FILLING OF METHANE/AIR MIXTURE IN A TUBE FOR PULSE DETONATION ENGINES

By

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Dedicated to my parents, sisters and Dr. Frank K. Lu

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November 18, 2011

ABSTRACT

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In pulse detonation engines, filling is a time consuming process; reducing these times will help to increase the frequency. The filling of a detonation tube, 1 m long tube with an internal diameter of 101.6 mm, closed at one end and opened at the other, was studied using the unsteady flow solver methane and air nominally at STP. Three cases were examined: (i) a 25.4 mm diameter port at the center of the closed end, (ii) nine ports of 25.4 mm diameter, one at the center of the closed end and eight distributed in two diametrically opposite rows, equally, four on each side, and (iii) the same configuration as case (ii) but with the openings replaced by “showerheads”. The common inflow condition for all three cases is that the average velocity at the inlet is 93 m/s. The criterion for the fill time is when the tube is filled with 90 percent of the premix.

TABLE OF CONTENTS

APPENDIX

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

Table Page

CHAPTER 1

INTRODUCTION

1.1 Pulse Detonation Engine

Pulse detonation engine (PDEs) are intermittent devices[1] that have seen much recent interest. Compared to other engines, pulse detonation engines have better performances on cost, higher fuel efficiencies, higher thrust-to-weight ratios[2,3]. PDEs are thought to be capable of operating up to Mach 5, being limited by the autoignition temperature. A comparison of specific impulse vs. Mach number regimes for various propulsion systems[4] is shown in Figure 1.1. The figure shows the superior performance of PDEs.

A detonation cycle consists of the following process: fill, detonation, exhaust and purge. While achieving reliable detonations poses its own problems, the other processes of fill, exhaust and purge have rarely been addressed but which are important as well. These processes take a long time compared to the detonation process, thereby inordinately influencing the entire cycle time. With a general consensus that, for aerospace propulsion, such engines should operate at high frequencies of 50-100Hz, there is therefore a desire to shorten these long processes.

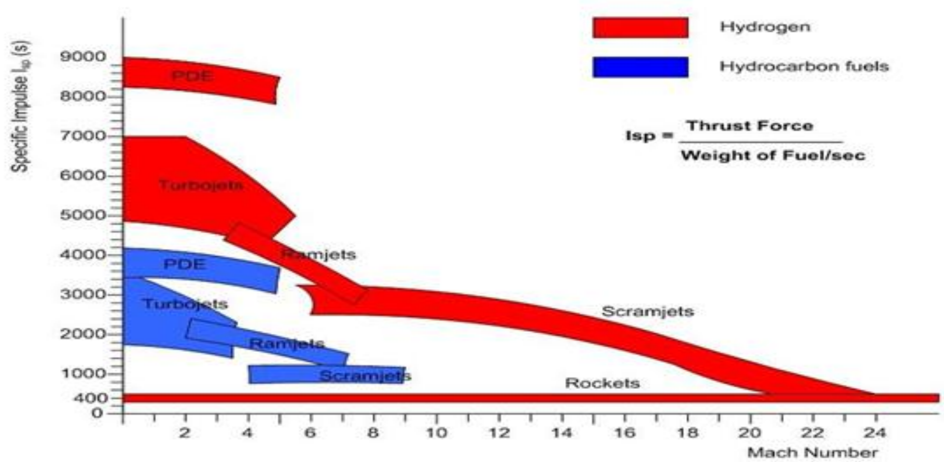


Figure 1.1 Specific impulse vs. Mach number of various propulsion systems[4]

Most of the PDEs reported in the literature have long detonation tubes to satisfy the deflagration-to-detonation transition requirements[5,6]. If the engine operates with air, it also needs to have a large diameter to accommodate the large detonation cell sizes. Both the length and the volume of such detonation tubes make it difficult to have a short fill or purge time due to the need to fill a large volume and the slow speed of the propellant front if the tube is filled from one end. Thus, this study seeks to examine in detail the filling process using a 2D/3D time-accurate numerical model.

1.1.1 Pulse Detonation Cycle Process

The parts of the cycle processes are shown in Figure1.2.

The PDE cycle processes are

1. Purging stage
2. Filling stage
3. Ignition/Initiation stage
4. Detonation wave propagation
5. Detonation wave reaches the exit
6. Exhaust stage and back to purging stage

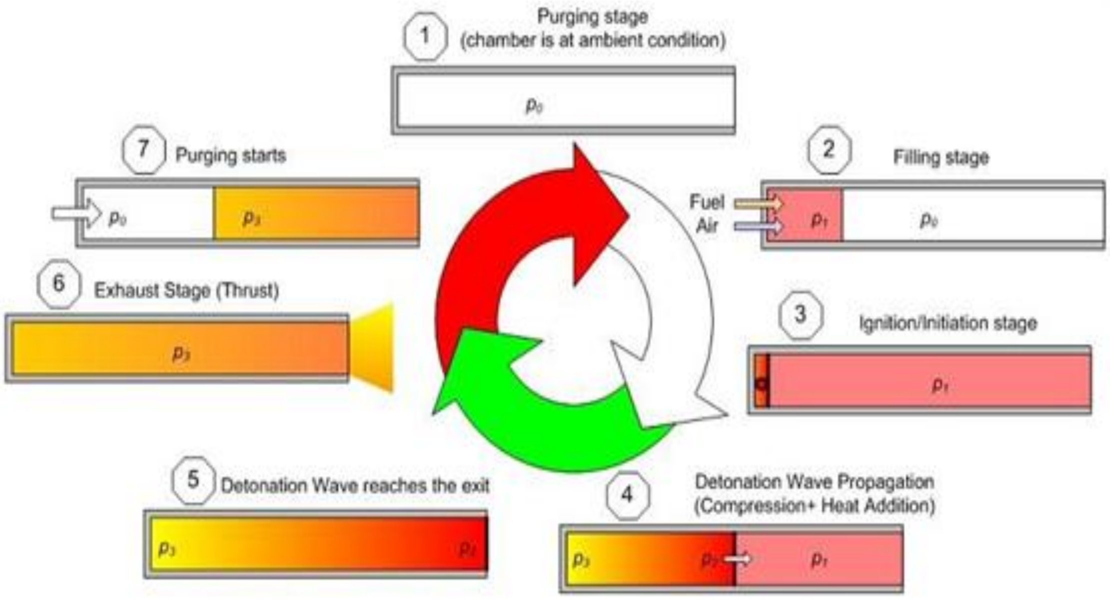


Figure 1.2 Schematic of pulse detonation engine cycle[7]

In this pulse detonation engine, a chamber is closed at the one end and opened at the other end. To start the process, the tube is filled with a fuel/air mixture at any certain pressure and temperature conditions. The filling time (t_{fill}) for the detonation tube is estimated as the length of the tube over the filling velocity. The second stage of this process is the detonation process. In this stage, the detonation process takes place within fraction of millisecond. As soon as the detonation wave reaches to the closed end region the pressure or velocity decreases from top end to bottom end region. The detonation wave for simplicity can be considered to be fully developed and traveling at the Chapman-Jouguet (CJ) speed. For fuel/air mixtures, the CJ speed is are in between 1400 to 1800 m/s. The detonation time of the wave (t_c) is therefore similarly estimated by the length of the tube over the CJ wave velocity. The next stage, is the blowdown. The time required for this process (t_b) can be estimated by the length of the tube to the rarefraction velocity. The last stage is the purging process. In this process the tube is scavenged off hot detonation products by using fresh air. This process is thought to be necessary to prevent autoignition of the fresh fuel/oxidizer mixture. The time taken for purging the tube with the fresh air (t_{purge}) is the length of the tube over the purging velocity.

The sum of the all the four stages are,

$$T = t_{fill} + t_c + t_b + t_{purge} \qquad (1)$$

1.2 Objective of Current Research

This work examines the filling of a detonation tube using numerical modeling. The objectives are:

- Determine how well the tube is filled with a representative fuel/air mixture for a selected number of filling configurations.
- Time required for filling the tube with the different configurations.

Three different cases are studied to examine the filling process. The tube will take long time to fill if it has only one inlet at the end of the tube. As the numbers of sidewall injector port are increased, the fill time is reduced. So, the results will examine the benefits of sidewall injection ports.

CHAPTER 2

INTRODUCTION

2.1 Cases Studied

For simplicity, a stoichiometric methane/air mixture at STP is injected into the detonation tube. A CAD model was first developed in Pro-E^{TM} and then imported in GAMBIT^{TM} to distribute tetrahedral meshes. FLUENT^{TM} enables steady or unsteady state modeling; the latter was used for this study. The step process is required to generate results for any given condition is shown in Figure 2.1. The steps outlined in Figure 2.1 are described in the subsections below.

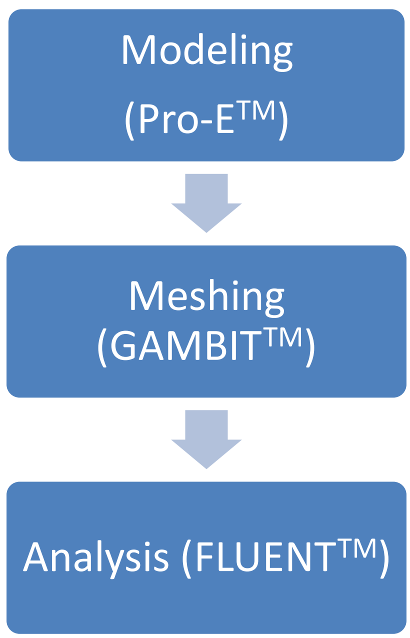


Figure 2.1 Steps to generate the results

2.1.1. Modeling

Three-dimensional modeling is done in Pro-E^{TM}. The pulse detonation tube is 1 m long, it has a 101.6 mm bore, and injection ports with 25.4 mm diameter circular openings.

Case 1: This model with end wall injection. One of these ports is located at the closed end of the tube as shown in Figure 2.2. The fuel/air mixture is introduced from the closed end of the tube.

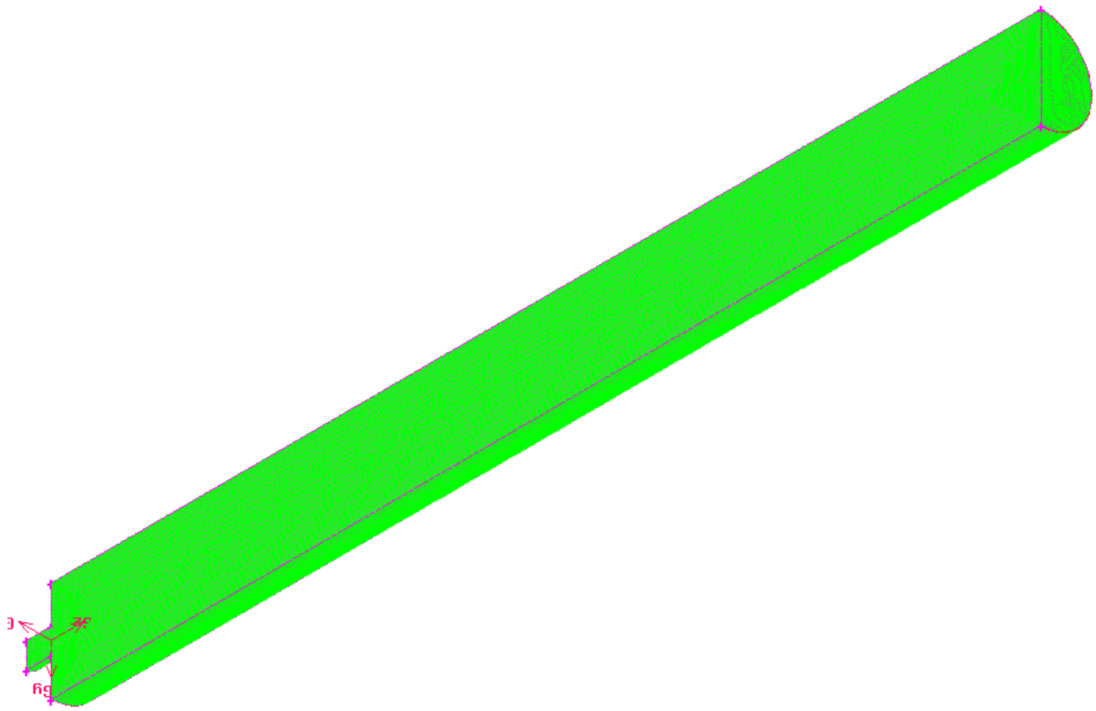


Figure 2.2 Case 1: model with endwall injection port

Case 2: The other eight are arranged in diametrically opposite pairs at 150, 350, and 550 mm from the closed end as shown in Figure 2.3. A stoichiometric methane and air mixture at STP leaves these inlets. Sidewall injection is suggested as a method to reduce the filling time[8]. The number of sidewalls is chosen to fill the tube rapidly.

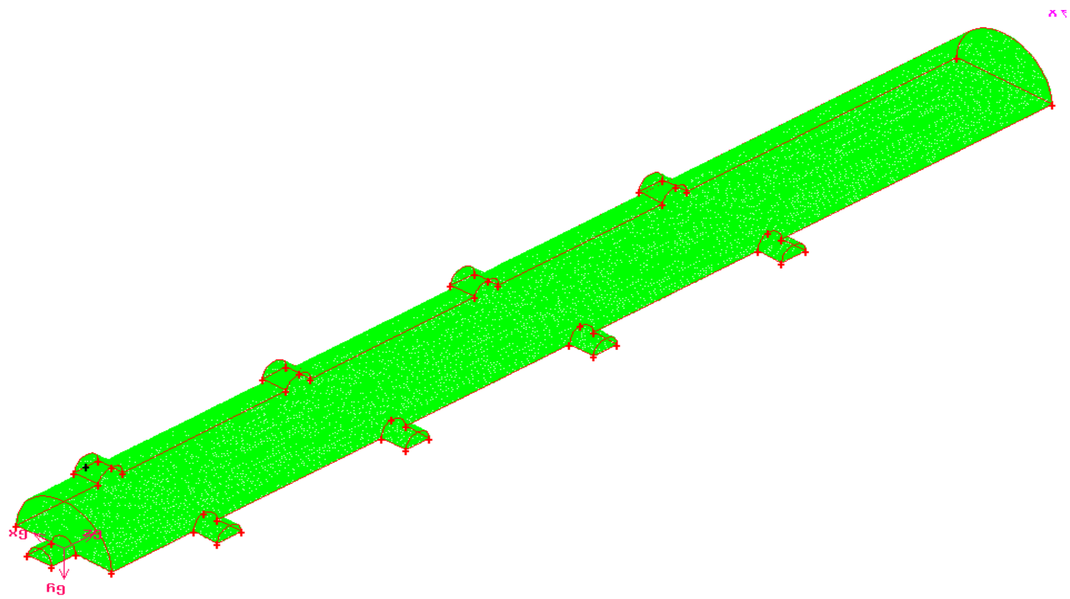


Figure 2.3 Case 2: model with eight diametrically sidewall injection ports and one at the closed end

Case 3: It aims to speed up the fill. To distribute the fuel/air mixture further into the detonation tube, the original ports are replaced by a so-called showerhead. A schematic of the showerhead is shown in Figure 2.4. The original port is replaced by four smaller openings each 3mm in diameter mounted in a circular plug 3.18mm thick. These openings are angled at 30 deg from the axis of the port. This model has same configuration as case 2 but with the openings replaced by "showerheads" as shown in Figure 2.5.

