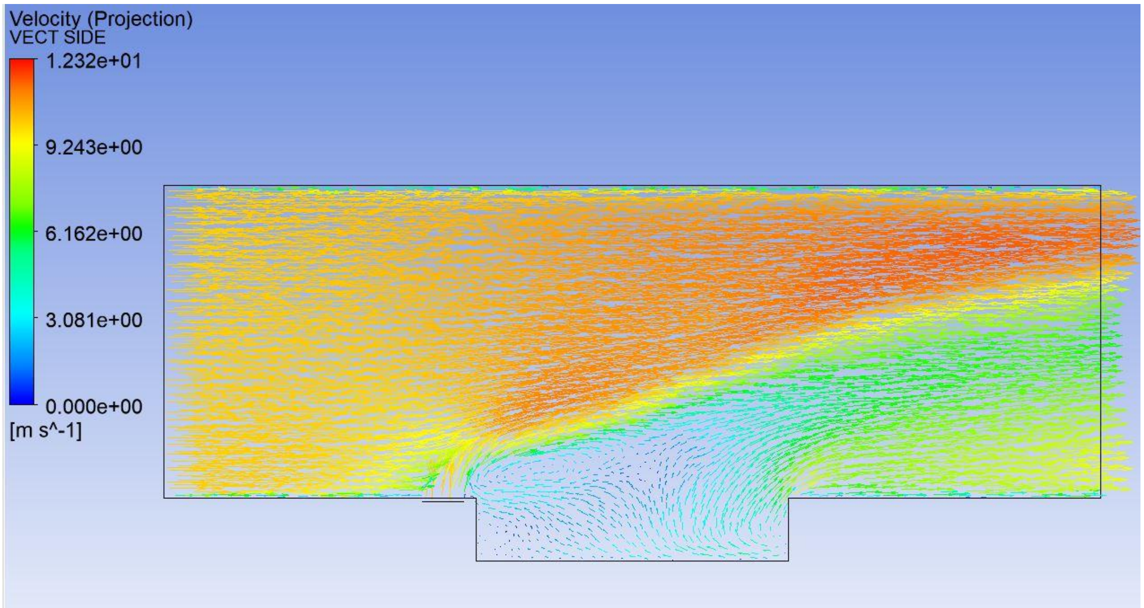

Figure 37. Side view of vectors, 82 mm injector spacing, 60° injector angle, and 10 m/s injector inlet velocity.

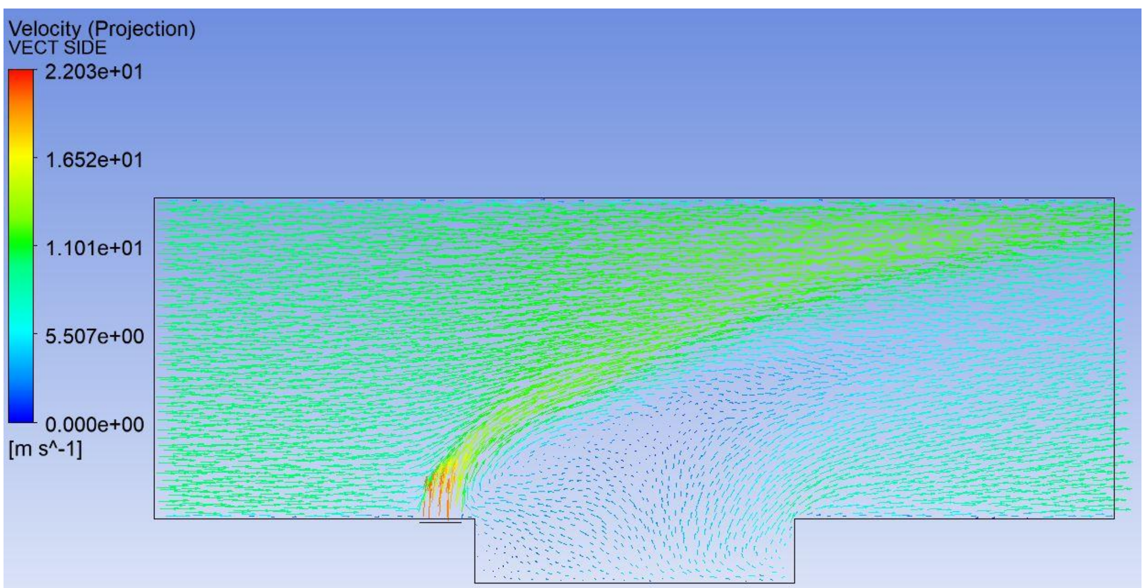

Figure 38. Side view of vectors, 82 mm injector spacing, 60° injector angle, and 20 m/s injector inlet velocity.

