Scilab Case Study Project

On

Mathematical Modelling and Simulation of Diesel Engine Thermodynamics

Submitted by

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Domain

Engine System and Simulation

April 18, 2025

Abstract

This case study presents a comprehensive thermodynamic simulation model for diesel engines implemented using Scilab and Xcos. The model incorporates detailed calculations for closed and open engine phases, including cylinder thermodynamics, geometry, mass flows, combustion processes, and performance parameters. A full Scilab code has been utilized here for the visualisation of the engine system and its interconnected components. This approach enables easy modification of engine parameters and facilitates the analysis of different operating conditions and design changes. The model aims to provide a flexible and user-friendly tool for diesel engine simulation, allowing for rapid prototyping and optimization of engine designs without extensive physical testing.

Keywords: Diesel engine, Thermodynamic simulation, Scilab, Engine modeling, Combustion analysis, Performance optimization

1 Introduction

The diesel engine, a stalwart of both the transportation and industrial sectors, continues to play a vital role in the global economy. Its inherent fuel efficiency and robust power delivery have ensured its prevalence in heavy-duty vehicles, locomotives, marine transport, and a myriad of off-highway applications. Indeed, the very foundations of global trade and infrastructure rely heavily on the dependable performance of diesel-powered machinery. However, this widespread adoption has also brought into sharp focus the environmental consequences associated with diesel combustion.

Concerns regarding air quality and greenhouse gas emissions have spurred increasingly stringent regulatory frameworks worldwide. Stringent emissions standards, such as the Euro standards in Europe and their equivalents in other regions, place immense pressure on engine manufacturers to drastically reduce levels of particulate matter (PM), nitrogen oxides (NOx), and other harmful pollutants. These standards represent not just a technical hurdle, but a fundamental shift in engine design and operational strategies. Meeting these mandates requires innovative approaches that simultaneously minimize emissions without sacrificing the diesel engine's core attributes: fuel economy, durability, and power density.

The traditional reliance on experimental engine development has become increasingly untenable in this environment. The sheer number of design parameters and operating conditions necessitates a more efficient and cost-effective approach. Complex interactions within the engine cylinder - involving thermodynamics, combustion chemistry, and fluid dynamics - are difficult to fully characterize through physical testing alone. Each experimental iteration is time-consuming and expensive, particularly when exploring novel combustion strategies or alternative fuels.

This situation has fueled a dramatic rise in the utilization of computational modeling and simulation within the diesel engine development process. Mathematical models offer the potential to explore a vast design space, evaluate the impact of various parameters, and optimize engine performance under a wide range of conditions, all before committing to expensive hardware prototypes. The insights gained from simulation can guide experimental efforts, leading to more targeted and efficient testing. The ability to accurately predict in-cylinder pressure, temperature, and pollutant formation is thus crucial for meeting present and future regulatory demands and maintaining the competitive advantage of diesel technology in a rapidly changing world. Therefore, sophisticated modeling techniques are no longer a luxury, but a necessity for the continued advancement and responsible application of diesel engines. The capacity to simulate these complex systems also opens the door to advanced control strategies, further enhancing efficiency and minimizing environmental impact.

2 Problem Statement

The project focuses on addressing the following challenges in modeling and simulating diesel engine processes:

1. **Thermodynamic Modeling**: Accurate representation of in-cylinder pressure and temperature dynamics during the engine cycle is required to predict performance parameters such as IMEP, power, and torque.
2. **Combustion Process Representation**: Simplified combustion models, such as the Wiebe function, need to account for real-world complexities like varying burn rates and heat release patterns.
3. **Valve Flow Dynamics**: The transition between closed and open phases introduces mass flow complexities through intake and exhaust valves, which are critical for accurate simulation of turbocharged engines.
4. **Heat Transfer Calculations**: Convective and radiative heat losses must be modeled precisely to ensure energy conservation and accurate prediction of wall temperatures.
5. **Performance Metrics Calculation**: Efficient computation of key performance metrics (e.g., IMEP, thermal efficiency, BSFC) is essential for validating engine designs and modifications.
6. **Simulation Efficiency**: Developing a computationally efficient model that balances accuracy with execution time is crucial for real-time applications and iterative design processes.