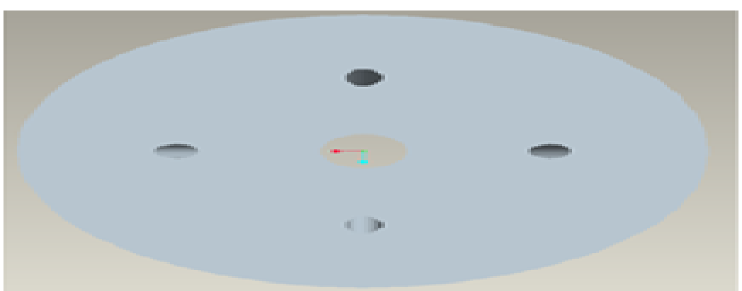


Figure 2.4 Shows bottom view of an orifice plate

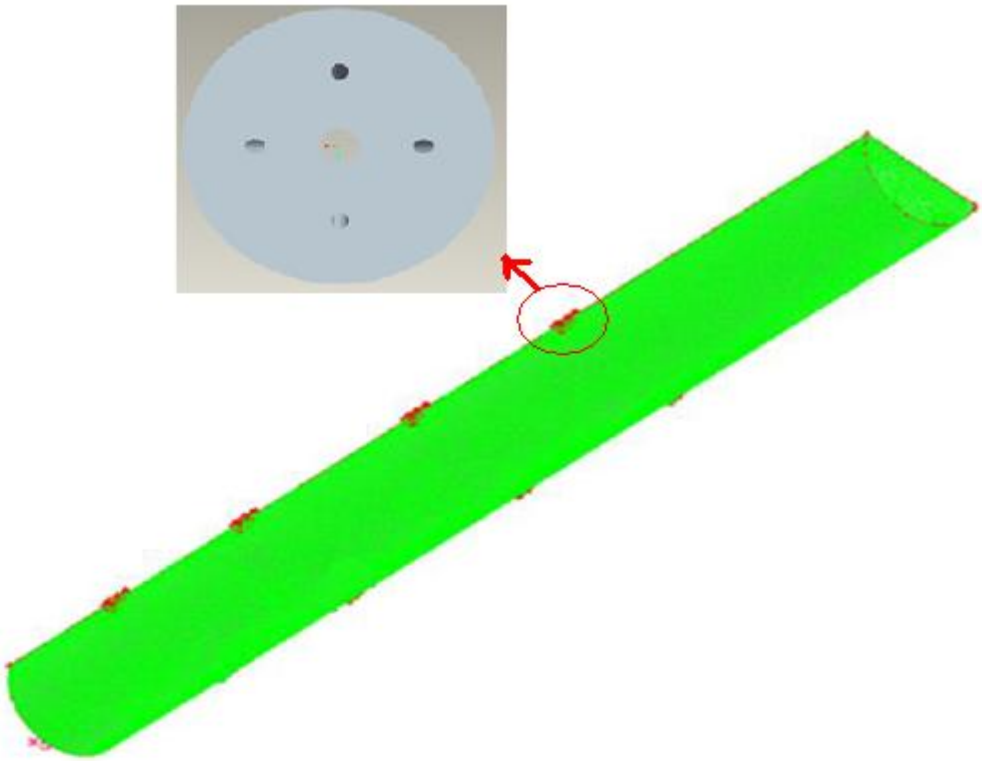


Figure 2.5 Case 3: model has same configurations as case 2 but with the openings replaced by "showerheads"

2.1.2. Meshing

Meshing and boundary conditions are given in GAMBIT™ to distribute tetrahedral meshes. A fine mesh was used at the edges in order to resolve the steep gradients expected near the walls. The smallest and largest node sizes used for meshing were 0.5 and 2 mm respectively. Figure 2.2 is an example of the mesh distribution in this case for a tube with eight diametrically opposed ports. The final pre-processing in GAMBIT™ included adding boundary conditions such as wall, inlet, and outlets.

A summary of the meshing is provided below:

Case 1: 3D mesh configuration details are shown in Table 2.1. The meshing structure is shown in Figure 2.6.

Table 2.1 3D mesh configuration details for endwall injection port (Case 1)

	Cells	Faces	Nodes
Case 1	305126	681156	65933

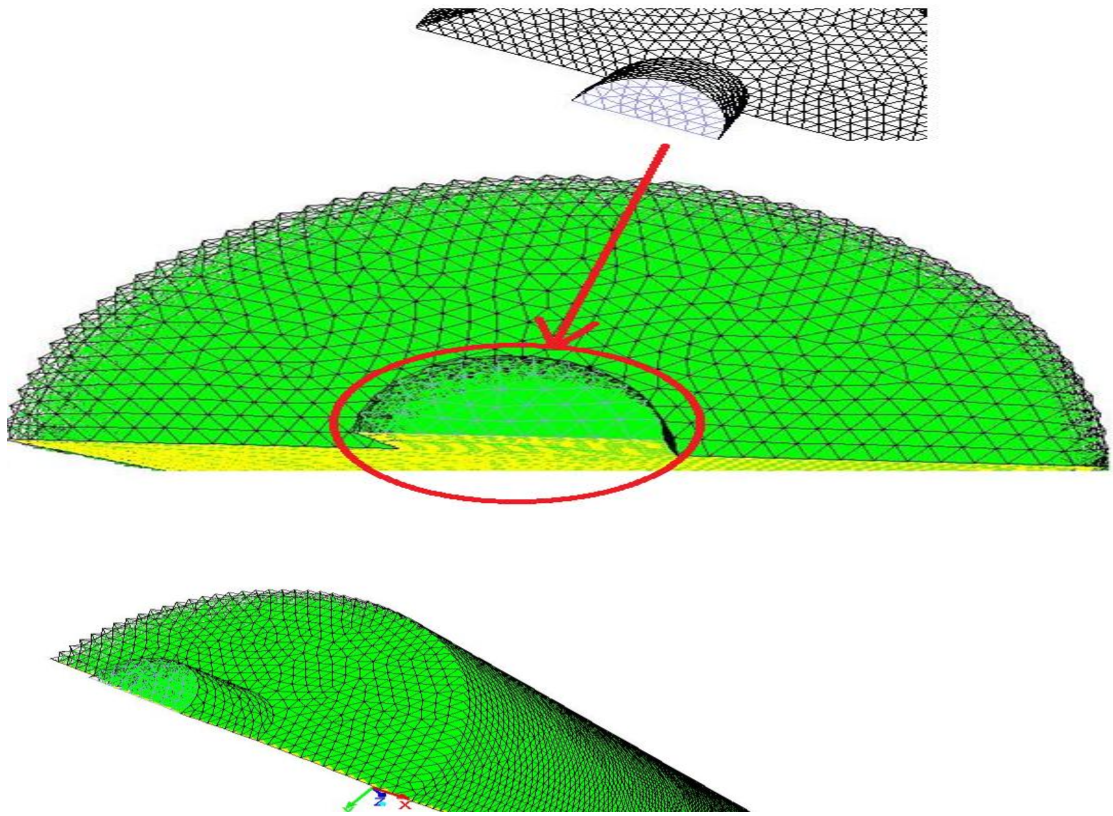


Figure 2.6 Mesh for a model with endwall injection port (Case 1)

The boundary conditions for Case 1 are given in Table 2.2

Table 2.2 Boundary condition details for Case 1

Zone	Type
Inlet	Velocity-Inlet
Outlet	Outflow
Wall	Wall

Case 2: 3D mesh configuration details are shown in Table 2.3. The meshing structure is shown in Figure 2.7.

Table 2.3 3D mesh configuration details for a model with eight diametrically sidewall injection ports and one at the closed end (Case 2)

	Cells	Faces	Nodes
Case 2	939992	1929918	175126

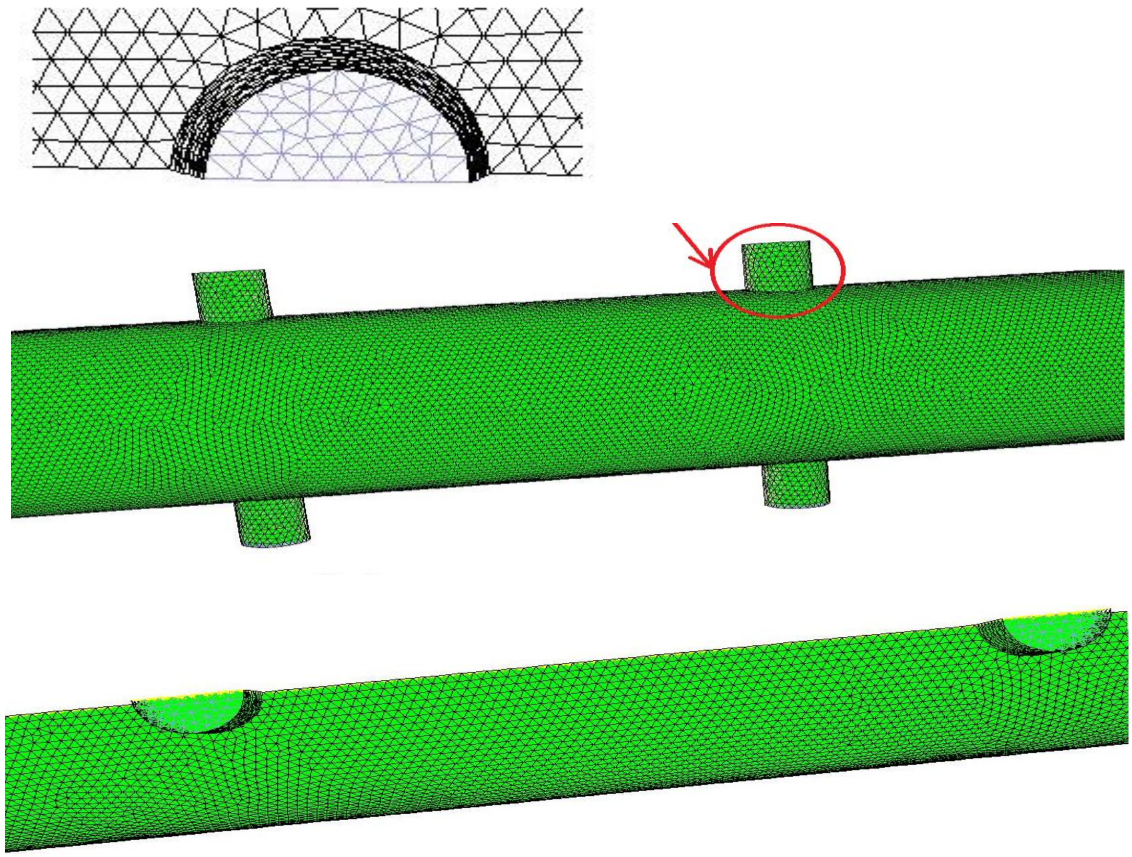


Figure 2.7 Mesh for a model with eight diametrically sidewall injection ports and one at the closed end (Case 2)

The boundary conditions for case 2 are given in Table 2.4. The meshing structure is shown in Figure 2.7.

Table 2.4 Boundary conditions details for Case 2

Zone	Type
Front	Velocity-Inlet
Sidewall Inlets	Velocity-Inlet
Outlet	Outflow
Wall	Wall

Case 3: For all the cases fine mesh is done because course mesh doesn't yield to good results. The intersection between orifice plate and detonation tube inlet an inlet shape function are used for meshing. The smallest node size is 0.5 mm and largest node size is 2 mm as shown in Figure 2.8.

Table 2.5 3D mesh configuration details for a model same configuration as case 2 but with the openings replaced by "showerheads" (Case 3)

	Cells	Faces	Node
Case 3	1506642	2038088	197344

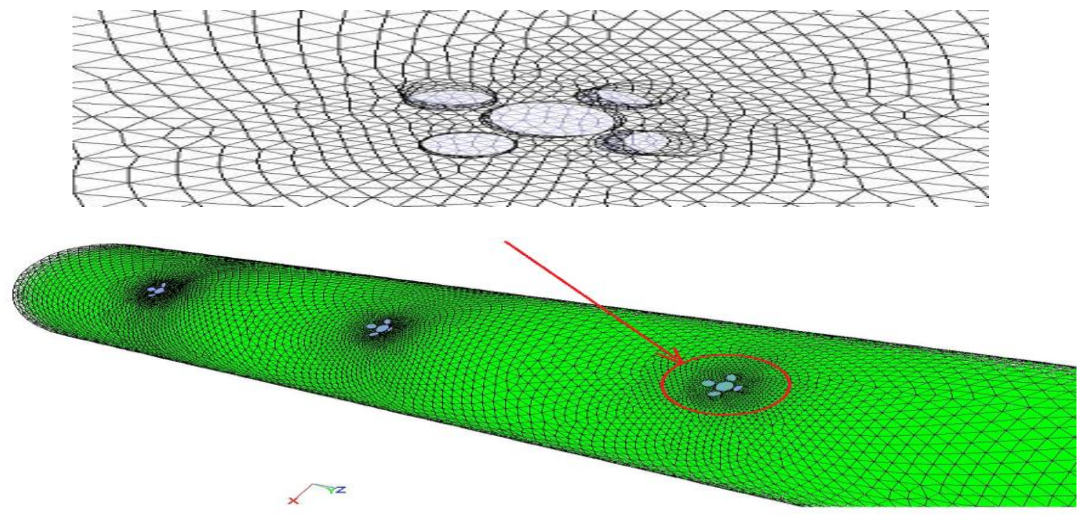


Figure 2.8 Mesh for a model same configuration as Case 2 but with the openings replaced by "showerheads"

The boundary conditions for case 3 are listed in Table 2.6.

Table 2.6 shows the boundary conditions for Case 3

Zone	Type
Down	Velocity- Inlet
Front	Velocity- Inlet
Up	Velocity- Inlet
Outlet	Outflow
Wall	Wall

2.1.3. Analysis

The SIMPLEC™ finite volume method in FLUENT™ was used to solve the partial differential equations. An unsteady solver was chosen to model the filling process. Double precision was used to minimize the error associated with the high aspect ratio grid.

The fluid filling the tube is a stoichiometric methane/air mixture, properties of which are available from the FLUENT database. Velocity conditions were set at the closed end of the detonation tube and also the sidewall injector ports. The mixture of methane and air is calculated for every 5 ms and the results are shown in the Chapter 3. Each time step was determined and monitored by the solver. In order to start the computations, the time step size (Δt) is required. It is calculated as

$$\Delta t = dx/V$$

where Δt is time step size, dx is the cell size, V is the velocity.

The following details are used for developing the FLUENT model

- Three-dimensional model
- Unsteady state condition
- Pressure based solver

- Implicit formulation
- k-epsilon turbulence model
- Energy Equation
- Inert, stoichiometric methane/air mixture
- Material Properties: These are available within FLUENT. In this study, a stoichiometric methane/air mixture at STP was chosen for illustrative purposes. It can be noted that the molecular weight of methane is close to that of air.
- Boundary Conditions: We have given only boundary condition in GAMBIT now in FLUENT we have to give the values like for velocity, mixture, outlet and, walls. We have to give the flow direction for the velocity inlet. The flow leaving the inlet ports is assumed to be 93 m/s for example. The walls are stationary with a temperature as 300K.
- Convergence is required to run the simulation in order to flow in the solution. For every 5ms we calculated the percentage of methane and air mixture inside the tube and also at the outlet. So for every 5ms iteration is set up.
- Finally, contour plots for velocity, and mixture concentrations, as well as any other property of interest, can be obtained. The graphical window is opened the results are saved.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Description of Results

As described in Chapter 2, three different cases are studied in FLUENT. The average velocity for the three different cases at the inlet is 93 m/s. The results are shown in 3D contour plots. In these results we can check the least time to fill the detonation tube and also least amount of dead zones. As the time varies we calculated the filling percent inside the tube and also at the outlet for all the cases.

3.1.1. Convergence

Convergence is checked in between residual monitors and iterations. For all the three cases, the energy converges rapidly compared to the velocity components, continuity, k, and epsilon. For the three different cases convergence plots are shown in Figs. 3.1-3.3. In these figures, the residuals of various flow properties are plotted against the number of iterations. When the residuals reach a constant value, the solution is said to have converged.