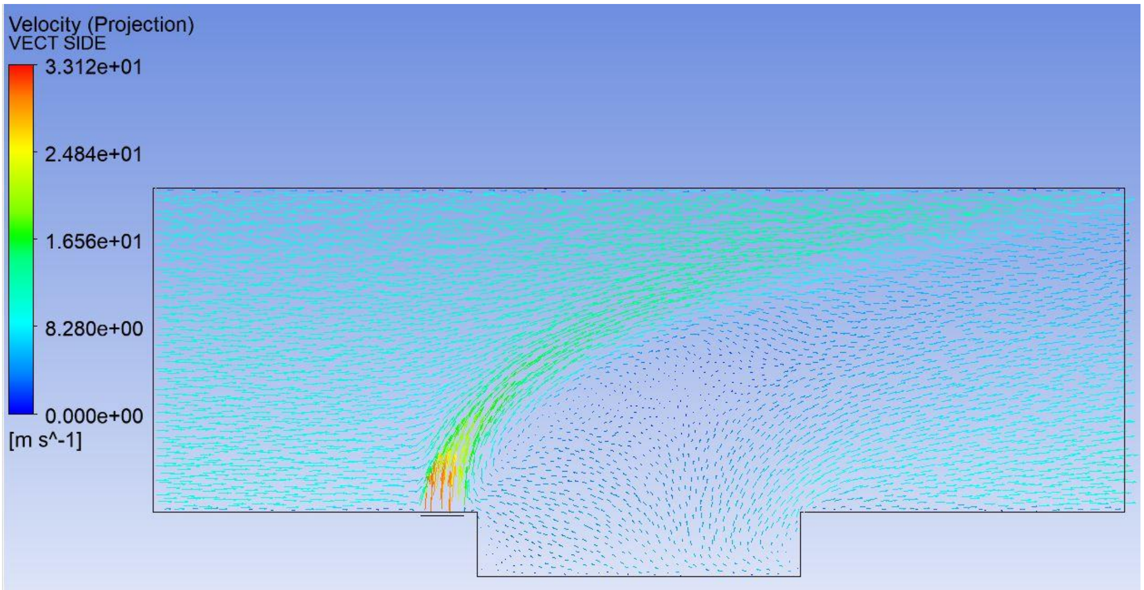

Figure 39. Side view of vectors, 82 mm injector spacing, 60° injector angle, and 30 m/s injector inlet velocity.