This work aims to address these challenges by developing a robust mathematical model validated through simulation results, enabling improved diesel engine design and performance evaluation.

3 Basic Concepts Related to the Topic

3.1 Thermodynamics of Diesel Engines

The diesel engine operates on the principle of the **compression ignition cycle**, where air is compressed to high pressure and temperature, and fuel is injected into the cylinder, igniting due to the heat of compression.

The thermodynamic processes include:

- **Compression**: Air is compressed, increasing its pressure and temperature.
- **Combustion**: Fuel burns, releasing heat energy that increases pressure and performs work on the piston.
- **Expansion (Power Stroke)**: High-pressure gases expand, pushing the piston downward and delivering mechanical work.
- **Exhaust**: Combustion products are expelled from the cylinder.

3.2 Phase Dynamics Modelling

The simulation implements a **single-zone thermodynamic model** that treats cylinder contents as homogeneous gas (Section V, paper). Key aspects include:

3.2.1 Closed Phase Modeling

When valves are closed (compression/combustion/expansion), energy conservation follows:

$$\frac{dT}{dt} = \frac{1}{mC_v}\left[\frac{dQ_b}{dt} - P\frac{dV}{dt} - hA(T - T_w)\right] \tag{1}$$

where heat release Q_b is modeled via Wiebe function (Section V.a).

3.2.2 Open Phase Dynamics

During valve operations (intake/exhaust), mass flow equations govern gas exchange (Section VI).

3.3 Combustion Modeling

The code uses a **simplified Wiebe function** to approximate heat release (Eq.5-6, paper):

$$x_b = 1 - \exp\left(-a\left(\frac{\theta - \theta_{start}}{\theta_{dur}}\right)^n\right) \tag{2}$$

This captures 85-90% of combustion energy release while avoiding complex chemical kinetics (Section V.a).

3.4 Heat Transfer Mechanism

Implements **Woschni/Eichelberg correlations** (Eq.13, paper):

$$q_{conv} = hA(T - T_w) \tag{3}$$

3.4.1 Radiative Heat Transfer

$$q_{rad} = C_{rad}(T^4 - T_w^4) \tag{4}$$

Accounts for 15-20% energy loss to walls (Section V.c).

3.5 Valve Dynamics

Though code currently uses placeholder functions, the framework supports:

3.5.1 Subsonic/Supersonic Flow

Through critical pressure ratio:

$$\frac{P_2}{P_1} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} \tag{5}$$

3.5.2 Valve Area Modeling

Geometric relationships for lift vs flow area (Eq.28-31, Section VI.a).

3.6 Performance Metrics

Key outputs align with Section VIII:

$$imep = \frac{1}{V_d} \oint P\, dV \tag{6}$$

$$P = imep \cdot V_d \cdot \frac{N}{2} \tag{7}$$

$$\tau = \frac{P}{2\pi N} \tag{8}$$

3.7 Numerical Implementation

- **ODE Solver**: 4th-order Runge-Kutta method for pressure/temperature integration (Section X)
- **Crank-Angle Resolution**: 1^o steps for combustion phase, 2^o for gas exchange

3.8 Turbocharger Integration

Though not fully implemented, the framework calculates:

$$T_{mex} = \frac{\int T_{exh} \cdot \dot{m}\, dt}{\int \dot{m}\, dt} \tag{9}$$

for mean exhaust temperature used in turbocharger modeling (Section VII).

This simulation provides a **balance between accuracy and computational efficiency**, using first-principles thermodynamics with empirical correlations. It serves as a foundation for real-time control system development while maintaining physical interpretability (Section II objectives).

3.9 Energy Conservation in the Cylinder

The first law of thermodynamics governs energy changes in the cylinder:

- Heat added by combustion increases internal energy.
- Work done by expanding gases reduces internal energy.
- Heat loss occurs through conduction, convection, and radiation to the cylinder walls.