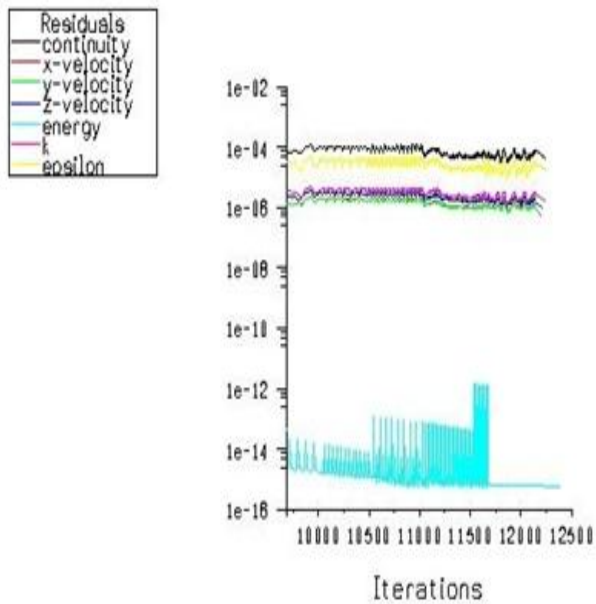


Figure 3.1 (Case 1) Residual plots for a model with endwall injection port

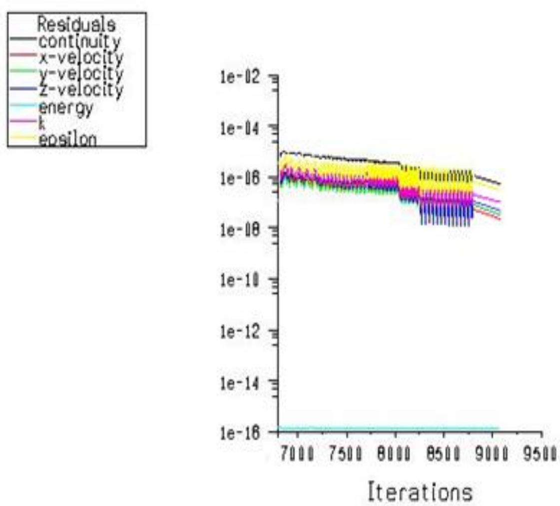


Figure 3.2 (Case 2) Residual plots for a model with eight diametrically sidewall injector ports and one at the closed end

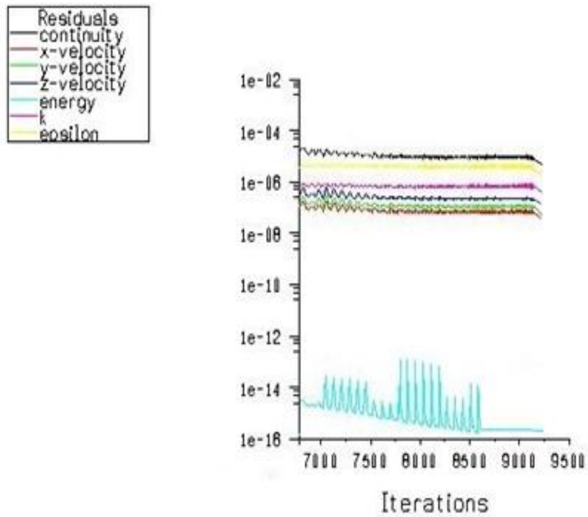


Figure 3.3 (Case 3) Residual plots for a model with same configuration as Case 2 but with the openings replaced by “showerheads”

FLUENT will display a prompt when the solution has converged. Otherwise, the convergence can be monitored by viewing the residual plots as shown in Figures 3.1-3.3 above. Case 1 takes the largest number of iterations to converge as can be seen in Figure 3.1. It turns out that the physical time required to fill the tube is also the longest.

3.1.2. Case 1

The concentration of methane/air in the tube is calculated every 5 ms. As time progresses, the concentration of methane/air in the tube increases. The mixture does not arrive at the outlet until 120 ms later. The mixture concentration at the outlet then rises rapidly and reaches a steady value of about 70 percent at 180 ms. The Figures 3.4-3.11 shows the methane/air mixture filling the tube. The velocity contours are shown in Figs. 3.12.