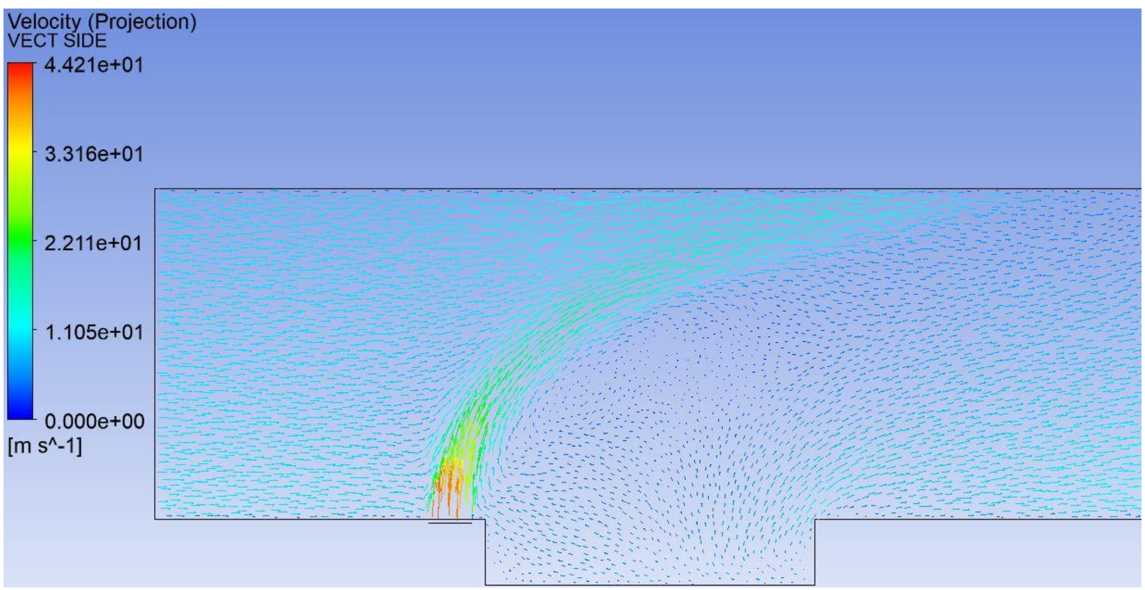

Figure 40. Side view of vectors, 82 mm injector spacing, 60° injector angle, and 40 m/s injector inlet velocity.

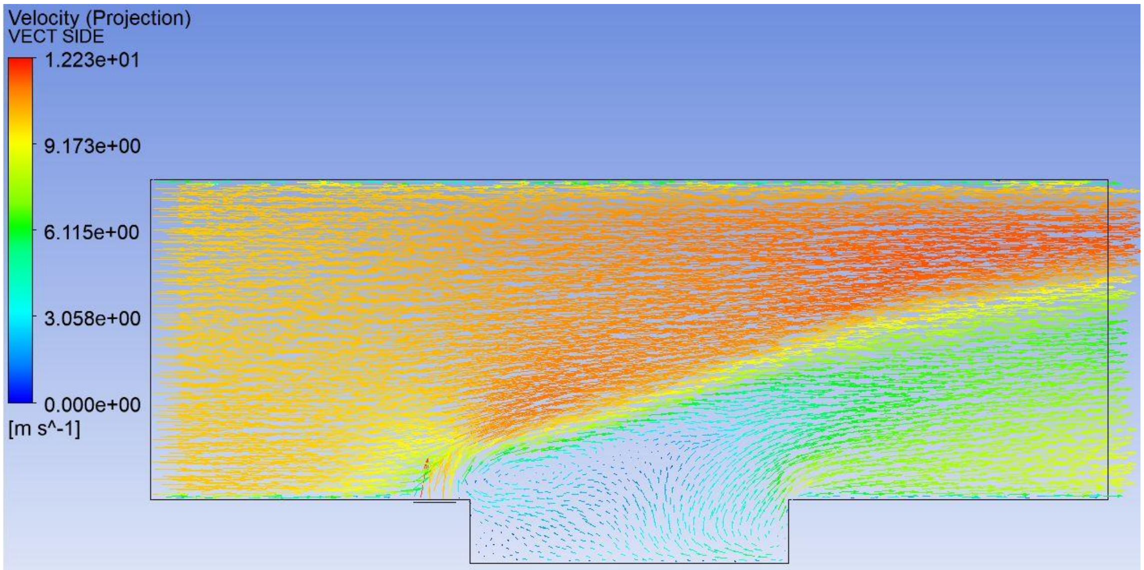

Figure 41. Side view of vectors, 82 mm injector spacing, 45° injector angle, and 10 m/s injector inlet velocity.