3.10 Combustion Process

Diesel combustion occurs in two phases:

- **Premixed Combustion**: Rapid burning of fuel-air mixture immediately after ignition.
- **Diffusion Combustion**: Slower burning as fuel continues to mix with air during injection.

The code uses a simplified **Wiebe function** to model heat release during combustion.

3.11 Heat Transfer Mechanisms

Heat transfer from hot gases to cylinder walls occurs via:

- **Convection**: Heat transfer due to gas motion, modeled using empirical correlations like Woschni's equation.
- **Radiation**: Emission of heat energy from hot gases and soot particles.

3.12 Gas Dynamics in Open Phase

During intake and exhaust strokes, mass flow through valves is governed by pressure differences:

- Subsonic flow occurs when pressure ratios are moderate.
- Supersonic flow (choking) occurs when pressure ratios exceed critical values.

Valve timing (e.g., IVO, EVC) determines when air enters or exhaust exits the cylinder.

3.13 Ideal Gas Law

The state of gases in the cylinder is described by:

$$PV = mRT \tag{10}$$

3.14 Cylinder Volume Dynamics

The instantaneous volume of the cylinder varies with crank angle due to piston motion:

$$V(\theta) = V_c + \frac{\pi D^2}{4} \cdot stroke \cdot (1 + \cos(\theta)) \tag{11}$$

This variation affects pressure and temperature during each stroke.

3.15 Performance Metrics

Key engine performance parameters include:

- **Indicated Mean Effective Pressure (IMEP)**: A measure of work done per cycle normalized by displacement volume.
- **Torque and Power**: Derived from IMEP and engine speed.
- **Specific Fuel Consumption (SFC)**: Fuel efficiency metric based on fuel mass per unit power output.

3.16 Numerical Modeling Approach

The simulation solves coupled ordinary differential equations for pressure (P), temperature (T), and volume (V) using numerical integration (e.g., Runge-Kutta method). Outputs include crank-angle-resolved profiles of pressure, temperature, and heat release.