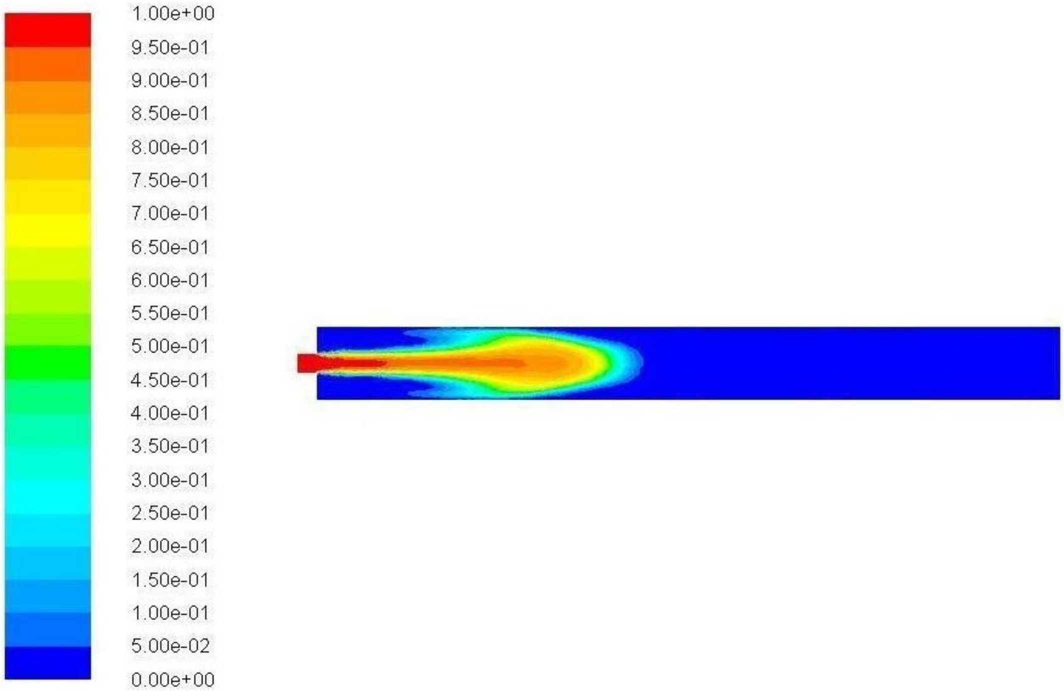


Figure 3.4 Contours of mixture of methane/air at 30 ms

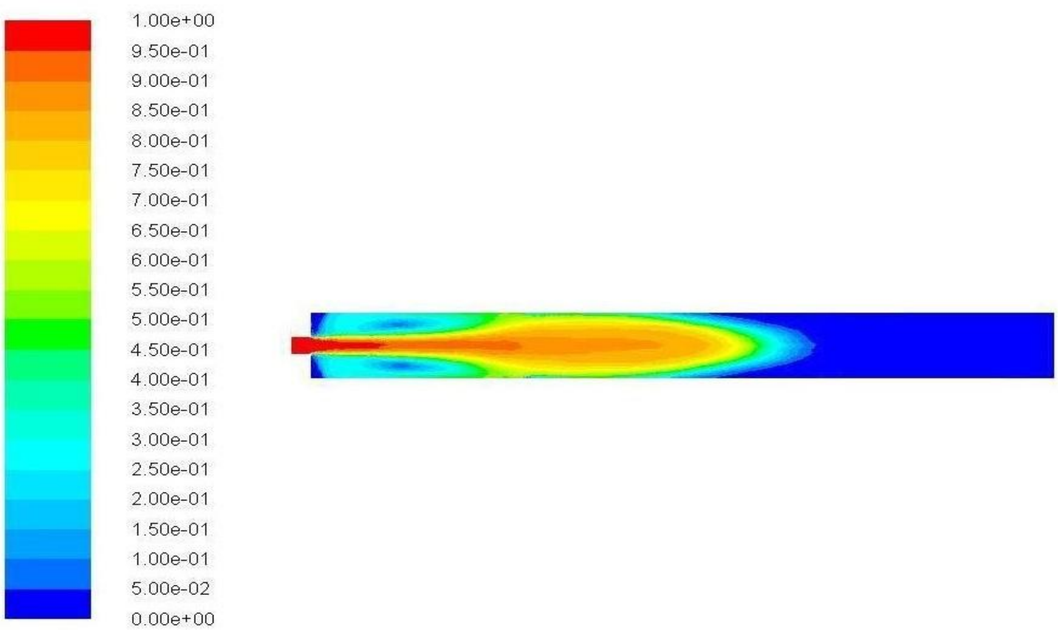


Figure 3.5 Contours of mixture of methane/air at 50 ms

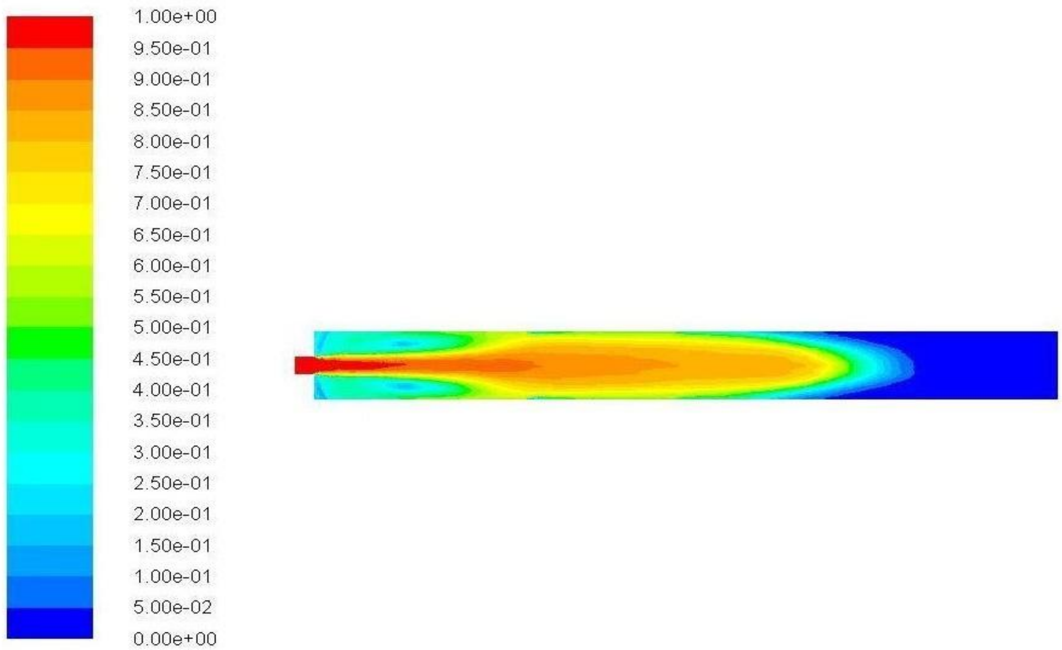


Figure 3.6 Contours of mixture of methane/air at 70 ms

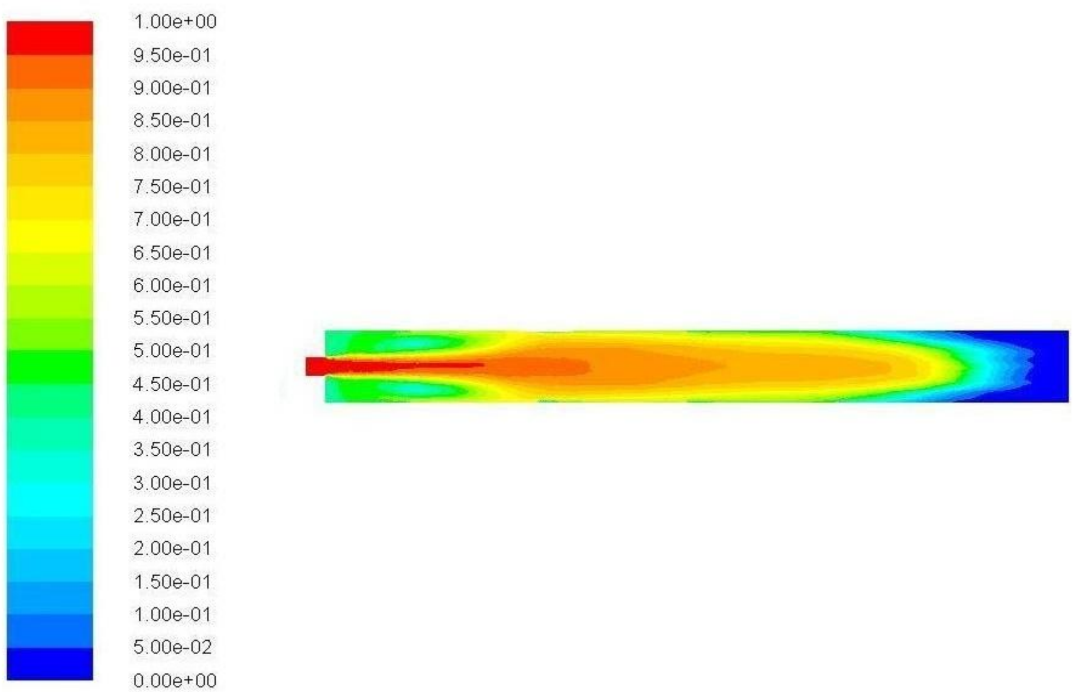


Figure 3.7 Contours of mixture of methane/air at 100 ms

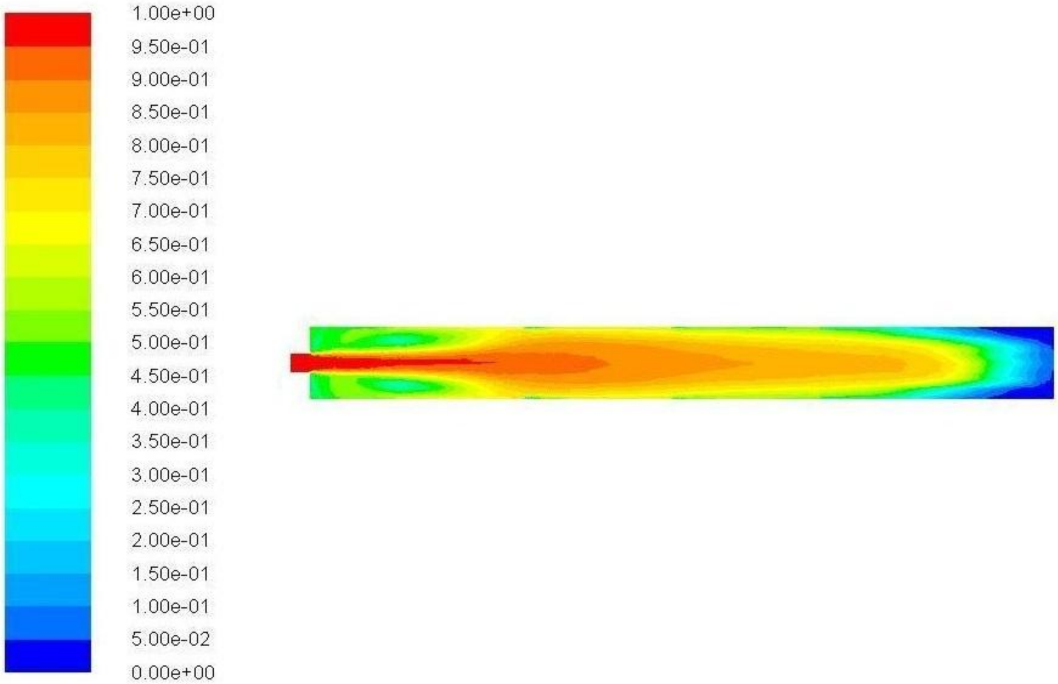


Figure 3.8 Contours of mixture of methane/air at 120 ms

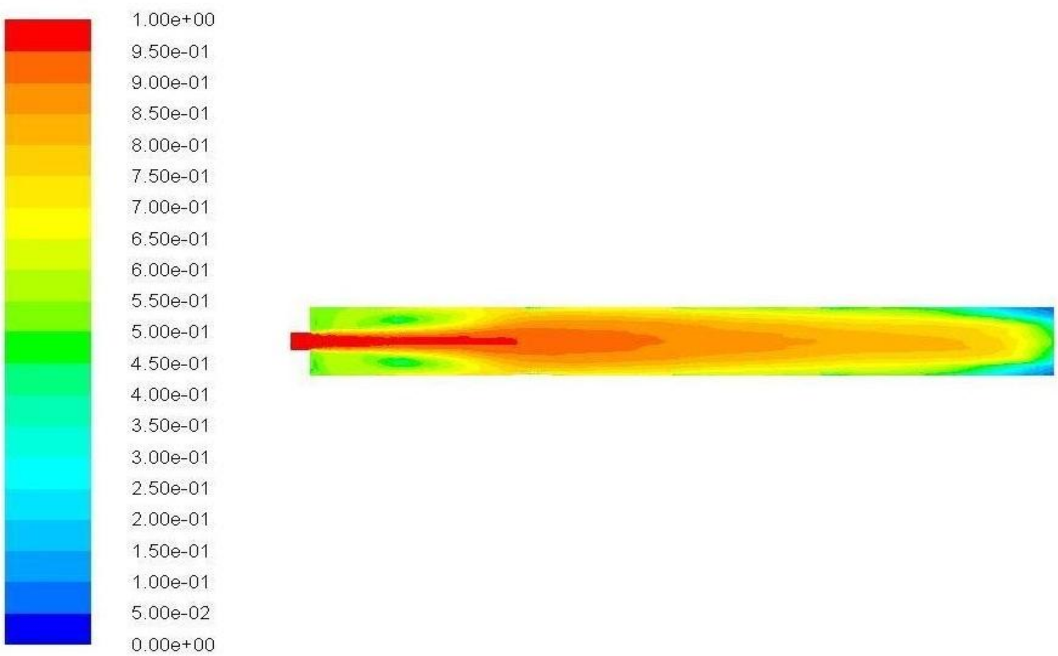


Figure 3.9 Contours of mixtures of methane/air at 150 ms

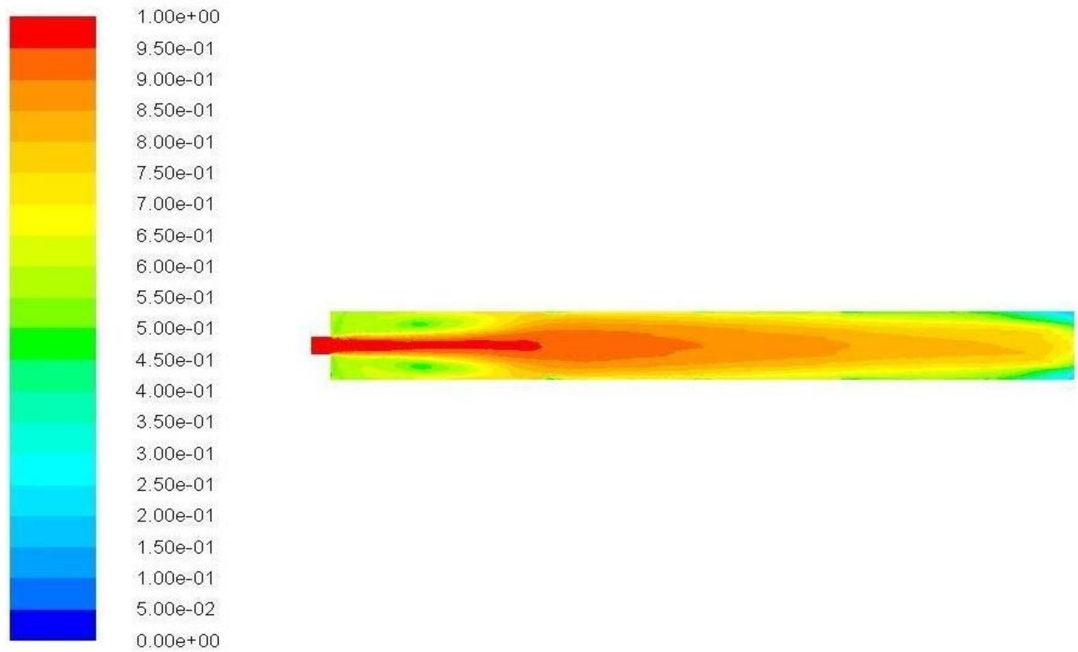


Figure 3.10 Contours of mixtures of methane/air at 160 ms

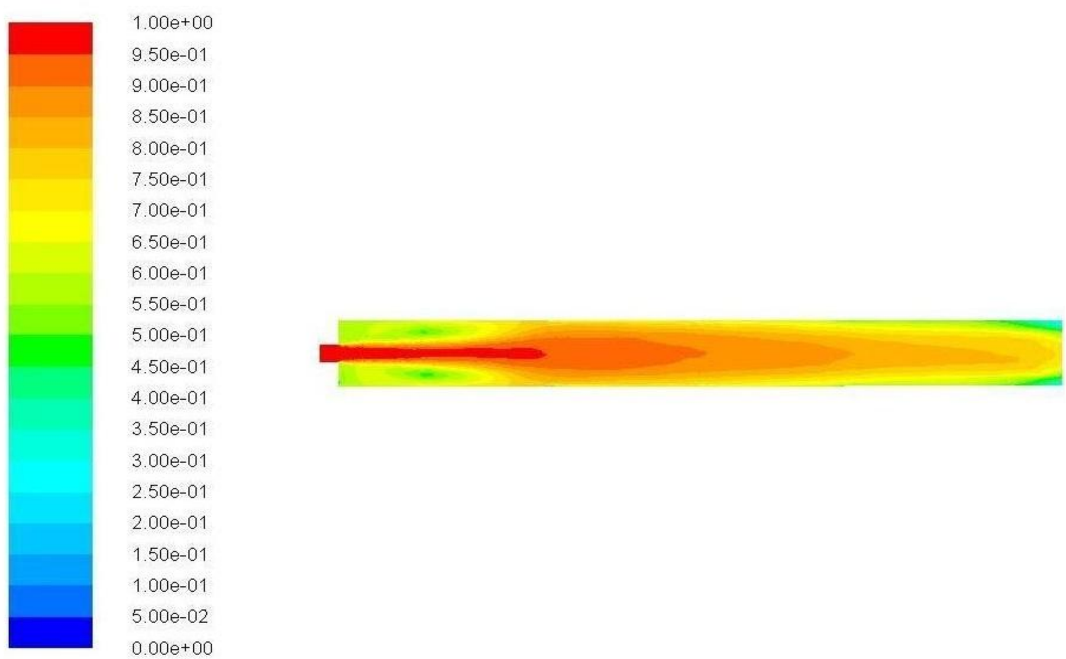


Figure 3.11 Contours of mixtures of methane/air at 170 ms

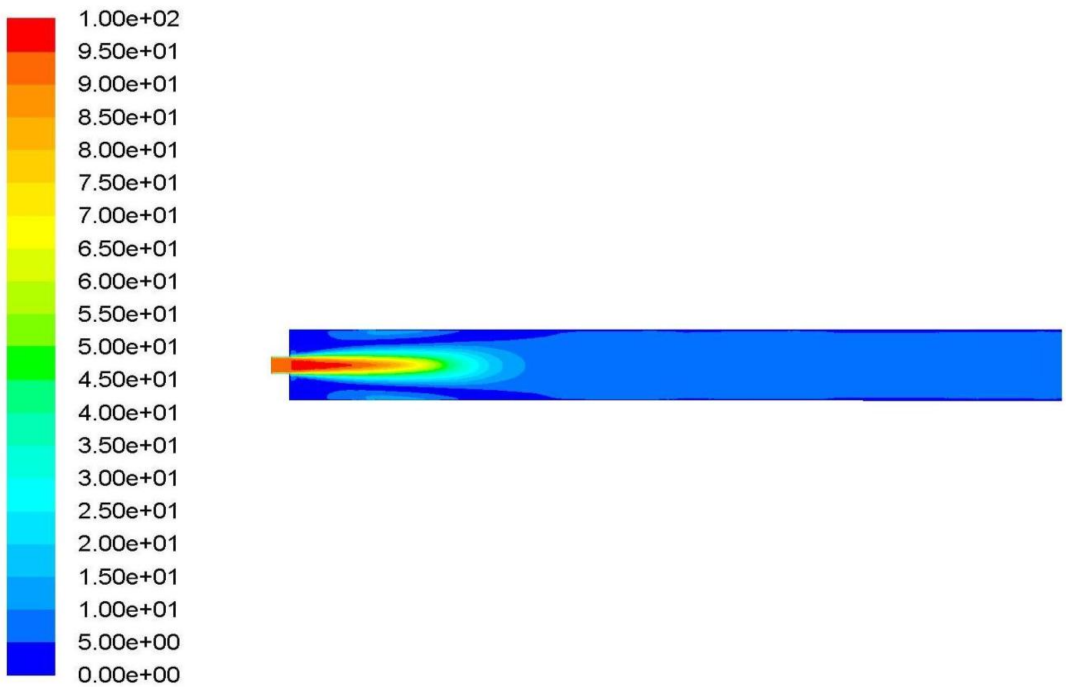
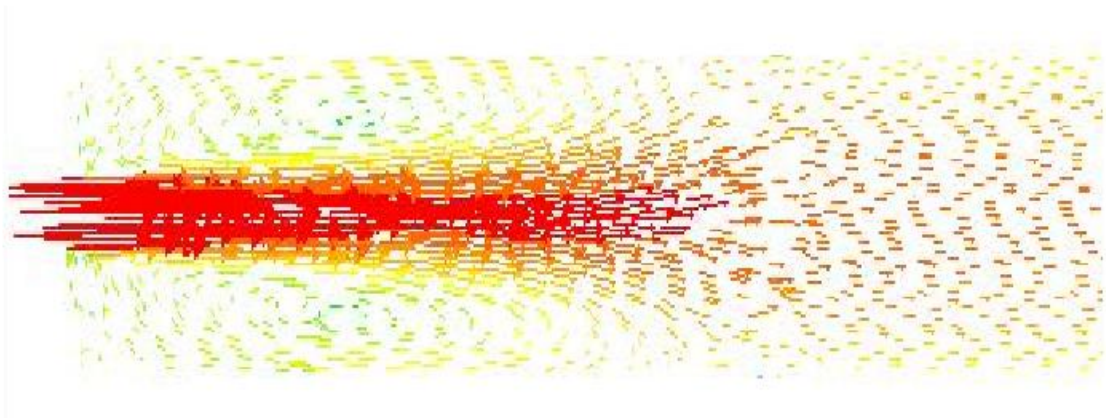
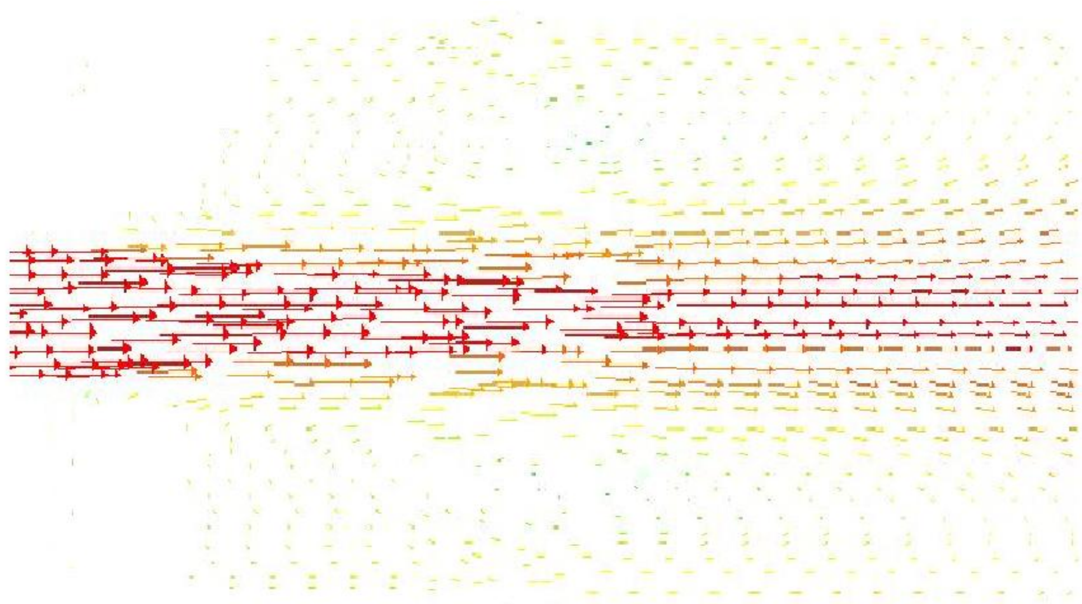


Figure 3.12 Velocity contours for endwall injection port at 170 ms

The methane/air mixture is passing from the one endwall injection port as it moves on with some distance there is a flow going circular direction near the wall but with the less filling as shown in Figure 3.13. It reduces the dead zones but not fully covered near the corners. So, we have chosen other case like case 2 and case 3 for least dead zones.



(a)



(b)

Figure 3.13 Shows vectors of velocity from the methane/air for endwall injection port (a) shows for endwall injection port at 170 ms and (b) Closer view for endwall injection port at 170 ms

As shown in the Figure 3.14, there is no mixture leaving the exit up to 120 ms. Beyond that time, a rapid rise of the mixture is seen, with a 50 percent mixture passing the outlet at 150 ms. The dead zones in the tube are much diminished at this time. After some time, the mixture concentration at the outflow increases to about 70 percent and stays fairly constant. The overall mixture concentration in the tube is about 75 percent. Due to the difficulty of attaining a higher fill ratio, the tube is considered to be filled at this time of about 160 ms.

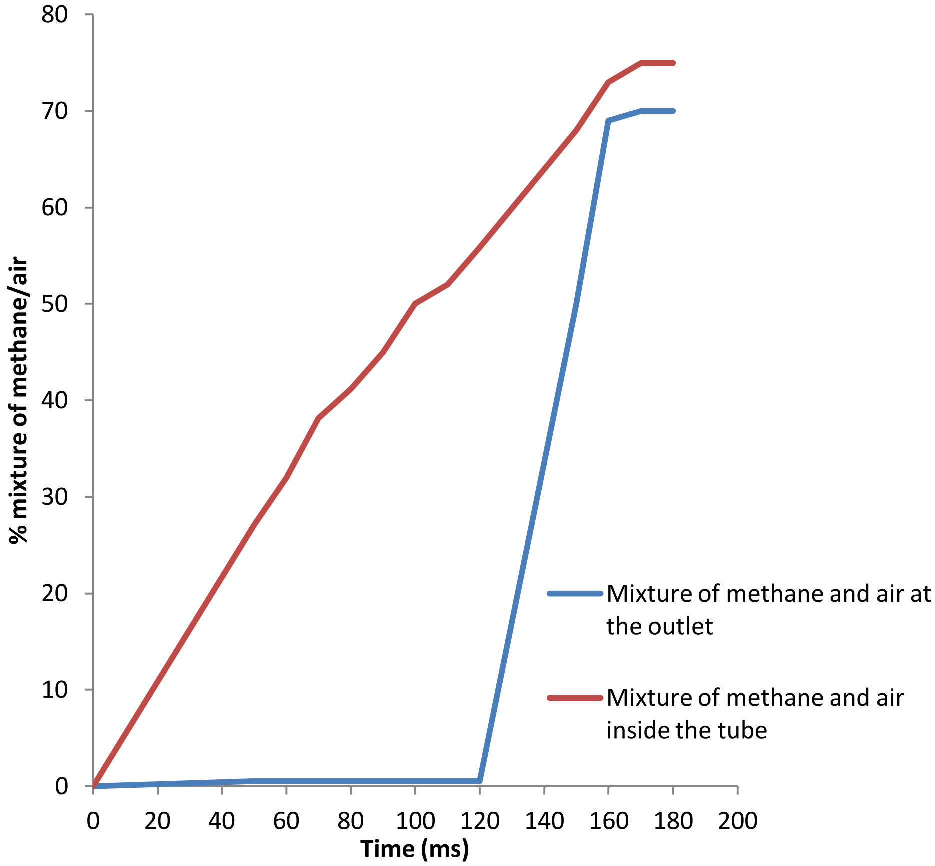


Figure 3.14 Shows the concentration plot of methane/air inside the tube and at the outlet for the endwall injection port

3.1.2. Case 2

In this case the flow passes from nine inlets; each at an average inlet velocity is 93 m/s. To decrease the time these sidewall injectors are placed with two diametrically opposite rows, equally, on four sides and one at the closed end of the tube. Figures 3.15-3.22 shows snapshots of the fill. While dead zones remain, the figures shows that the tube fills more rapidly than Case 1. This more rapid fill is attributed to the large number of distributed ports delivering nine times the flow rate as Case 1. With such an increase in mass flow, the tube is filled faster but not proportionately faster. As can be seen in Figures 3.15- 3.22, the flow proceeds with fewer dead zones than Case 1. Figure 3.23 shows the velocity contour plot at 35 ms.