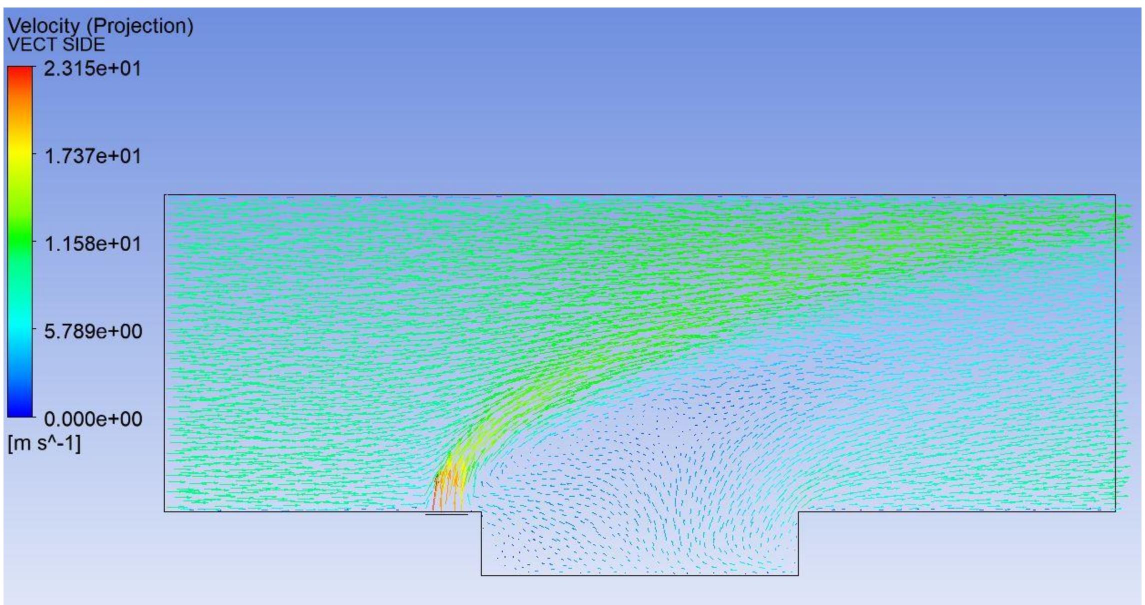

Figure 42. Side view of vectors, 82 mm injector spacing, 45° injector angle, and 20 m/s injector inlet velocity.

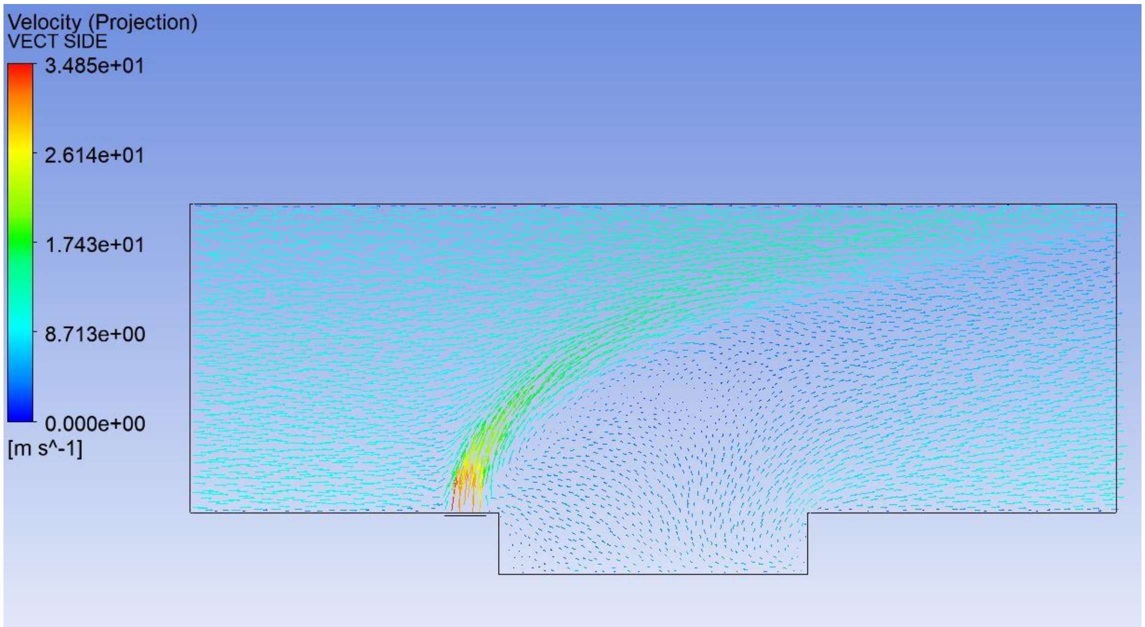

Figure 43. Side view of vectors, 82 mm injector spacing, 45° injector angle, and 30 m/s injector inlet velocity.