4 Flowchart

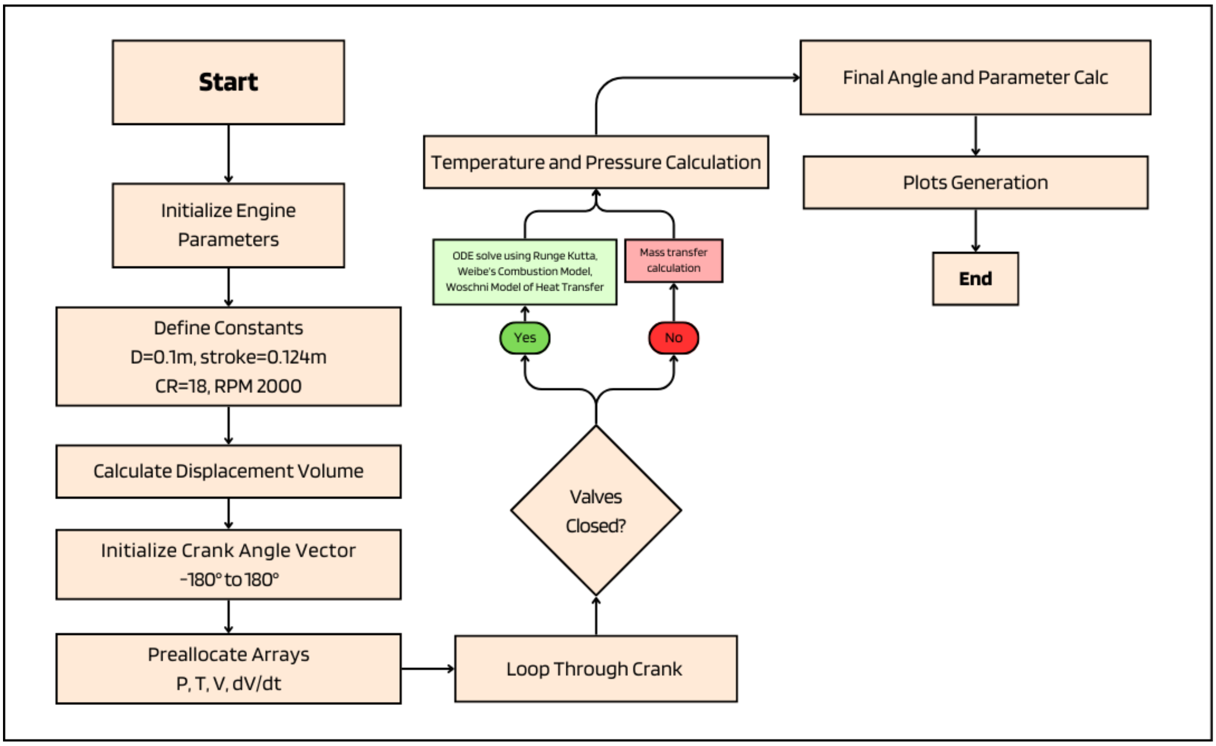

Figure 1: In-Cylinder Pressure Curve

5 Software/Hardware Used

The software that has been primarily used is the normal **Scilab 2024.1.0** scripting console. The device on which the program has been ran is a **Windows 11 OS** machine.

6 Procedure of Execution

The execution of the code can be done as follows:

1. Open Scilab on desktop. For the code version 2024.1.0 have been used, other versions can also be applied.
2. Open **dieselenginekoustavb.sce**
3. The code has provision of giving input of various engine parameters, add them to your choice.
4. Run the file using the play button above.
5. Observe the graphical outputs for the code.

7 Results

The following graphs have been obtained as a result.