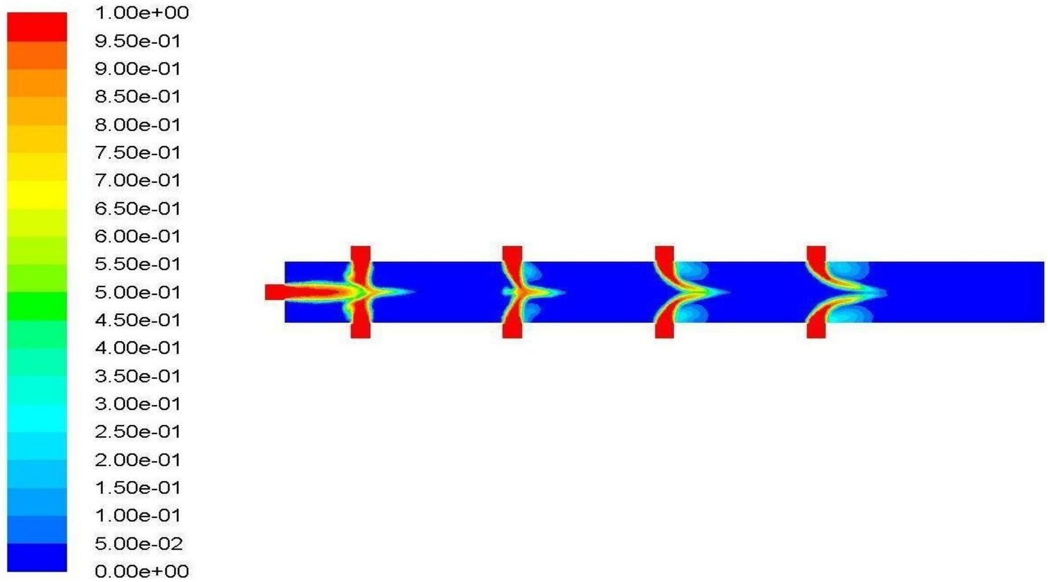


Figure 3.15 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 5 ms

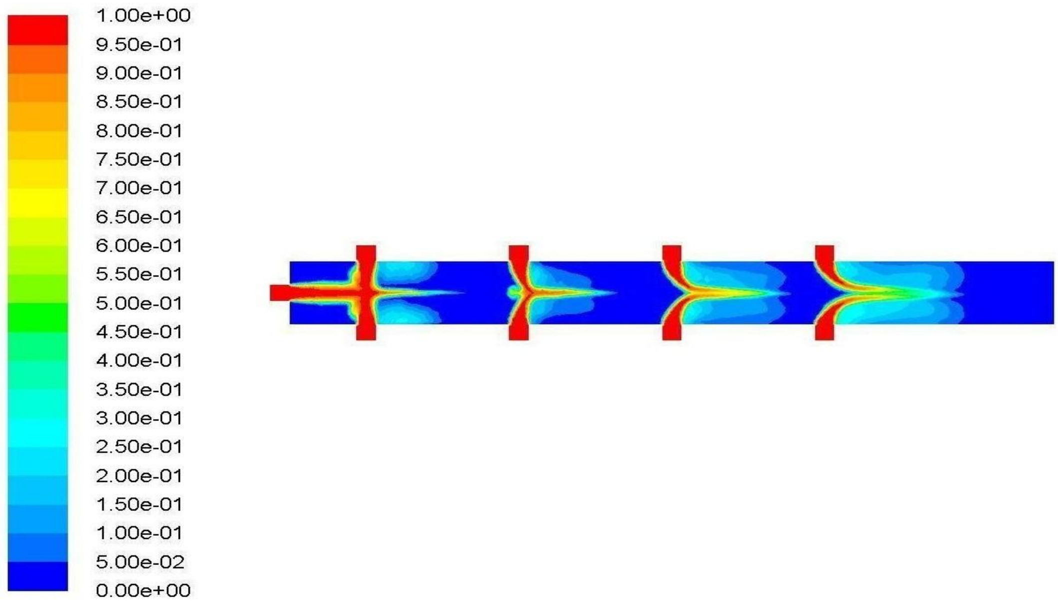


Figure 3.16 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 10 ms

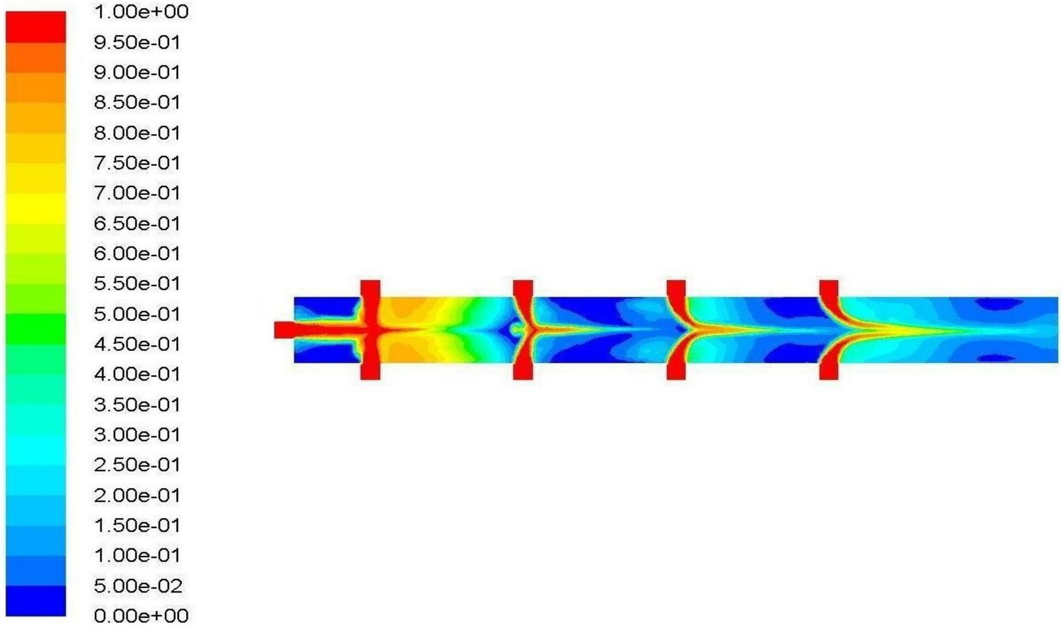


Figure 3.17 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end 15 ms

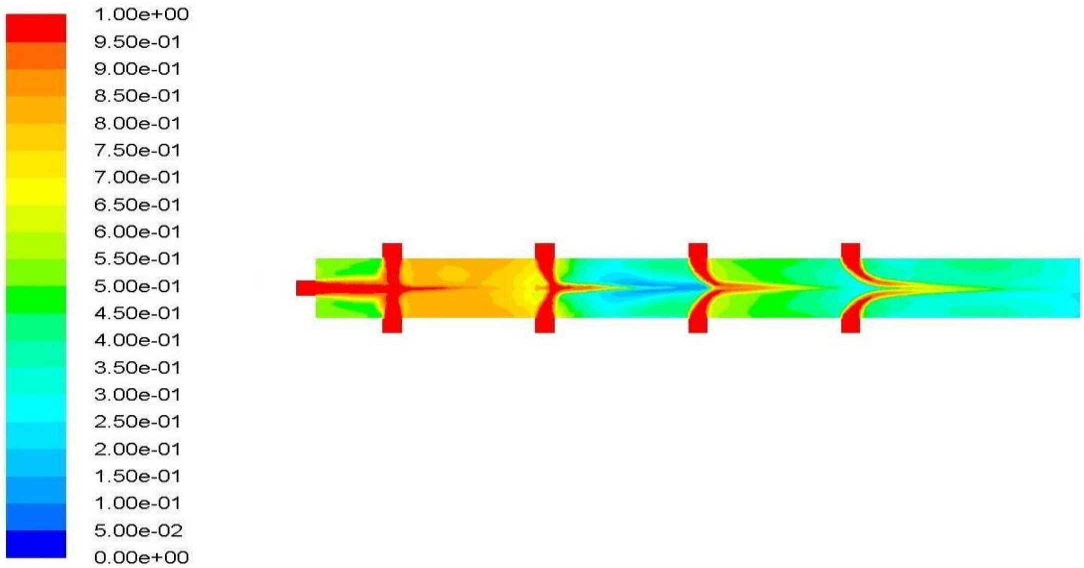


Figure 3.18 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 20 ms

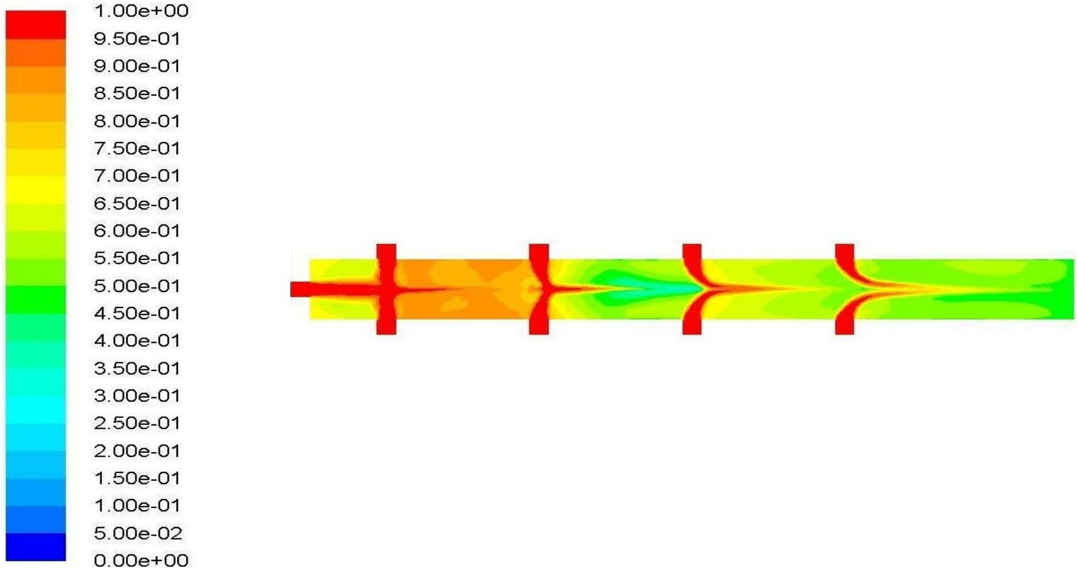


Figure 3.19 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 25 ms

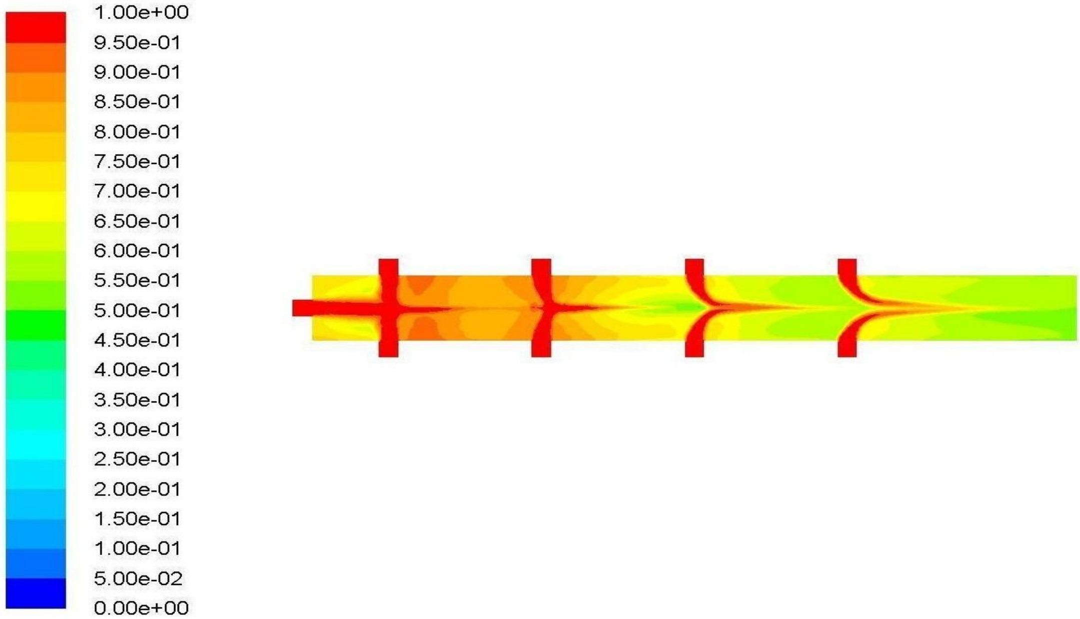


Figure 3.20 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 30 ms

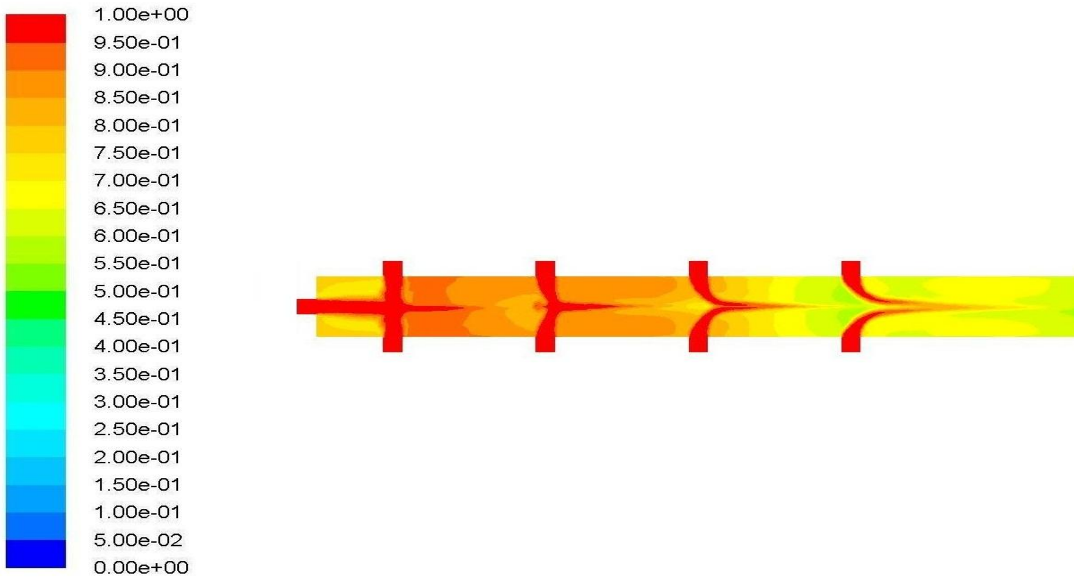


Figure 3.21 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 35 ms

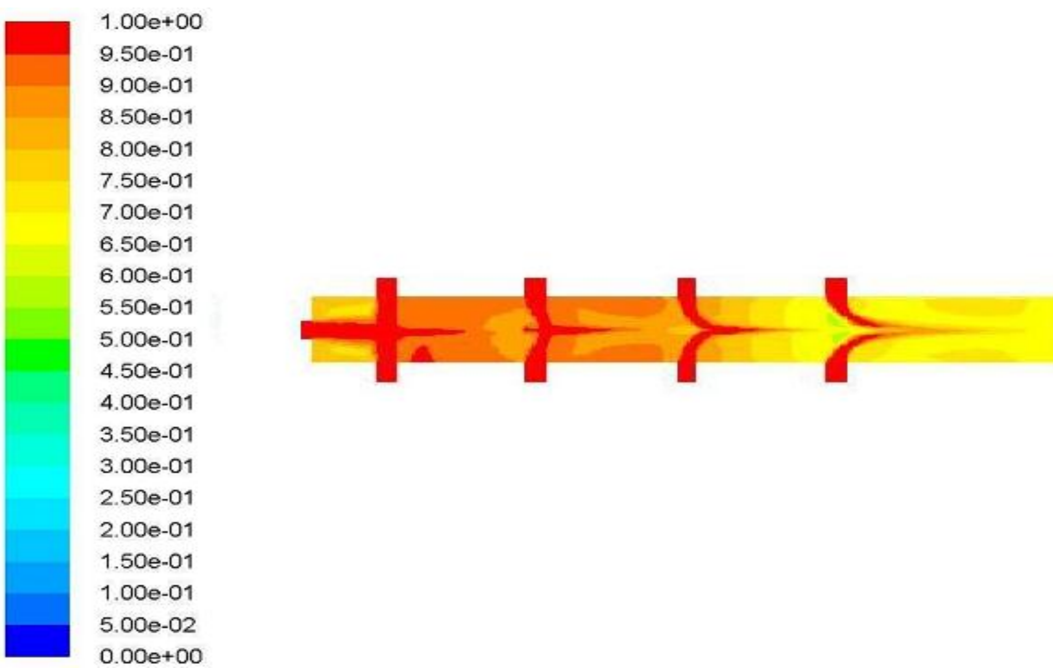


Figure 3.22 Contour plot methane/air mixtures with eight diametrically sidewall injection ports and one at the closed end at 50 ms