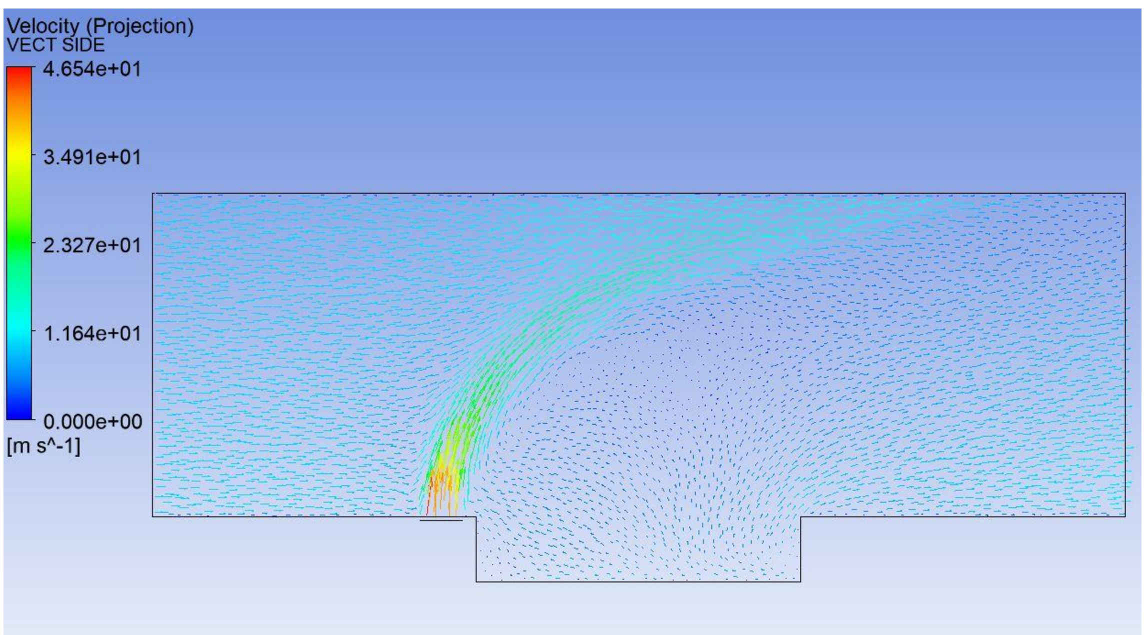

Figure 44. Side view of vectors, 82 mm injector spacing, 45° injector angle, and 40 m/s injector inlet velocity.

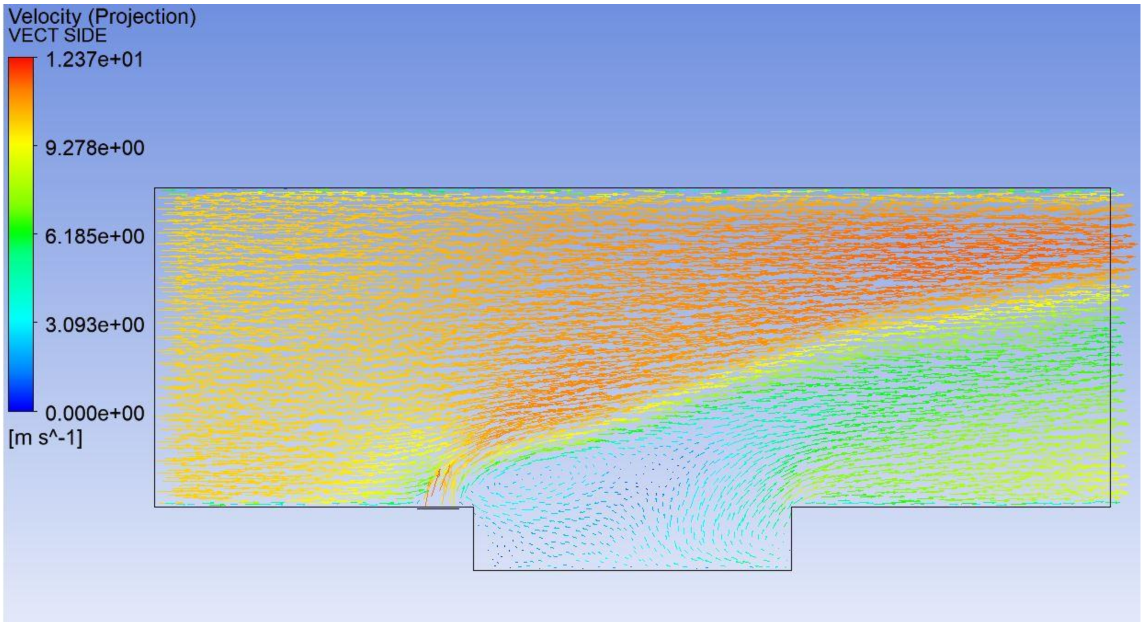

Figure 45. Side view of vectors, 82 mm injector spacing, 30° injector angle, and 10 m/s injector inlet velocity.

