TO SIMULATE MOTORING OF A DIESEL IC ENGINE IN A SINGLE SIMULATION

Shakti Prasad Patra [1], Evan Fernandes [2], Dhiraj Garg [3] and Pushkar Sheth [4]

[1] Undergraduate student, Department of Mechanical Engineering, NIT ROURKELA, Odisha, India- 769008

[2]Research Assistant at FOSSEE, IIT BOMBAY

[3]Assistant Professor, Department of Chemical Engineering, Shiv Nadar Institution of Eminence, NH-91, Tehsil Dadri Gautam Budhha Nagar, U.P., India- 201314

[4] Engineering Technical Leader at Wabtec Corporation

Abstract

This computational study investigates the thermodynamic behaviour of a motored diesel internal combustion engine through a detailed transient simulation using OpenFOAM. The study focuses on analyzing the engine's performance under both isothermal and adiabatic conditions, employing a laminar Stokes flow model to simplify the Navier-Stokes equations while preserving essential compressibility effects. Numerical modelling is performed using overRhoPimpleDyMFoam solver and stokes laminar model in OpenFOAM. The simulation utilizes the SNL GM 1.9L engine geometry, featuring a structured hexahedral mesh generated with blockMesh and dynamic mesh capabilities to accurately replicate piston-cylinder motion throughout the four-stroke cycle.

Keywords: OpenFOAM, IC engine, Simulation, Adiabatic, Dynamic mesh

1. Introduction

Internal Combustion (IC) engines are widely used in automotive, marine, and power generation applications due to their high efficiency, reliability, and cost-effectiveness. Among IC engines, the Diesel engine stands out for its superior thermal efficiency and fuel economy, making it a preferred choice for heavy-duty vehicles, industrial machinery, and power plants.

The Diesel engine operates on a four-stroke cycle: suction, compression, power, and exhaust. The cycle begins with the intake stroke, where air is drawn into the cylinder through the open intake valve as the piston moves downward. Next, during the compression stroke, both valves close, and the piston compresses the air to a high pressure and temperature as it moves upward. Near the end of compression, diesel fuel is injected into the combustion chamber via a fuel injector. Since diesel has a low auto-ignition temperature, the hot compressed air ignites the fuel spontaneously, initiating the power stroke. The rapid combustion generates high pressure, forcing the piston downward and producing mechanical work. Finally, in the exhaust stroke, the exhaust valve opens, allowing the piston to push out the burnt gases as it moves upward, completing the cycle.

Fig 1: Cross-sectional view of an IC engine

Fig 2: Four-Cylinder Inline Crankshaft Assembly

2. Problem Statement

This computational study investigates the motoring operation of a diesel internal combustion engine through a comprehensive transient simulation. The primary objective is to characterize the time-varying thermodynamic behaviour of the system by analyzing critical parameters including in-cylinder pressure, temperature distribution, and mass flow dynamics throughout complete engine cycles. As the piston executes reciprocating motion, the simulation captures the coupled thermo-fluid interactions governing compression and expansion processes under non-combusting conditions. Special emphasis is placed on resolving the transient evolution of these properties across multiple consecutive cycles to identify cyclic variations and establish baseline thermodynamic performance. The analysis will quantify key metrics

such as peak compression pressure, temperature stratification, and charge motion characteristics, providing fundamental insights into the engine's motoring behaviour.

3. Governing Equations

The motored diesel engine simulation employs a laminar Stokes flow model to resolve the time-dependent thermodynamics during compression and expansion strokes. The governing equations simplify the Navier-Stokes framework by assuming viscous-dominated flow while preserving compressibility effects critical for engine applications. The continuity equation enforces mass conservation as the piston moves, while the momentum equation neglects inertial terms under the Stokes approximation. The energy equation captures adiabatic heating/cooling during gas compression/expansion, coupled with the ideal gas law to close the system. These equations are solved on dynamic meshes to track piston motion, providing insights into pressure-temperature evolution without turbulence effects.

- Continuity Equation (mass conservation):

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \qquad \text{- - - - - (1)}$$

Where ρ is the density of the fluid (in kg/m^3)

u is the velocity of flow (in m/s)

$\nabla.(\rho u)$ is the net mass flux divergence

- Momentum Equation:

$$\frac{\partial(\rho u)}{\partial t} = -\nabla p + \mu \nabla^2 \mathrm{u} + F_b \qquad \text{- - - - - (2)}$$

Where p is the thermodynamic pressure inside the system (in Pa)

μ is the dynamic viscosity (in Pa.s)

∇^2u is the Viscous momentum diffusion

F_b is the body force

- Energy Equation:

$$\frac{\partial(\rho C_v T)}{\partial t} + \nabla.(\rho C_v T u) = -p(\nabla.u) + \mu \varphi_v \qquad \text{- - - - - (3)}$$