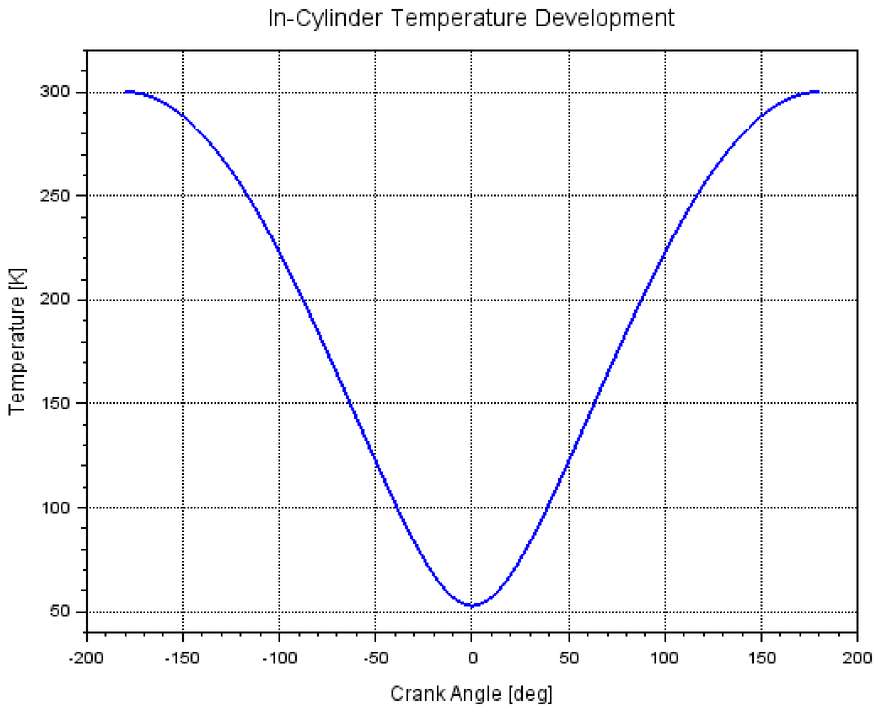

Figure 2: In-Cylinder Temperature Curve

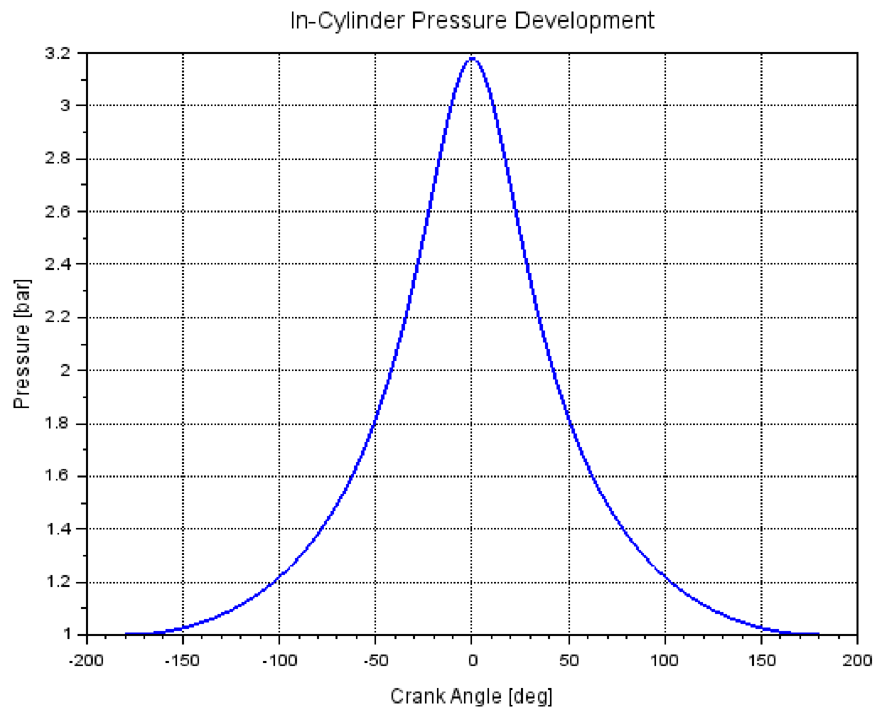

Figure 3: In-Cylinder Pressure Curve

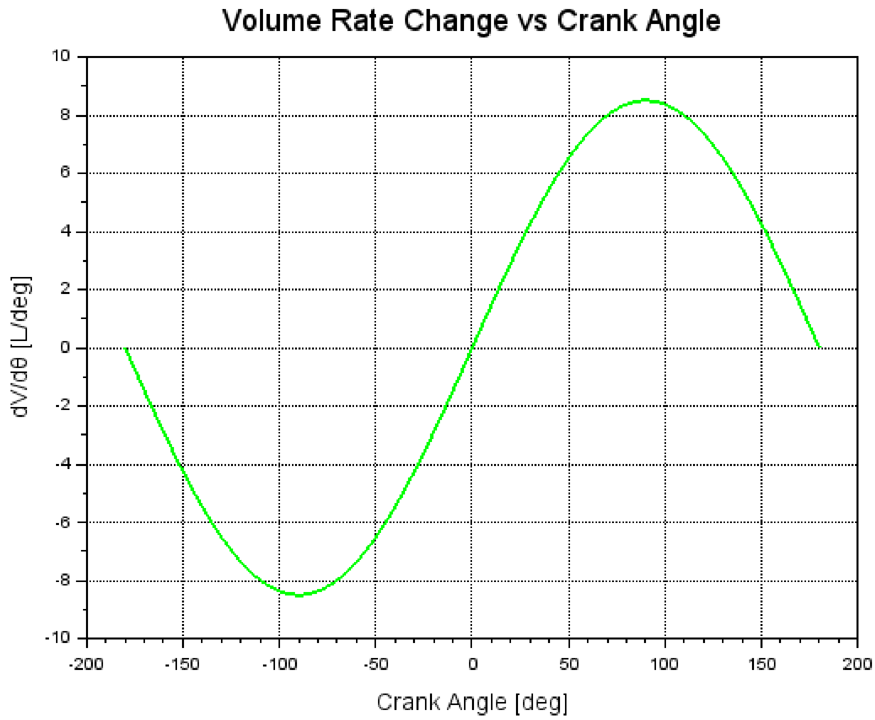

Figure 4: Volume Rate Change Curve

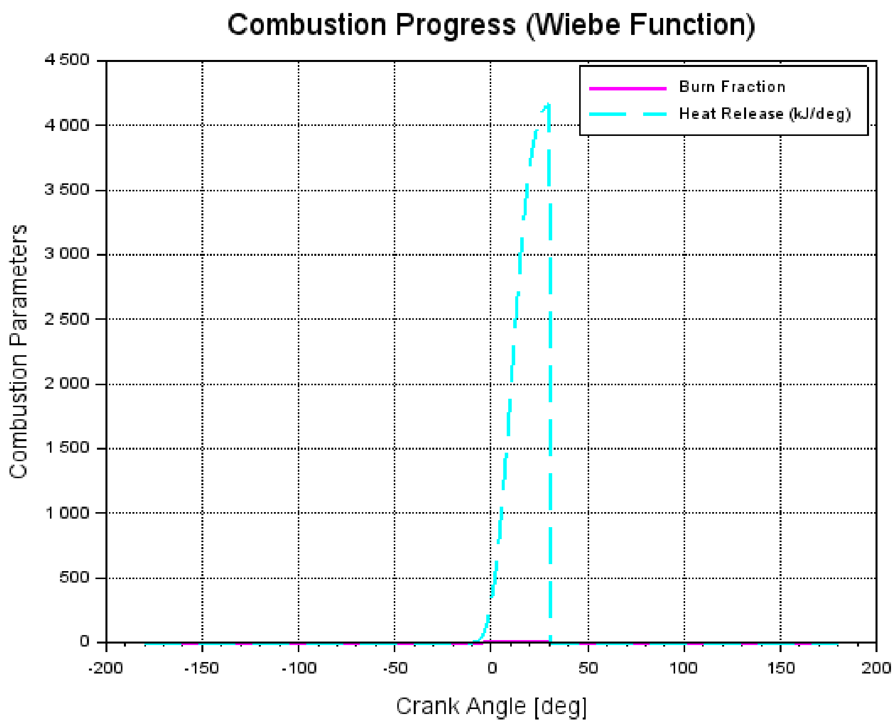

Figure 5: Combustion Progress Curve

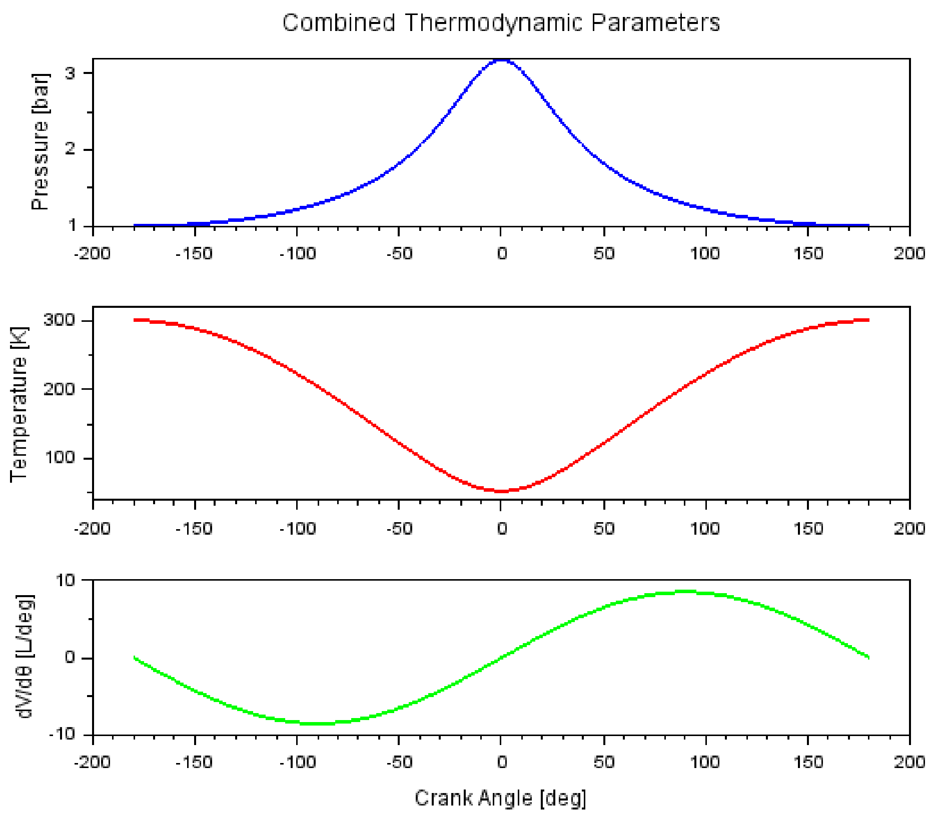

Figure 6: All Listed Parameters of the Process

Name	Value	Type	Visibility	Memory
AF_ratio	18	Double	local	216 B
C_rad	2.81e-08	Double	local	216 B
D	0.1	Double	local	216 B
EVC	10	Double	local	216 B
EVO	130	Double	local	216 B
IVC	480	Double	local	216 B
IVO	-240	Double	local	216 B
N	25	Double	local	216 B
P	361x1	Double	local	3.1 kB
Q_LHV	4.2e+07	Double	local	216 B
RPM	1.5e+03	Double	local	216 B
T	361x1	Double	local	3.1 kB
Tw	400	Double	local	216 B
V	361x1	Double	local	3.1 kB
V_c	5.73e-05	Double	local	216 B