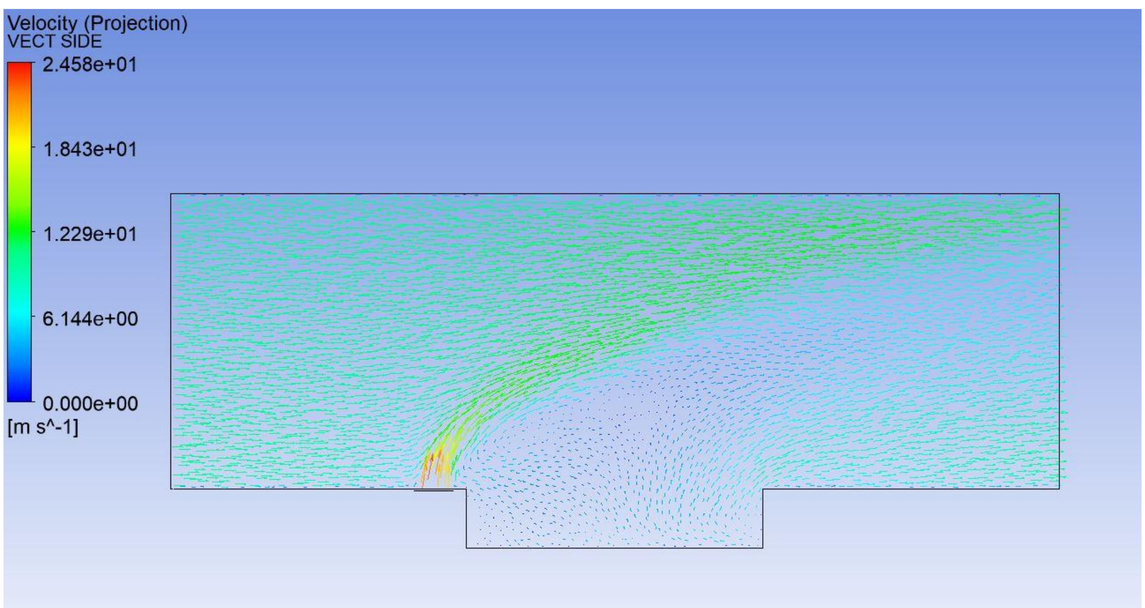

Figure 46. Side view of vectors, 82 mm injector spacing, 30° injector angle, and 20 m/s injector inlet velocity.

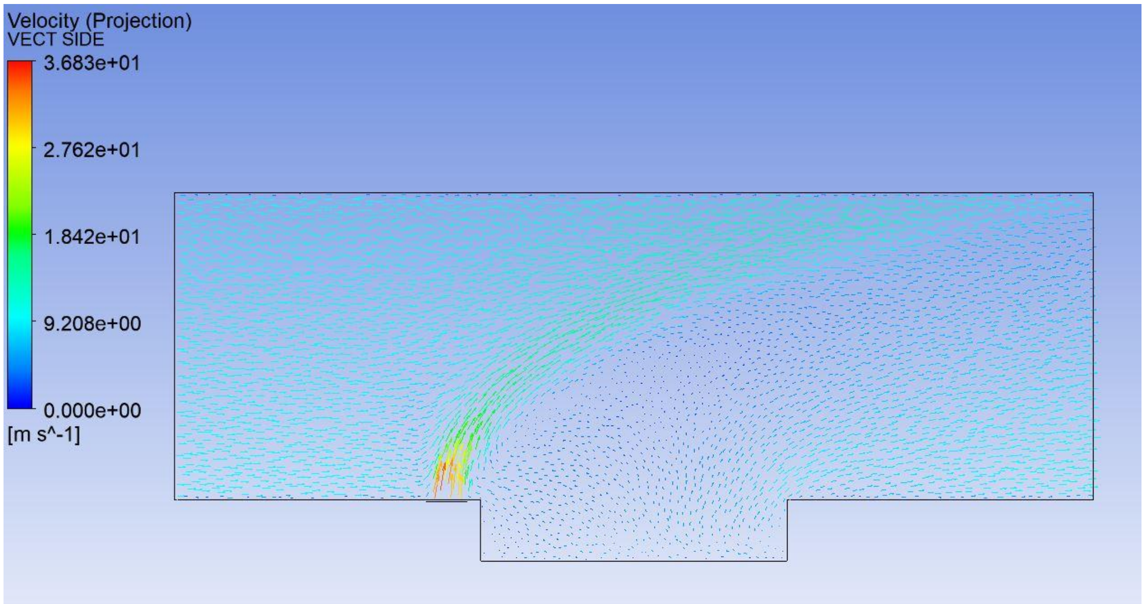

Figure 47. Side view of vectors, 82 mm injector spacing, 30° injector angle, and 30 m/s injector inlet velocity.