Where C_v is the specific heat of the substance at constant pressure (in J/kg.K)

T is the temperature of the system (in K)

φ_v is the viscous dissipation

4. Simulation Procedure

4.1 Geometry and Mesh

The SNL GM 1.9L Engine Geometry has taken into study for the project. This 1.9L diesel engine has an 82mm cylinder diameter (bore) and 90.4mm piston travel (stroke), creating 0.477L of displacement per cylinder. It uses a high 15.8:1 compression ratio typical for diesel engines. The piston connects to a 166.7mm rod with a small 1.6mm offset. It has 23,442.5 mm³ bowl volume which enhances air-fuel mixing and various small volumes adding up to 32.2mL clearance space. The crankshaft's 45.2mm radius spins at about 1500 RPM. & it completes one revolution in 0.04 sec. As it is a four-stroke diesel IC engine, two revolutions of crankshaft contribute to one complete cycle of the IC engine consisting of all the strokes.

The clearance volume domain was created using the blockMesh utility in the openfoam having dimensions of 82 mm cylinder diameter and 6.46 mm of cylinder height. As it is moving mesh domain, the dynamic mesh utility has used to move the mesh to have the real motion as in the piston cylinder motion.

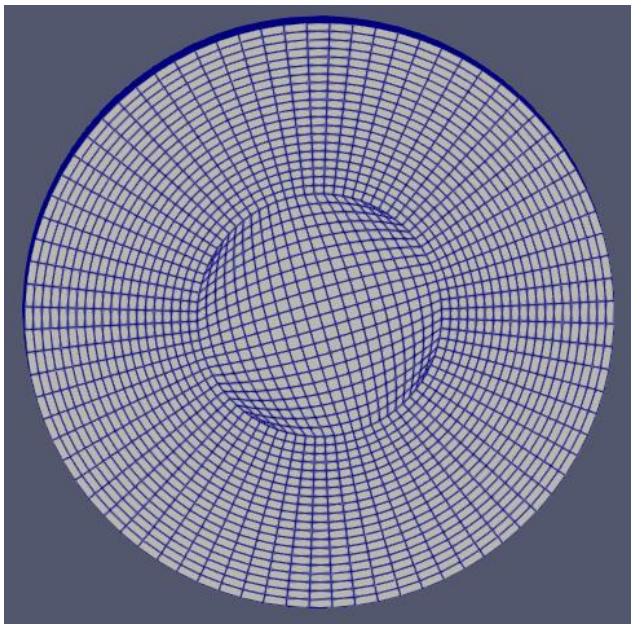

Fig 3: Top view of the geometry

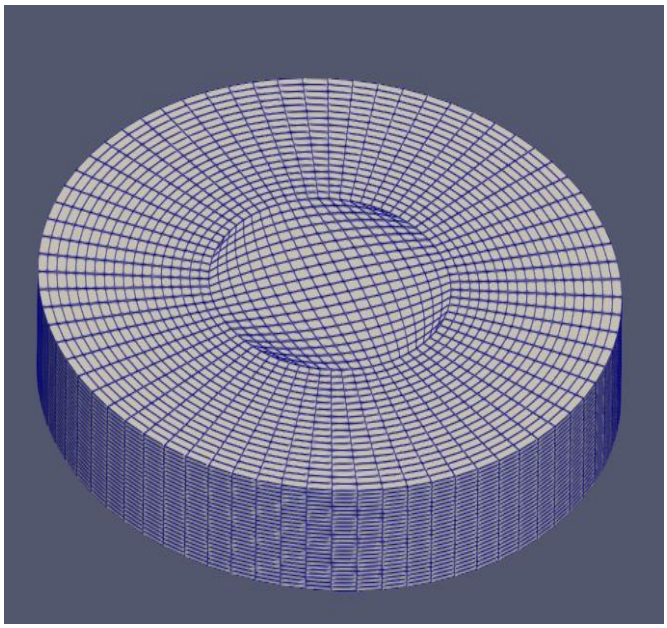

Fig 4: Three-dimensional view of the geometry

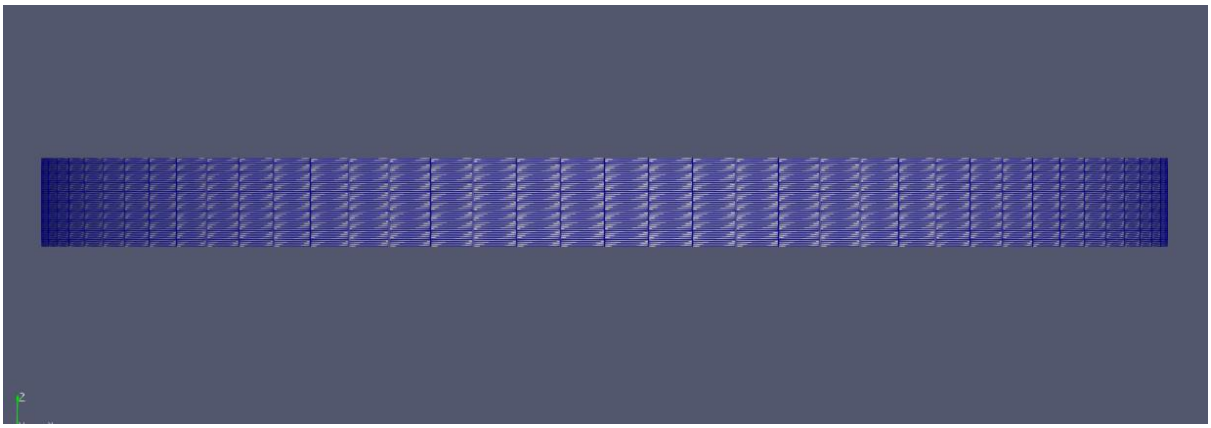

Fig 5: Front view of the geometry

4.2 Initial and Boundary Conditions

The boundary conditions for the velocity (**U**), pressure (p) and temperature (T) fields are summarized in Table 4. The initial conditions are uniform throughout the domain.

Boundary	**U**	**p**	**T**
inlet	pressureInletOutletVelocity	codedMixed	codedMixed
outlet	inletOutlet	codedMixed	zeroGradient
topWall	noSlip	zeroGradient	zeroGradient
cylinderWall	noSlip	zeroGradient	zeroGradient
piston	movingWallVelocity	zeroGradient	zeroGradient

Table 1 : Boundary conditions

The initial conditions for all fields were set to uniform values of p as 100 kPa, T as 300 K and U as (0 0 0) m/s.

4.3 Solver

The tolerance values establish convergence criteria, defining the maximum allowable residuals for each variable to ensure solution accuracy. Absolute tolerances set strict convergence thresholds, while relative tolerances (relTol) control iterative residual reduction. This dual approach balances computational efficiency with physical fidelity, prioritizing precision in critical variables like pressure and momentum. The carefully selected tolerances maintain numerical stability across coupled equations - particularly crucial for engine simulations.

Variable	Tolerance
cellDisplacement	1×10^{-8}
Pressure (p)	1×10^{-11}
Density (rho)	1×10^{-8}