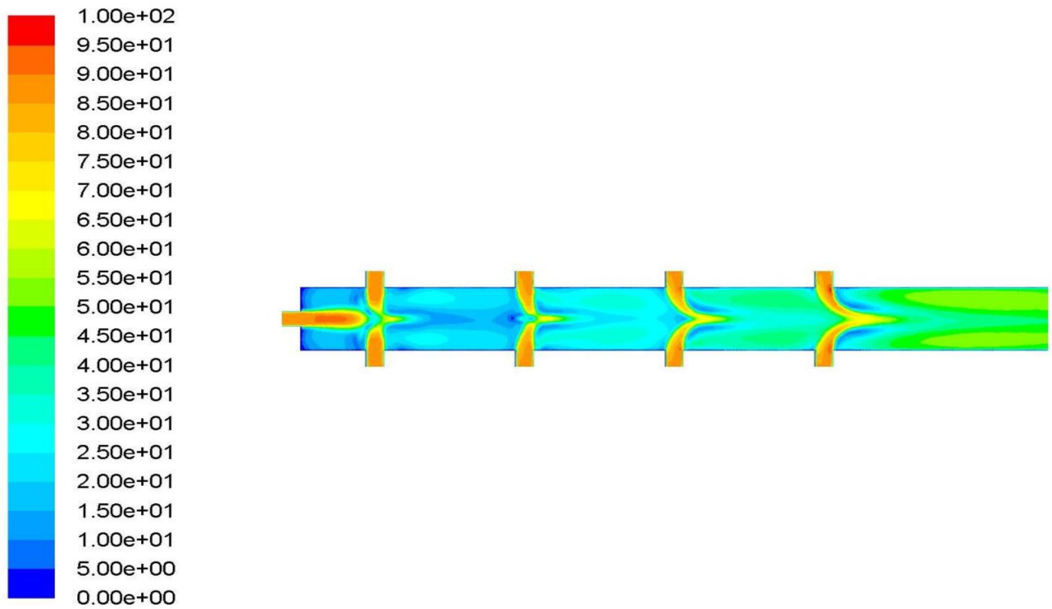
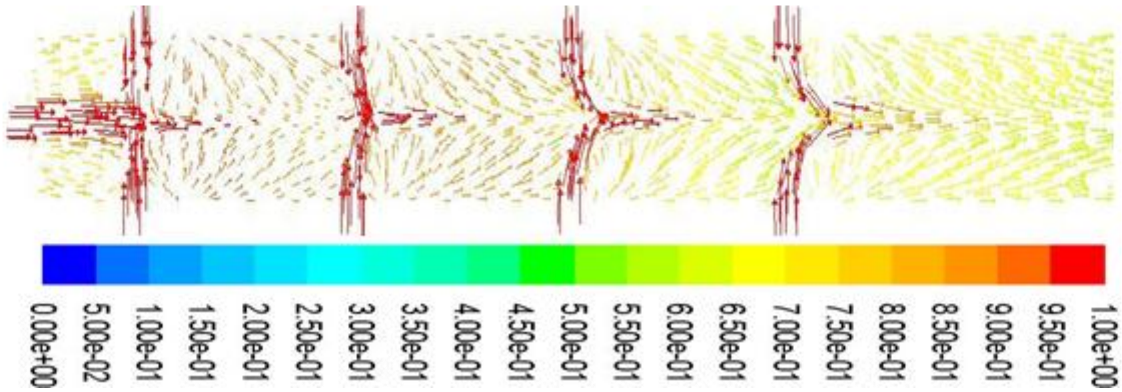
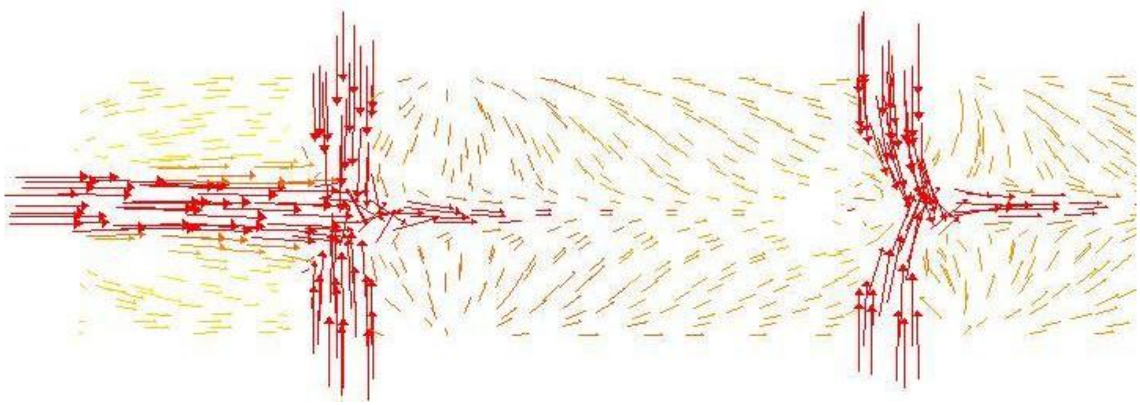


Figure 3.23 Shows velocity contour plot for eight sidewall injector ports and one at closed end at 35 ms

As shown in Figure 3.24 the flow direction is passing from the eight sidewall injector port and also one from closed end of the tube. The sidewall injector ports hits each and pumps downwards sideward's so it covers the corner wall or region to fill. So it reduces the dead zones and reaches at the outlet within less time when compared to Case 1.



(a)



(b)

Figure 3.24 Shows vector plots for methane/air mixture for eight sidewall injection ports and one placed at the closed end (a) shows for sidewall injection ports at 50 ms and (b) closer view for sidewall injection ports at 50 ms

As shown in the Fig. 3.25 a methane/air mixture concentration of about 70 percent is reached at the exit at about 40 ms. The overall concentration of the mixture in the tube at this time is about 76 percent.

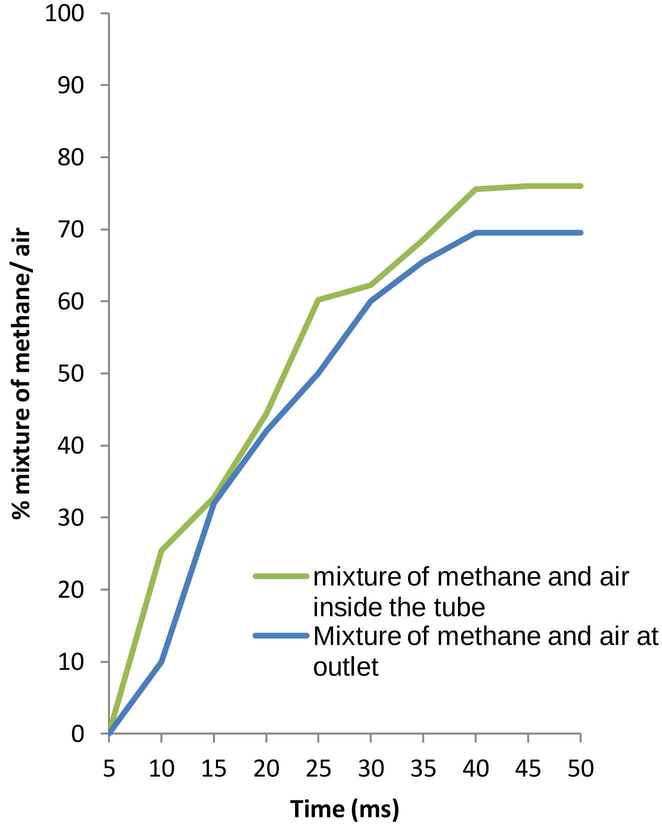


Figure 3.25 shows the concentration plot of methane/air mixture for nine inlets and one at the closed end of the tube

3.1.2. Case 3

In this case the showerhead is same configuration as Case 2 but with the openings replaced by “showerheads”. The average velocity inlet is 93 m/s as in Case 2. It can be seen in Figs. 3.26-3.38 that the tube fills rapidly with the least amount of dead zones. Figure 3.41 shows that at 50 ms, the mixture concentration in the tube is about 90 percent and the mixture at the exit plane is also about 90 percent. Thus, the best fill is obtained with this configuration. Figure 3.39 shows the velocity contour plot at 50 ms.