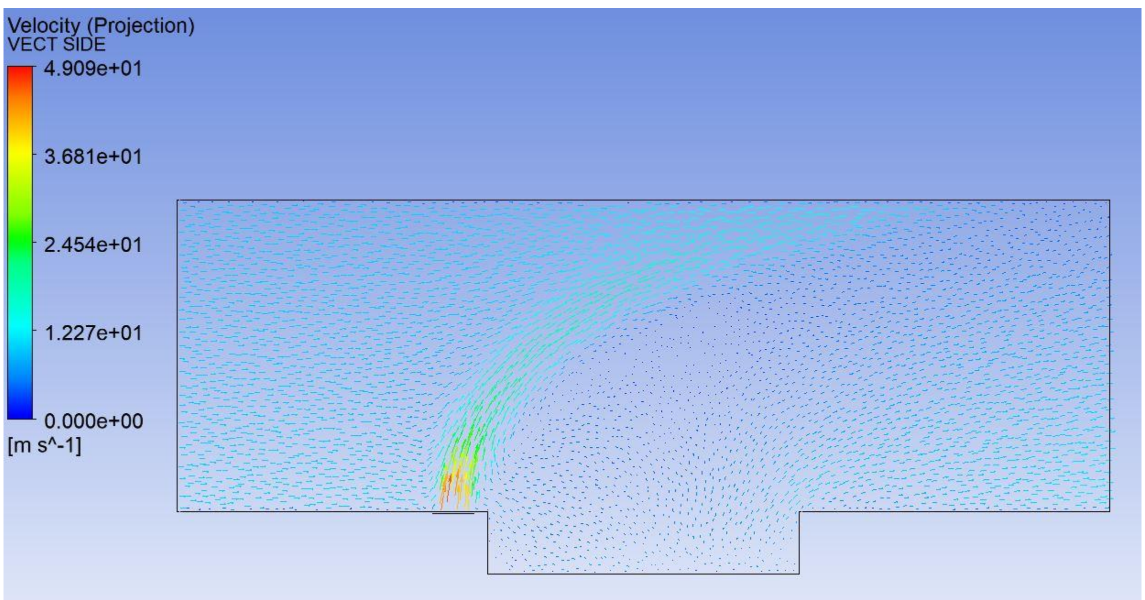

Figure 48. Side view of vectors, 82 mm injector spacing, 30° injector angle, and 40 m/s injector inlet velocity.

Conclusion

Experimental simulations were performed on a model scramjet engine to understand the effects of changing the spacing, angle, and blowing ratio of the fuel injectors on the fuel air mixing characteristics within the engine. In all variants that were tested there was some flow recirculation behind the fuel injectors. These areas of recirculation are a desirable flow feature, because recirculation promotes, and increases the fuel air mixing within the engine. In the comparison between the fuel injector spacing of 18mm, 54mm, and 82mm spacing, the engines with fuel injectors spaced at 54mm had large areas of flow recirculation within the flame holder cavity. The engines with the fuel injectors spaced at 18mm and 82mm showed much smaller areas of recirculation, but the areas of recirculation were not within the flame holder cavity. Blowing ratios were compared by changing the fuel injector inlet velocity, while keeping the main inlet velocity at 10m/s, and the tested fuel injector inlet velocities were 10m/s, 20m/s, 30m/s, and 40m/s. An increased blowing ratio can have either positive effect or a detrimental effect depending on the location of the recirculation region. In the cases where the fuel injector spacing was 54mm, which had the recirculation region within the flamer holder cavity, increasing the blowing ratio led to the upper region of recirculation reaching above the top of the flame holder cavity while not raising the lower portion if the recirculation region, increasing the area of recirculation. In the cases with fuel injector spacing of 18mm and 82mm increasing the blowing ratio led to the area of recirculation shrinking, and lifting higher above the flame holder cavity. This shows that when the blowing ratio is increased, it will improve mixing if the recirculation area is within the flame holder, but will decrease mixing if the area of recirculation is outside of the flame holder. In the tests of fuel injectors at 60°, 45°, and 30° showed no noticeable impact on the flow or recirculation area when compared to fuel injectors at a 90° angle.

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