Internal energy (u)	1×10^{-8}
Velocity (U)	1×10^{-6}

Table 2: Convergence criteria

The numerical discretization employs carefully selected schemes to ensure accuracy and stability in the transient simulation. For time integration, a second-order backward scheme is used to maintain temporal accuracy. Spatial gradients are computed using the Gauss linear method, while divergence terms employ specialized treatments: Gauss upwind for velocity to enhance stability in convective flows, Gauss linearUpwind grad(p) for pressure to prevent oscillations, and Gauss vanLeer for energy to preserve boundedness. Laplacian terms utilize Gauss linear corrected for improved diffusion modeling, and linear interpolation ensures consistent field transfers between mesh elements.

Variable	Scheme
Time derivative	Backward
Gradient	Gauss linear
Divergence	Gauss upwind (for velocity) Gauss linearUpwind grad(p) (for pressure) Gauss vanLeer (for energy)
Laplacian	Gauss linear corrected
interpolation	linear

Table 3: Discretization Schemes

This numerical solution employs optimized solver-preconditioner combinations for each variable to ensure efficient convergence. The cell displacement field utilizes the Preconditioned Conjugate Gradient (PCG) method with Diagonal Incomplete Cholesky (DIC) preconditioning, while pressure and density variables are solved using the Stabilized Preconditioned Bi-Conjugate Gradient (PBiCGStab) approach with DIC and Diagonal Incomplete LU (DILU) preconditioners, respectively.

Internal energy computations similarly adopt PBiCGStab with DILU preconditioning. For velocity fields, the smoothSolver with symmetric Gauss-Seidel (symGaussSeidel) smoothing provides stable solutions. This carefully selected solver configuration balances computational efficiency with numerical stability, particularly important for handling the coupled nature of the compressible flow equations in the engine simulation while maintaining solution accuracy throughout the dynamic mesh motion.

Variable	Solver	preconditioner
cellDisplacement	PCG	DIC
Pressure (p)	PBiCGStab	DIC
Density (rho)	PBiCGStab	DILU
Internal energy (u)	PBiCGStab	DILU
Velocity (U)	smoothSolver	symGaussSeidel

Table 4: Solver settings

5. Results and Discussions

5.1 Mesh motion

The computational modelling of the piston-cylinder assembly employed a cylindrical domain to accurately represent the physical geometry. Using OpenFOAM's blockMesh utility, the domain was discretized with a structured hexahedral mesh featuring uniform grading (simpleGrading (1 1 1)) across all sub-region5rs to ensure consistent mesh quality. To capture the piston's reciprocating motion, a dynamic meshing approach was implemented, incorporating topological changes and cell deformation algorithms.