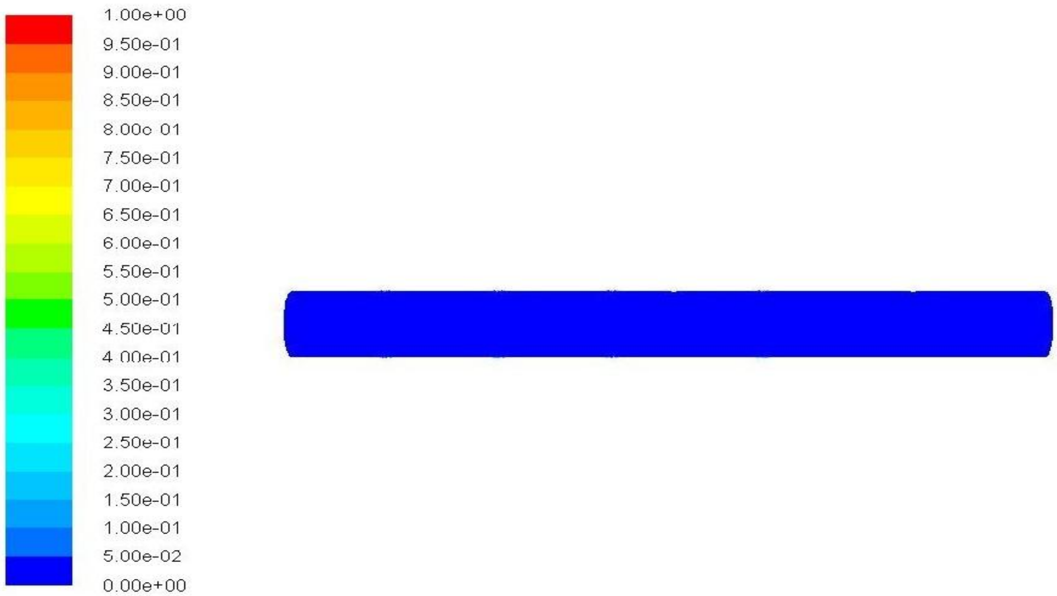


Figure 3.26 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 0 ms

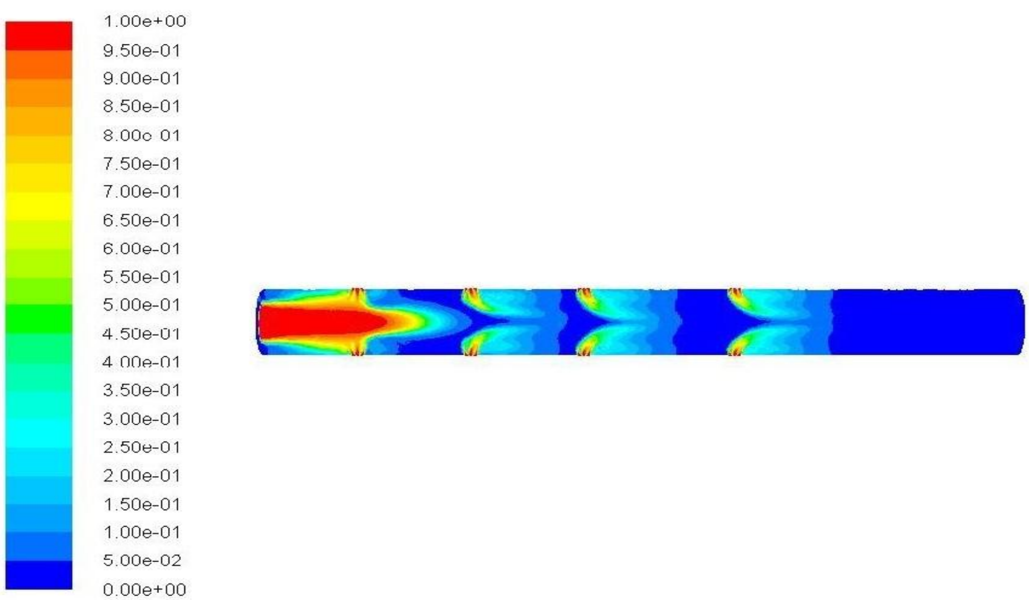


Figure 3.27 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 5 ms

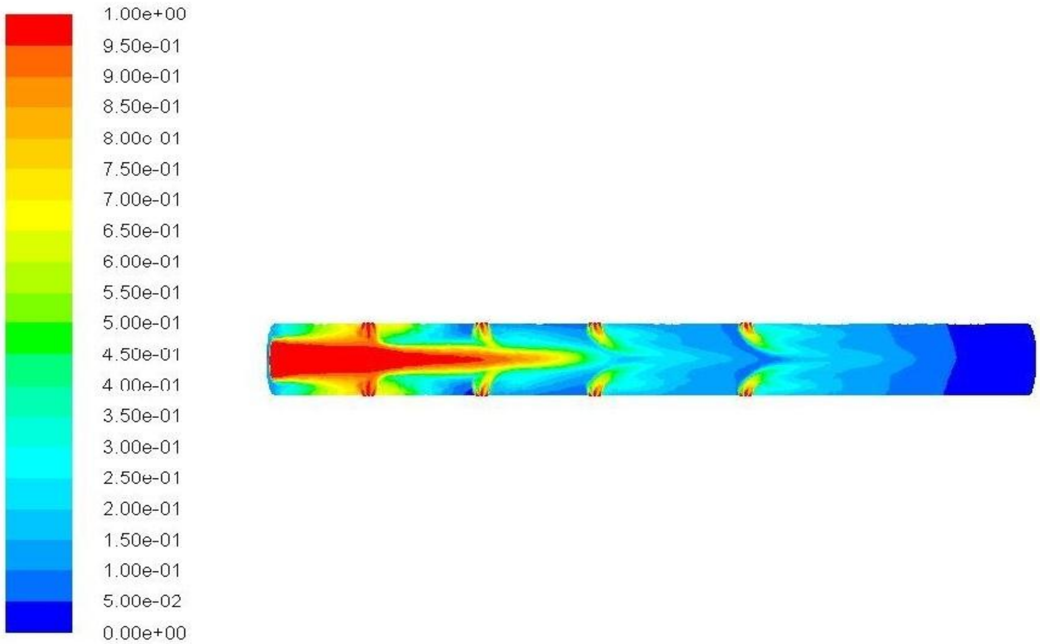


Figure 3.28 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 10 ms

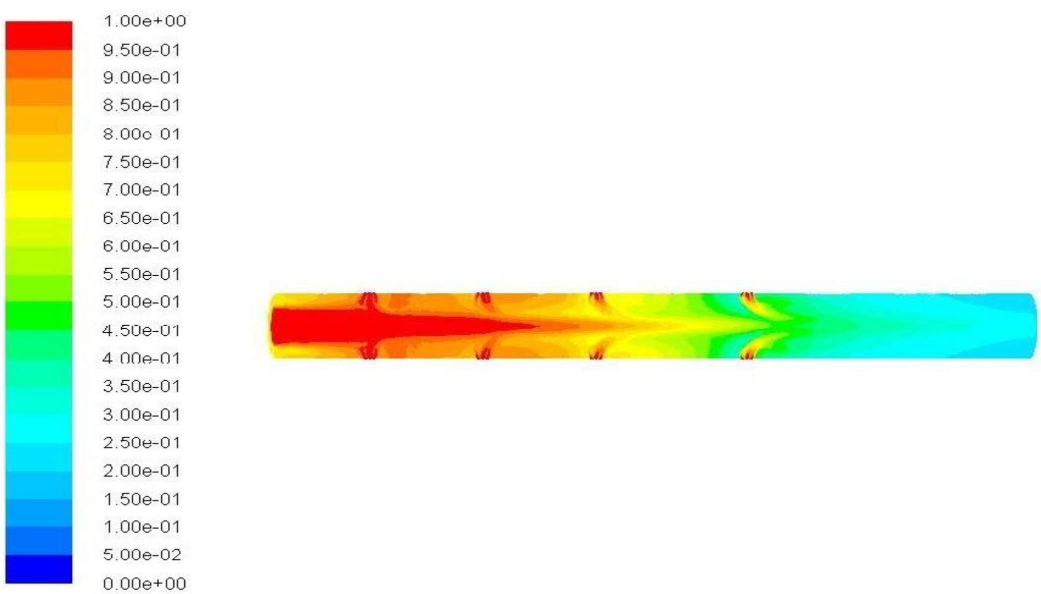


Figure 3.29 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 15 ms

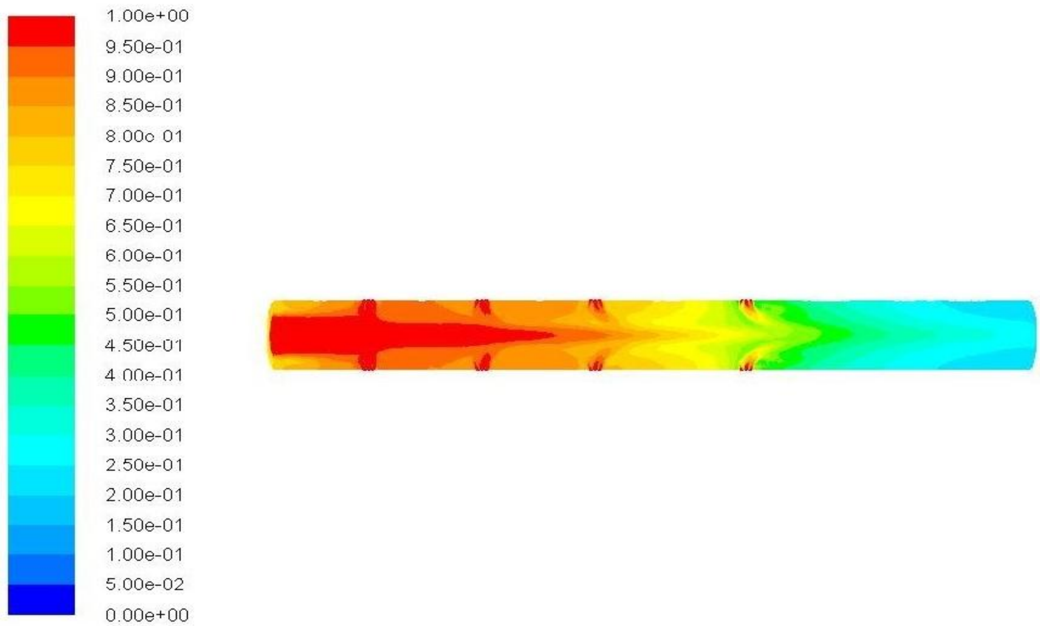


Figure 3.30 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 20 ms

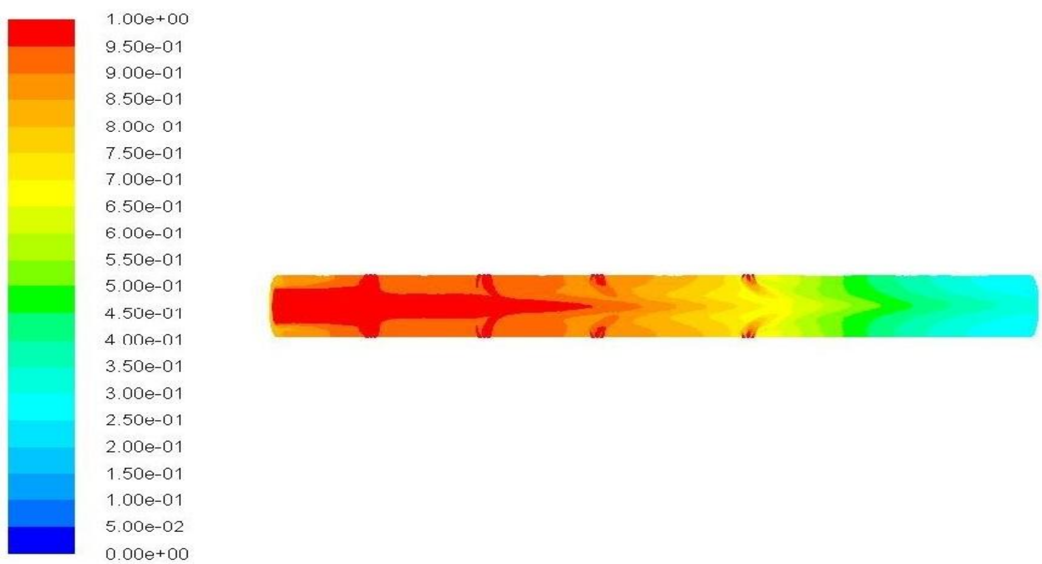


Figure 3.31 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 25 ms

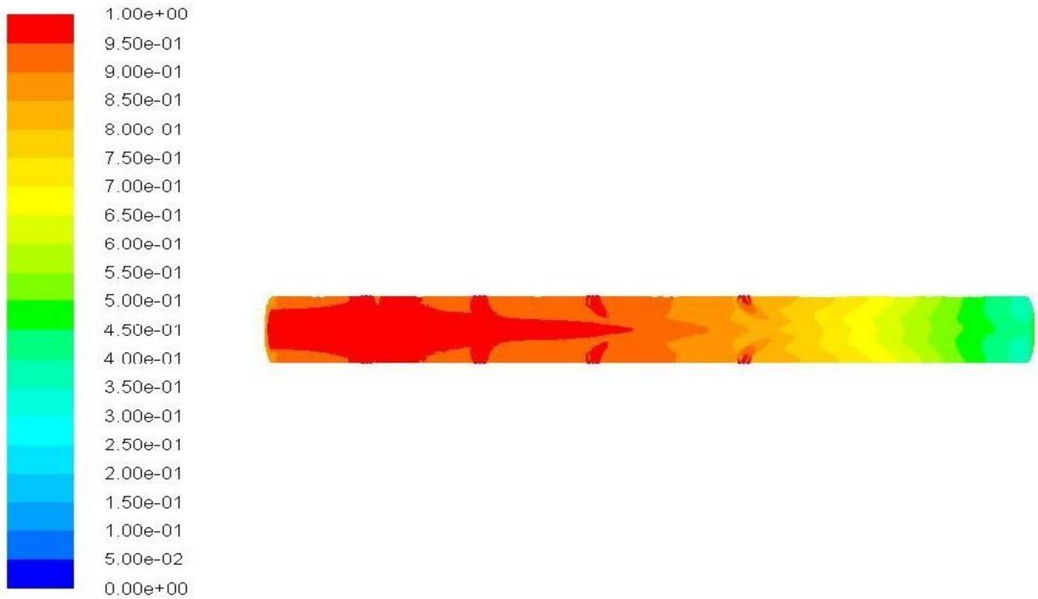


Figure 3.32 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 30 ms

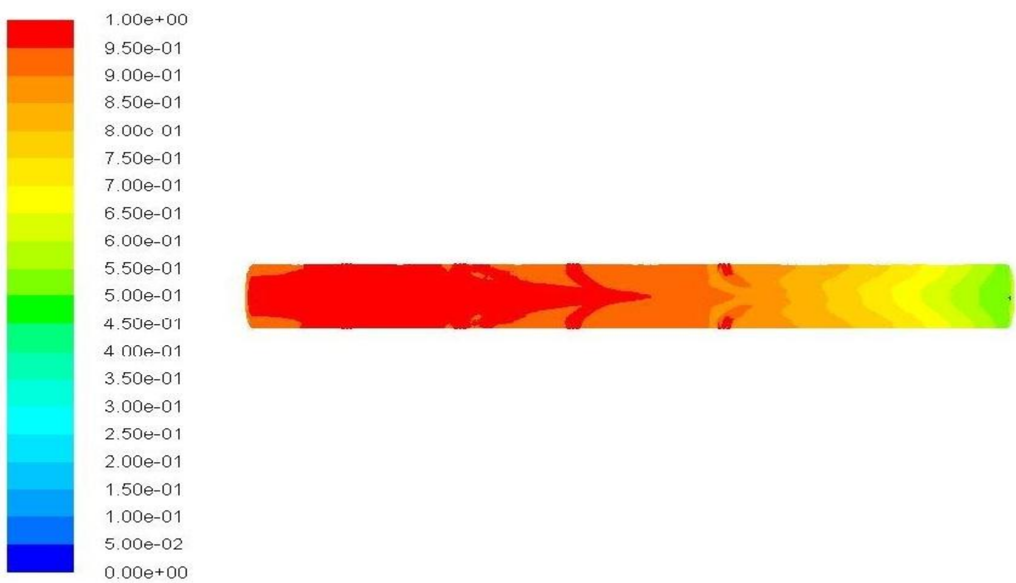


Figure 3.33 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 35 ms

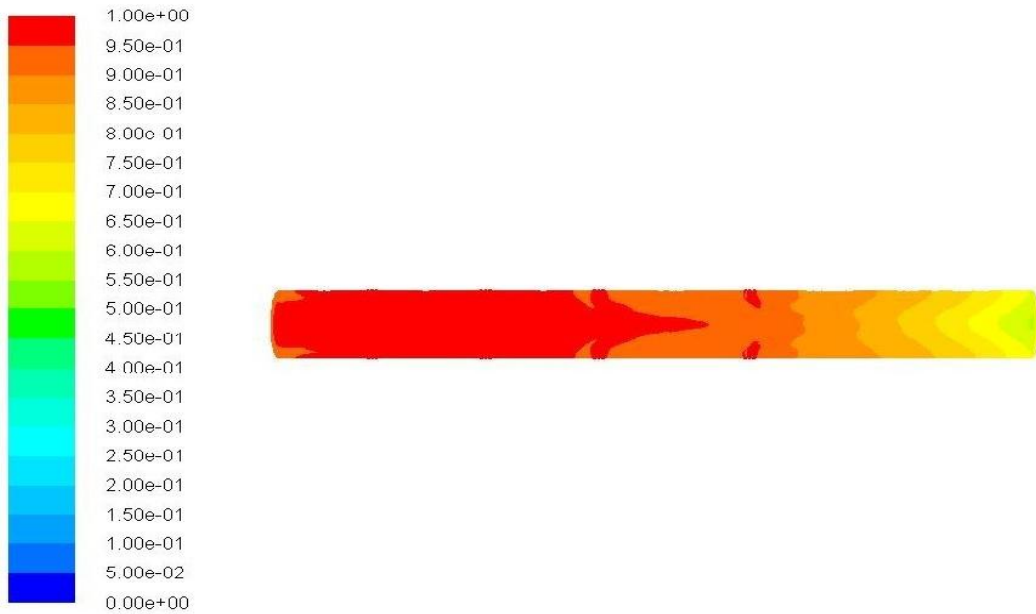


Figure 3.34 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 40 ms

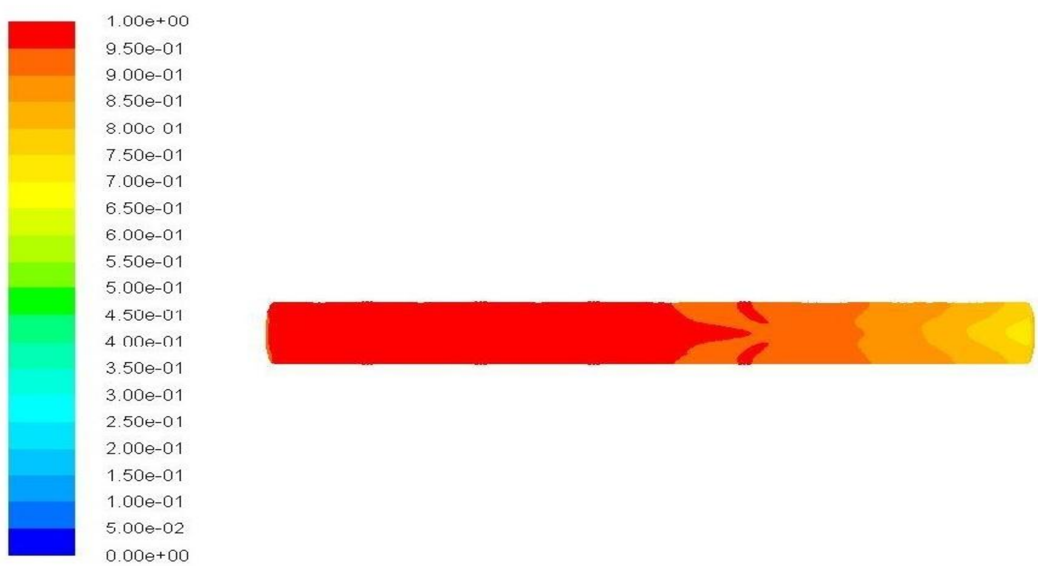


Figure 3.35 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 43 ms

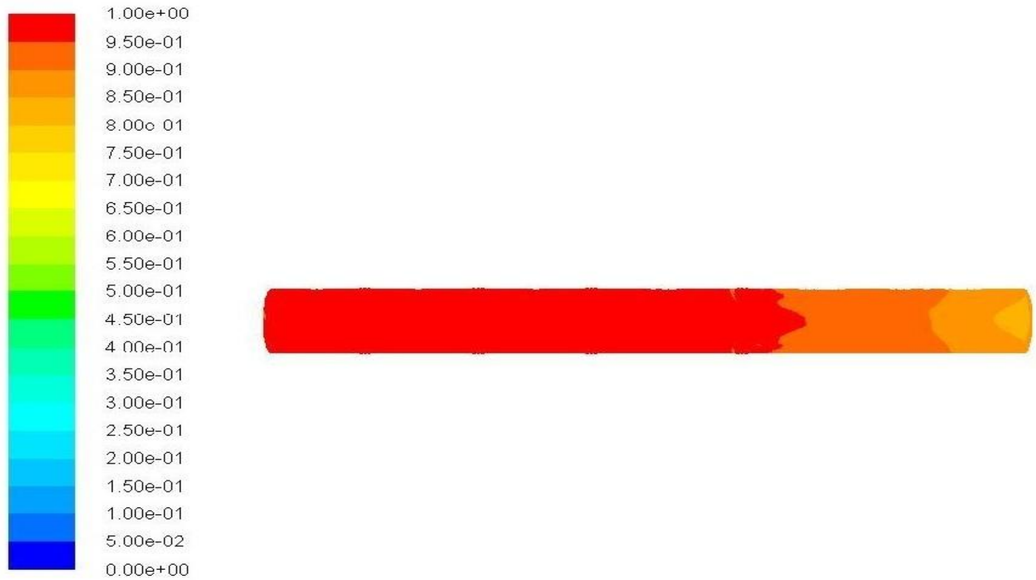


Figure 3.36 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 45 ms

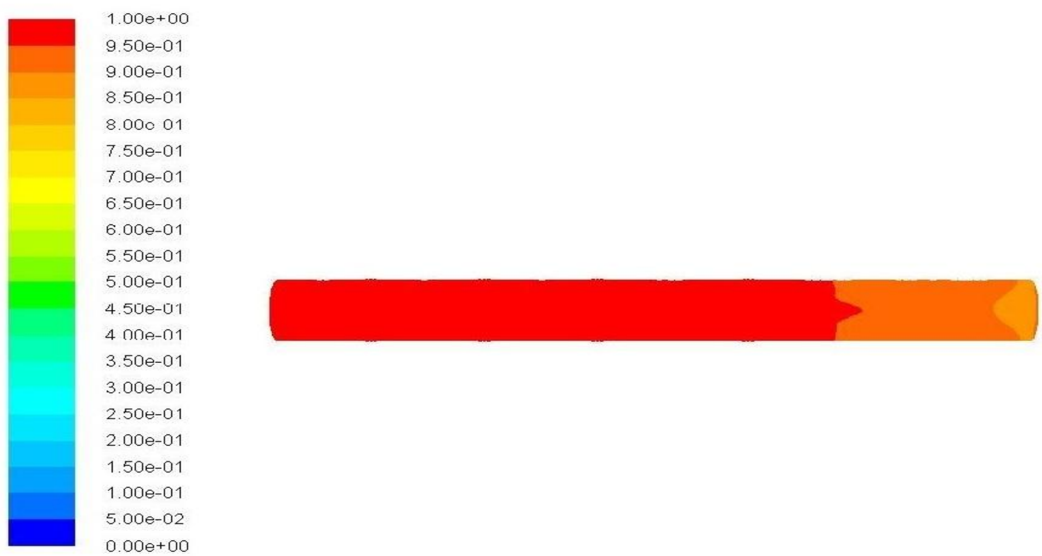


Figure 3.37 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 47 ms

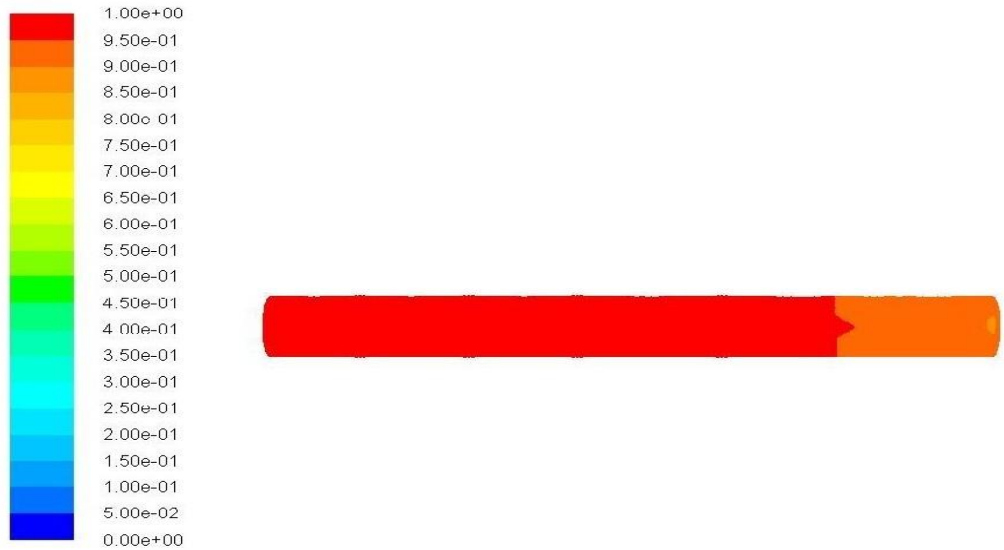


Figure 3.38 Contour plot of methane/air mixture is same configuration as Case 2 but with the openings replaced by “showerheads” at 50 ms