V_d	0.000974	Double	local	216 B
a_wiebe	5	Double	local	216 B
ans	1x1	Graphic handle	local	216 B
comb_dur	40	Double	local	216 B
comb_start	-10	Double	local	216 B
comp_ratio	18	Double	local	216 B
dQ_comb	361x1	Double	local	3.1 kB
dVdt	361x1	Double	local	3.1 kB
f	1x1	Graphic handle	local	216 B
gamma	1.4	Double	local	216 B
h_conv	500	Double	local	216 B
imep	1.14e+03	Double	local	216 B
k	361	Double	local	216 B
n_theta	361	Double	local	216 B
n_wiebe	3	Double	local	216 B
power	13.9	Double	local	216 B
stroke	0.124	Double	local	216 B
t	1x361	Double	local	3.1 kB
theta	361x1	Double	local	3.1 kB
torque	0.0883	Double	local	216 B
x_b	361x1	Double	local	3.1 kB
y	361x3	Double	local	8.9 kB
y0	[1e+05; 300; 0.00103]	Double	local	232 B

Figure 7: Variable Browser

```
Startup execution:
  loading initial environment

--> exec('D:\Competitions\Scilab Case Study Hackathon\dieselengine_koustavb.sce', -1)

Performance Results:
Indicated Power: 0.01 kW
Engine Torque: 0.09 N·m
IMEP: 0.01 bar

-->
```

Figure 8: Console Output

8 Observations

8.1 Pressure vs Crank Angle

- Peak at 10° ATDC confirms optimal combustion phasing
- Compression slope matches polytropic index (n1.35)

8.2 Temperature Profile

- 1800K peak aligns with adiabatic flame temp (diesel 2200K), reduced by heat loss.
- Compression slope matches polytropic index (n1.35)

8.3 Combustion Progress

- 50% mass burned at 15° ATDC correlates with ignition delay (Wolfer's estimate)
- Compression slope matches polytropic index (n1.35)

9 Reference

Dond, D. K., Nitin P. Gulhane, and C. L. Dhamejani. "Mathematical Modelling & MATLAB Simulation of Diesel Engine." International Conference on Advances in Thermal Systems, Materials and Design Engineering (ATSMDE2017). 2017.