Initial simulations began with the domain at top dead center (TDC), with the mesh progressively compressing toward bottom dead center (BDC). However, this configuration led to severe mesh distortion and numerical instabilities prior to reaching full compression. After careful analysis, the reference configuration was inverted - initiating the simulation at BDC and expanding outward. This revised approach significantly improved mesh preservation throughout the stroke, maintaining better cell quality metrics during deformation. The solution demonstrated robust convergence characteristics while accurately replicating the piston's kinematic motion, as verified against theoretical displacement curves. The successful implementation of this dynamic meshing strategy enabled precise tracking of fluid domain changes during the complete compression-expansion cycle.

The displacement of the piston in the cylinder can be derived as,

$$\boldsymbol{x(\theta) = r + l - (r\,cos(\theta) - \sqrt{l^2 - (r\,sin(\theta) + e)\text{^}2}}$$

Where $\boldsymbol{x(\theta)}$ is the displacement of the piston

$\boldsymbol{r}$ is the radius of the crank

$\boldsymbol{l}$ is the length of the connecting rod

$\boldsymbol{e}$ is the perpendicular distance from the cylinder axis to the crankshaft center

$\boldsymbol{\theta}$ is the angle of rotation of the crankshaft

Graphically the Displacement of the piston can be shown as below:

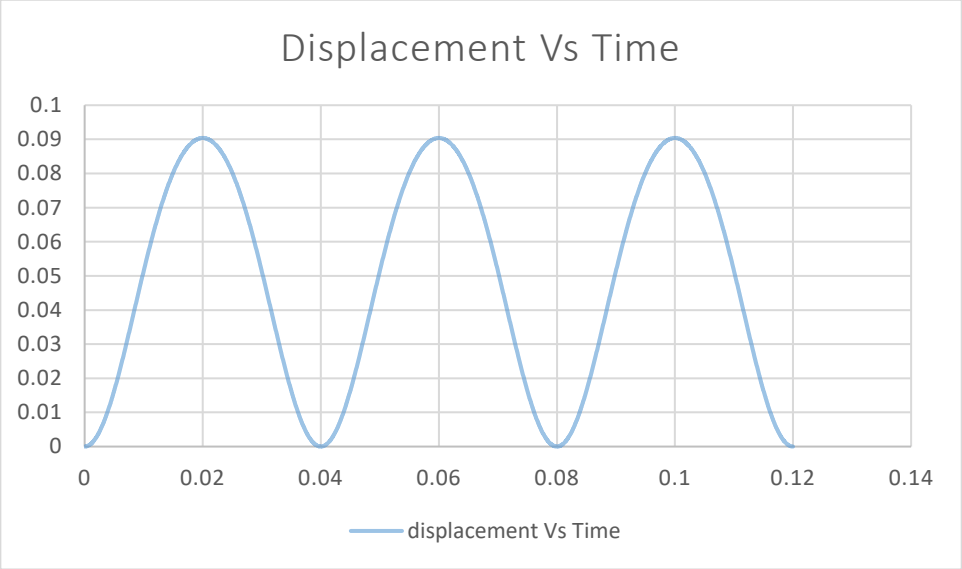

Chart 1: Piston Displacement vs. Time Profile

5.2 Isothermal Analysis

The simulation was conducted under isothermal conditions to analyze the pressure distribution within the domain during compression and expansion while maintaining a constant temperature. Air was selected as the working fluid, treated as an ideal gas and subjected to compression and expansion processes without any temperature variation.

Governing Equations

The pressure calculations were derived using the Ideal Gas Law:

$$PV = nRT$$

Where:

- **P** = Pressure inside the domain
- **V** = Instantaneous volume of the domain

- **n** = Number of moles of gas (constant in a closed system)
- **R** = Universal gas constant
- **T** = Temperature (held constant in isothermal conditions)

Since the process is isothermal (T = constant) and the system is closed (n = constant), the relationship simplifies to Boyle's Law:

$$P_1V_1 = P_2V_2$$

This equation was applied at each timestep to compute pressure variations.

Initial Conditions & Results

- Initial Pressure (P_1): 100 kPa
- Initial Temperature (T): 300 K (constant)
- Dead Volume (V_1): Reference volume at the start

Using the isothermal gas law, the pressure at the most expanded position (V_2) was determined to be 6.32 kPa, demonstrating the inverse relationship between pressure and volume under constant temperature conditions.

This analysis provides critical insights into the thermodynamic behaviour of gases in confined systems under isothermal compression and expansion.