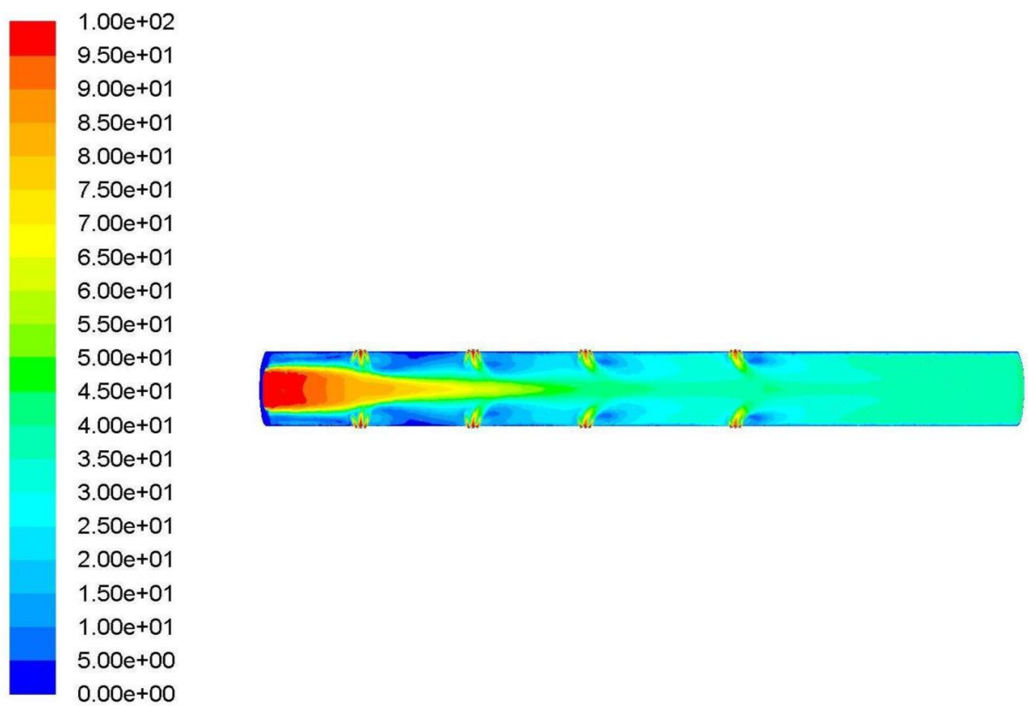
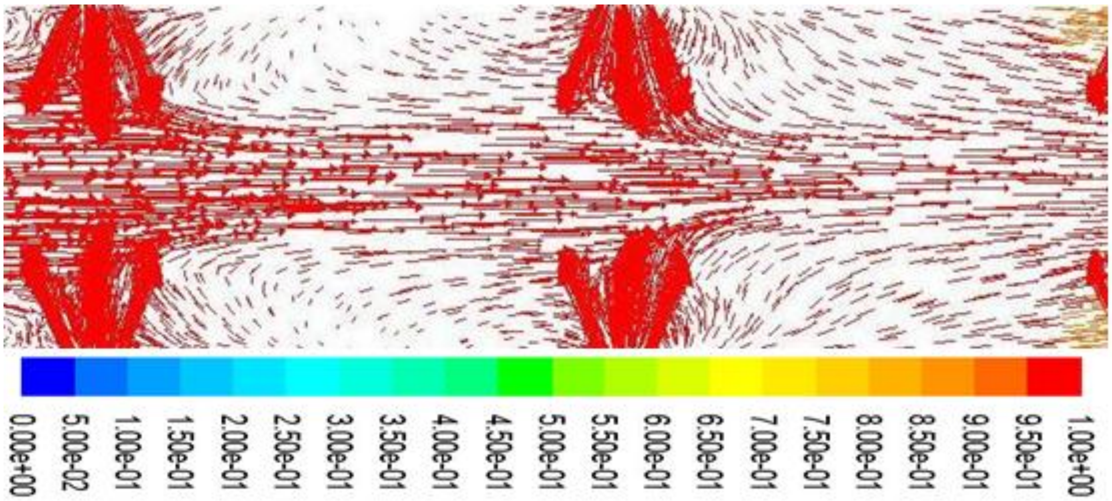
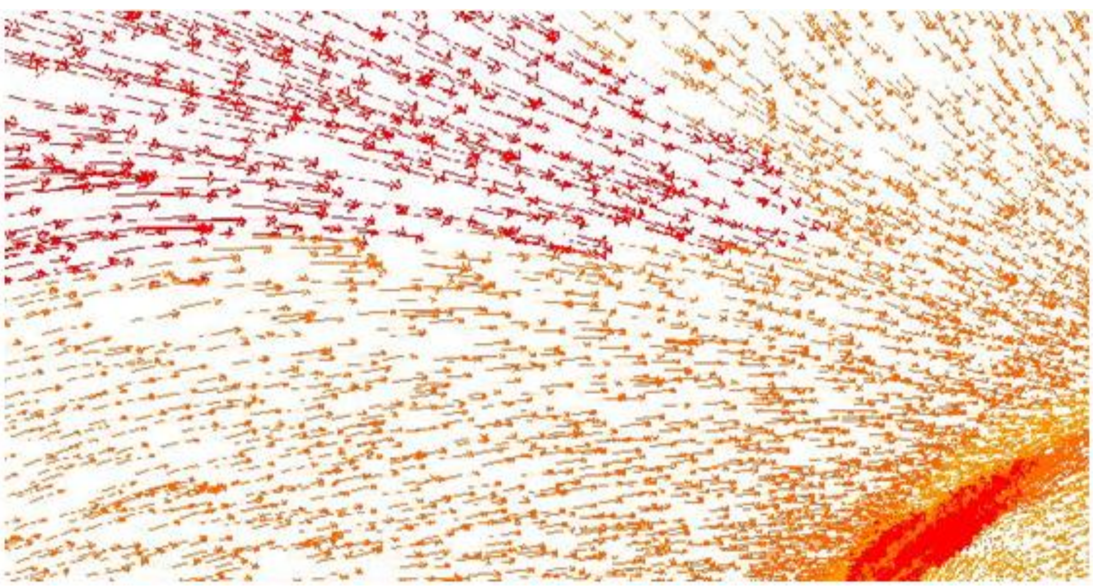


Figure 3.39 Velocity contour plots for nine showerhead inlets at 50 ms

As shown in Figure 3.40 as the flow passes through the showerhead inlets it will go directly downwards and covers the entire region firstly with least dead zones within less time when compared to Case 1 and 2.



(a)



(b)

Figure 3.40 Vector plots for methane/air mixture for nine showerhead inlets (a) shows for showerhead case at 50 ms and (b) closer view for showerhead case at 50 ms

As shown in Figure 3.41 the abscissa represents time (ms) and the ordinate represents percentage mixture of methane/air. As time increases, there is an increase in the filling tube and at the outlet. At 50 ms the mixture inside the tube is 90.2 percent and 89.9 percent coming out of the tube with the very least dead area region. After 50 ms it gives constant values.

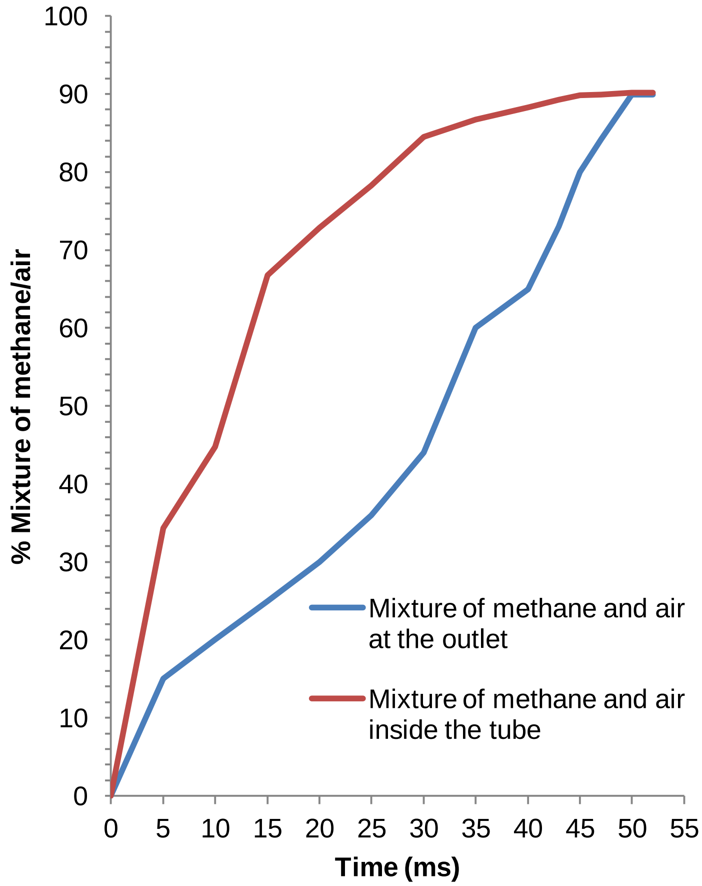


Figure 3.41 Concentration plot of methane/air mixture for showerhead case

CHAPTER 4

CONCLUSION AND FUTURE WORK RECOMMENDED

4.1 Conclusion

In order to reduce the tube filling time we examined: Three different fill configurations were examined for application in pulse detonation engines. Case (i) has filled only 75 percent of methane/air mixture inside the tube at 170 ms, Case (ii) has filled only 75 percent of methane/air mixture inside the tube within 50 ms, whereas Case (iii) has filled 90 percent of methane/air mixture inside the tube and 90 percent of mixture coming out from the tube within 50 ms and with the less dead area zones. Hence it shows Case (iii) is the best process to fill the tube within less time and with least dead zones.

4.2 Future Work Recommended

The thesis research filled the detonation tube with a stoichiometric methane/air premix. Future work can include other mixtures of hydrogen or propane as fuels, and air or oxygen as oxidizers. It is expected that the fill times may change with the molecular weight of the mixture. In addition, alternative injector configurations can be explored. These include staggered and phased sidewall injector arrays.

APPENDIX A

ANALYSIS IN FLUENT^{TM}

The analysis is done in FLUENT™, this model is solved in the unsteady state condition.

Step 1: To run a simulation the step taken is to read a case or a mesh file and then check the grid as shown in Figure A.1.

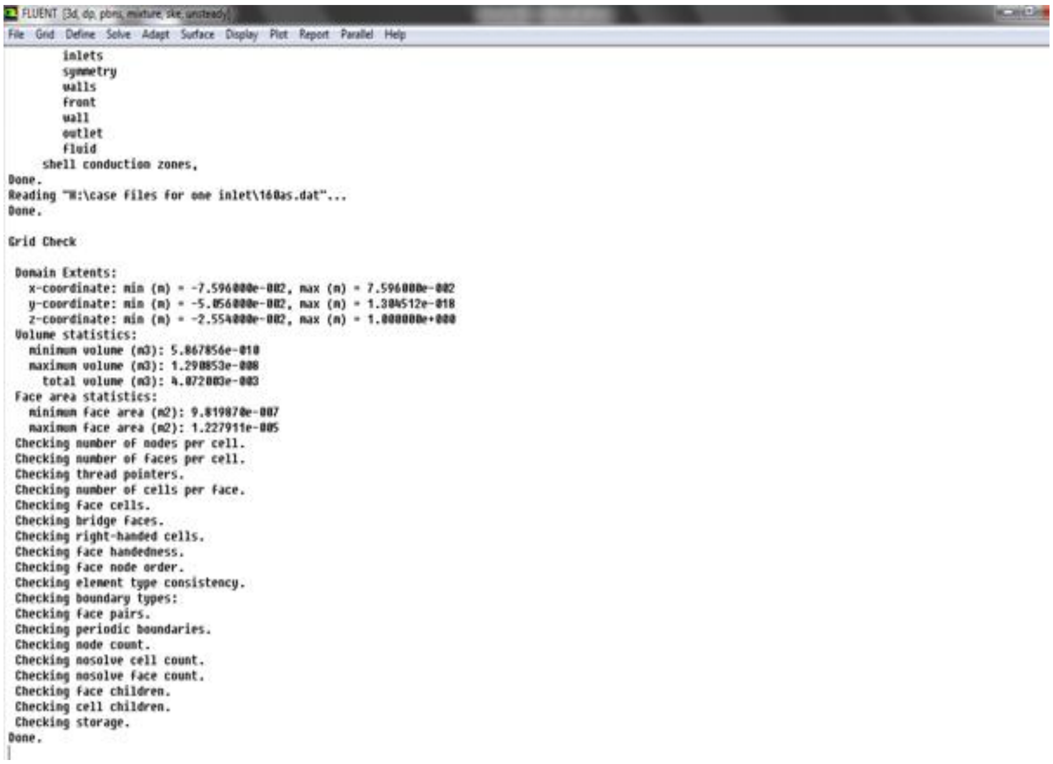


Figure A.1 shows to run the case or mesh file and check the grid

Step 2: Then go to define and then click on model. Then make it as 3D model, unsteady state condition, and pressure based solver as shown in Figure A.2.

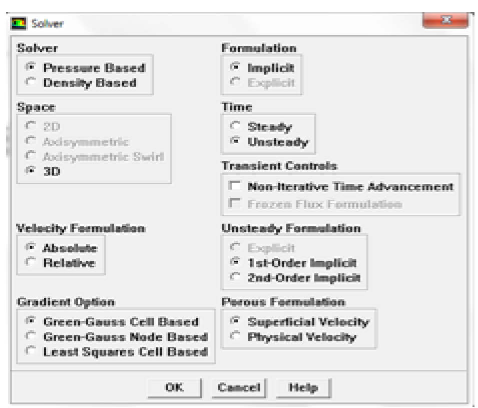


Figure A.2 Shows model conditions

Step 3: Define the viscous model in order to choose K-epsilon turbulence model as shown in Figure A.3.

Figure A.3 Shows the viscous model

Step 4: Created a material methane/air as a mixture as shown in Figure A.4.

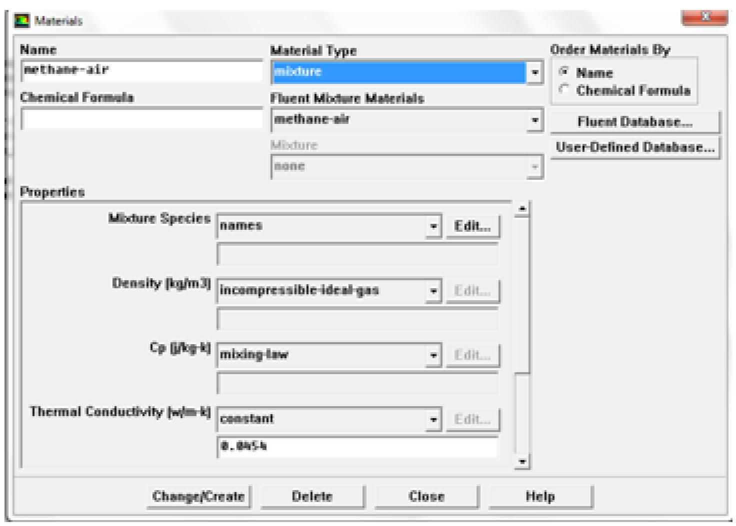


Figure A.4 Shows the materials properties

Step 5: Set for the boundary condition. In that inlets are taken as velocity inlet, outlet, wall with a given inlet as 93 m/s as shown in Figure A.5.

Figure A.5 Shows the boundary conditions

Step 6: Set to residual monitors. To check the solution is converged. The iteration is shown in the main window as shown in Figure A.6.

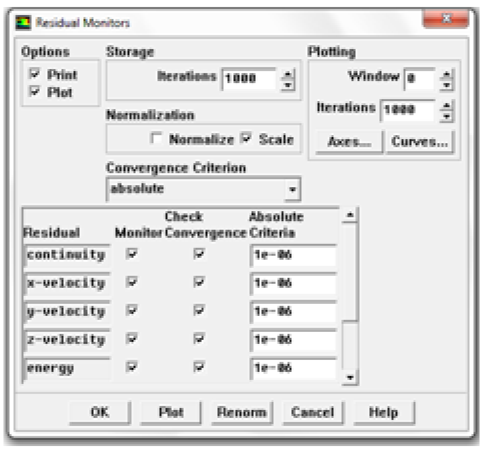


Figure A.6 Shows the residual monitors.

Step 7: Once the solution is converged. Contour plots, velocity vectors of methane/air mixture, velocity magnitude are displayed.

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BIOGRAPHICAL INFORMATION

Shravani Dwarakapally had her early education in Nalgonda, India. She completed her Bachelor’s degree in Mechanical Engineering from the J.N.T.University, in 2009. Her keen interest in CFD made her pursue Master’s thesis in University of Texas at Arlington guided by Dr. Frank K. Lu. Her research interests include Fluid Dynamics, Finite Element Methods.