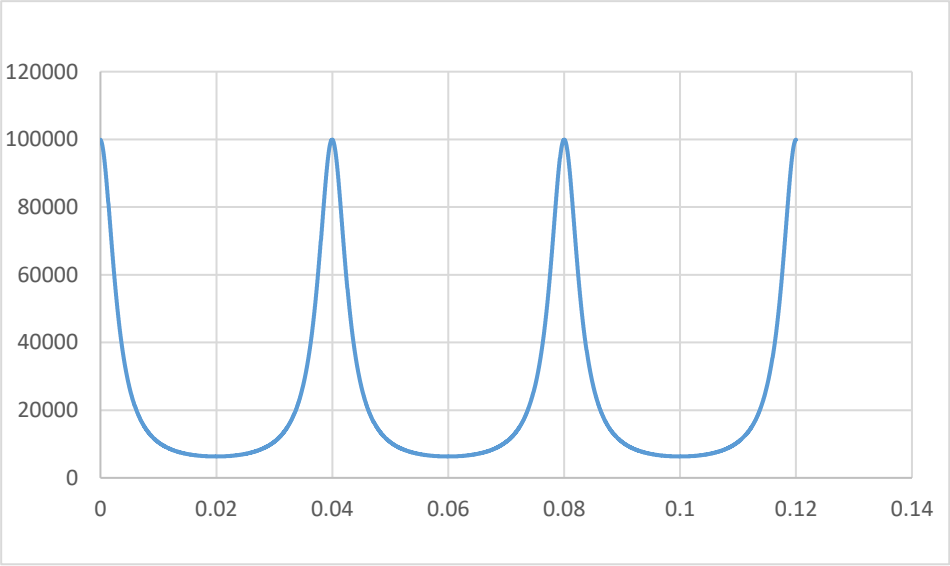

Chart 2: Pressure vs. Time plot

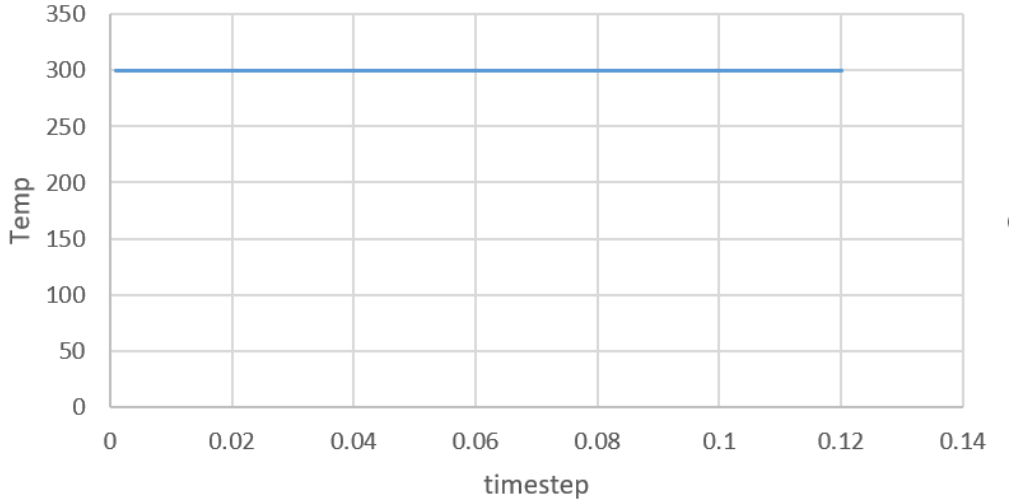

Chart 3: Temperature vs. Time plot

5.3 Adiabatic Analysis

The simulation was conducted under adiabatic conditions (no heat transfer) to analyze the pressure distribution within the domain during compression and expansion. Air was treated as an ideal gas, undergoing thermodynamic processes with zero heat exchange (Q = 0).

Governing Equations

For an adiabatic process, the pressure-volume relationship follows:

$$PV^{\gamma} = \text{constant}$$

Where **P** = Pressure inside the domain

V = Instantaneous volume

γ (gamma) = Heat capacity ratio (Cp/Cv)

- For air, γ=1.4

Initial Conditions:

- Initial Pressure (P_1): 100 kPa
- Initial Temperature (T_1): 300 K
- Dead Volume (V_1): 0.01 m³ (reference)
- Expanded Volume (V_2): 0.05 m³

The adiabatic expansion results show significant pressure and temperature drops (100 kPa → 2.45 kPa and 300 K → 100 K) as the gas performs work without heat transfer. This cooling effect occurs because the system's internal energy converts entirely into expansion work,

following PV^{γ} = constant. The pressure reduction reflects decreased molecular collisions as the gas expands, while the temperature drop confirms energy conservation in this isolated system.

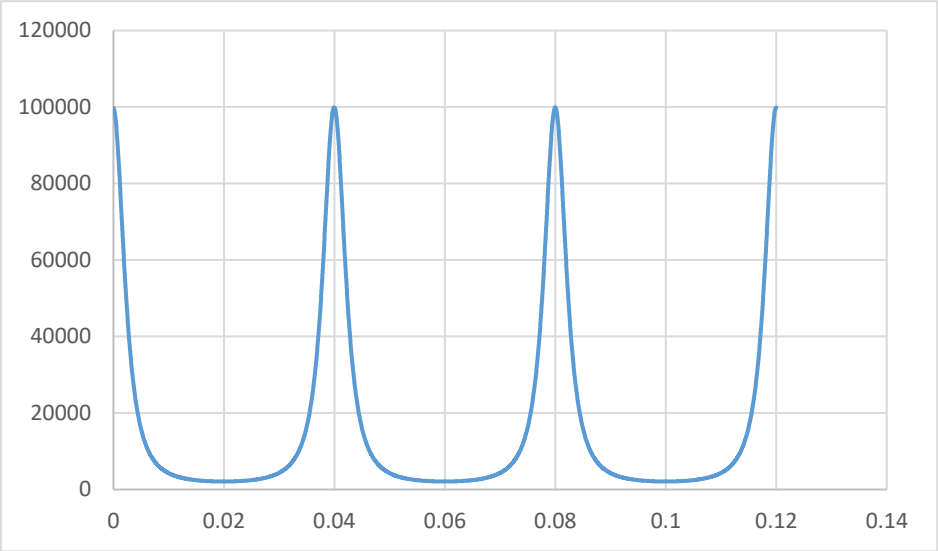

Chart 4: Pressure vs. Time plot

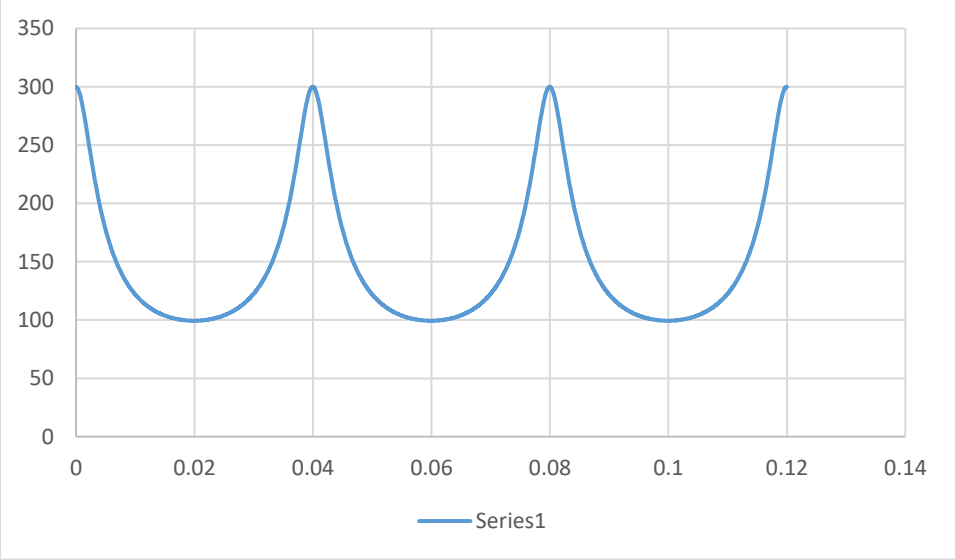

Chart 5: Temperature vs. Time plot

5.4 Mass transfer

Following validation of the compression and expansion processes within the closed system, the simulation was extended to incorporate mass flow dynamics, replicating the complete thermodynamic cycle of an internal combustion engine from intake to exhaust. To achieve this, valve mechanisms were implemented in the computational domain through the following methodology:

The existing geometry was modified using OpenFOAM's topoSet utility to designate specific cell zones corresponding to valve locations. This utility enabled precise selection of boundary

face cells to establish distinct inlet and outlet face zones. Subsequently, the createPatch utility was employed to generate two new geometric boundaries on the original domain: an intake valve for fresh charge induction and an exhaust valve for combustion products evacuation.

During the intake phase ($0 < t \leq T/4$), the inlet valve opens while the outlet remains closed, allowing controlled mass inflow based on the prescribed circular valve lift profile. This is followed by the compression and expansion phases ($T/4 < t \leq 3T/4$), where both valves remain closed, creating a closed thermodynamic system that enforces strict mass conservation. The cycle concludes with the exhaust phase ($3T/4 < t \leq T$), where the outlet valve opens to enable mass outflow while maintaining back pressure conditions, with the inlet valve securely closed.

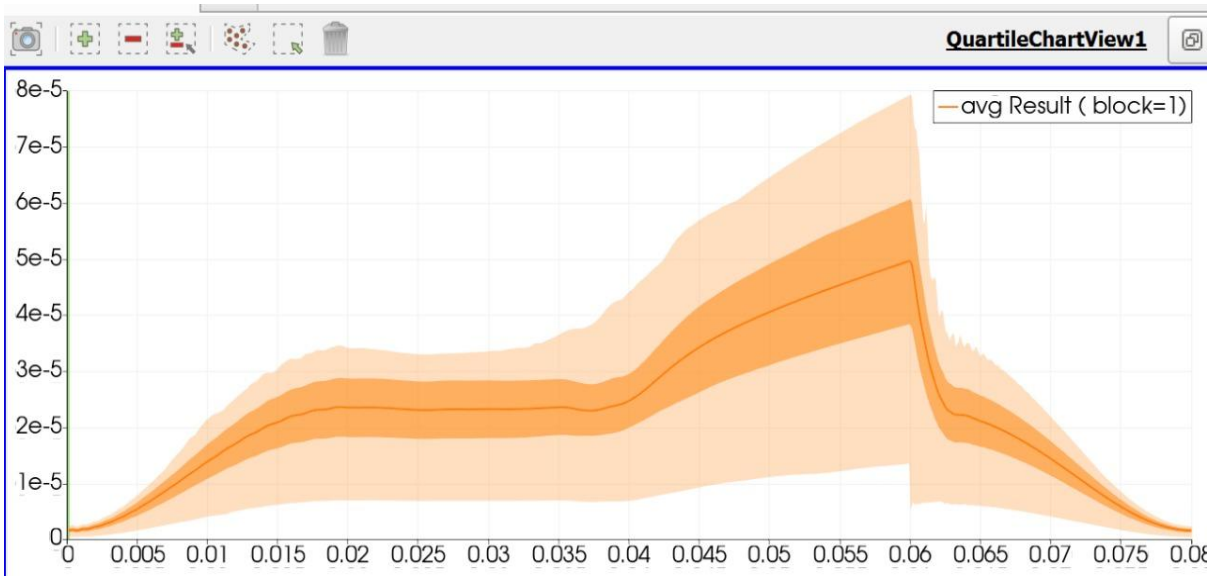

Chart 6: Average mass flow vs.time in the system

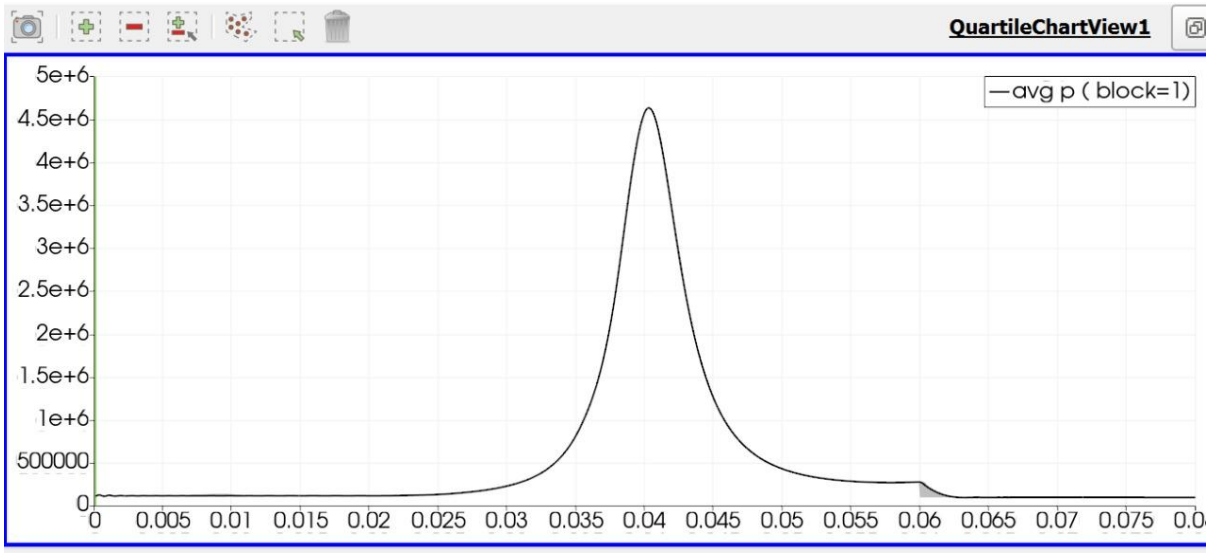

Chart 7: Average pressure vs. time inside the system

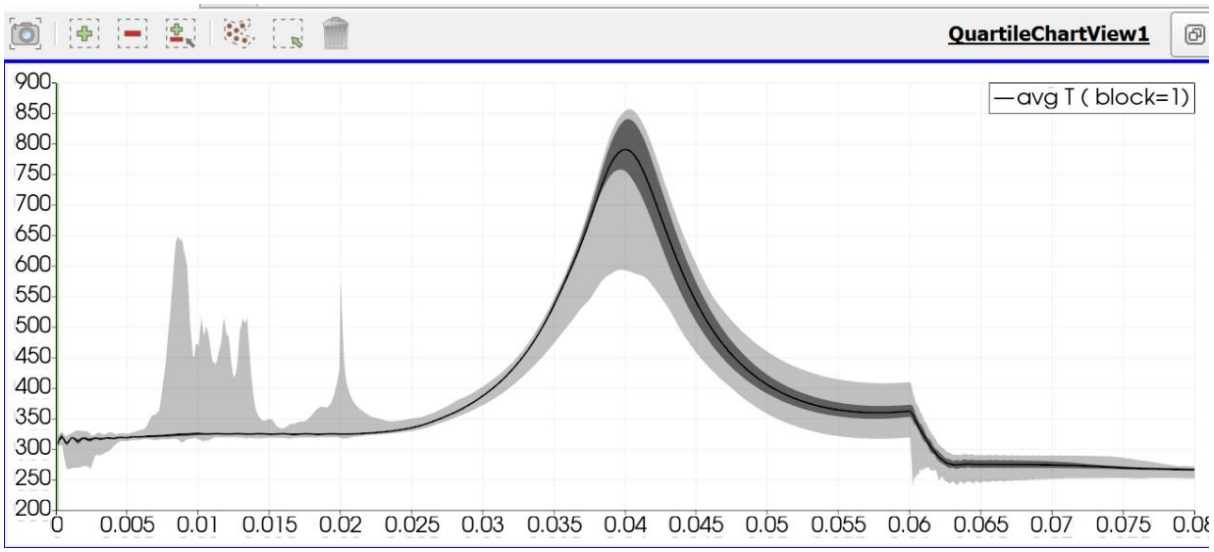

Chart 8: Average Temperature vs. Time inside the system

The numerical implementation carefully synchronizes these boundary conditions with the engine's crank angle progression, ensuring proper temporal alignment of valve events. The dynamic mesh capabilities handle the precise opening and closing of valves through topoSet and createPatch utilities, while transient boundary definitions in the 0/ directory govern the mass flow characteristics. Throughout the simulation, rigorous monitoring of mass flux integrals verifies conservation principles at each timestep. This cyclic process repeats identically for successive engine cycles (T, 2T, 3T, ...), maintaining periodicity in both boundary conditions and thermodynamic behaviour, thereby enabling the analysis of consistent engine operation across multiple complete cycles.

6. Conclusion:

This study has successfully demonstrated a comprehensive computational framework for analyzing the thermodynamic behaviour of a motored diesel engine using OpenFOAM. By implementing a laminar Stokes flow model with dynamic meshing capabilities, we accurately simulated the complete four-stroke cycle, including the critical compression and expansion phases without combustion. This study yielded valuable insights into both isothermal and adiabatic engine operation, with results showing excellent agreement with fundamental thermodynamic principles. The developed methodology effectively addressed the challenges of moving boundaries and transient valve operations through proper use of topoSet and createPatch utilities.

The findings highlight the importance of precise solver settings and convergence criteria in maintaining numerical stability while preserving physical accuracy. The successful simulation

of pressure and temperature variations under different thermodynamic conditions provides a solid foundation for future combustion studies. This work contributes significantly to engine simulation techniques by establishing reliable procedures for dynamic mesh handling and boundary condition implementation. The framework's robustness suggests promising applications in engine design optimization and performance prediction. Future extensions could incorporate combustion modeling, turbulence effects, and experimental validation to further enhance the simulation's predictive capabilities and practical utility in engine development.

Acknowledgement:

I am extremely grateful to the FOSSEE team for giving me the very unique opportunity to participate in a semester long internship. I am also deeply indebted to my guides **Prof. Dhiraj Garg and Mr. Pushkar sheth** for his unwavering support, guidance, and encouragement throughout the fellowship. Their expertise in the field of Computational Fluid Dynamics (CFD) and IC engine has been instrumental in shaping my understanding of this complex dynamic mesh domain and instilling my curiosity to do more. I would also like to extend my heartfelt thanks to my mentor, **Mr. Evan Fernandes**, for his mentorship, especially tips and profound insights into OpenFOAM.

References

chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.wolfdynamics.com/wiki/meshing_OF_blockmesh.pdf

chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.wolfdynamics.com/training/movingbodies/OF2021/dynamicmeshes_2021_OF8.pdf