# Thermodynamics and Heat Transfer Project
# Performance of a Single-Cylinder Compression Ignition Engine

**Group C Members**

**Nguyen Xuan Binh (887799)**

**William Bergman (790462)**

**Jaime Montero de la Plaza (100066384)**

**Lucas Foley (910527)**

**Niklas Sterpi (790365)**



## I. Description & Project Plan

In this project, we will operate a practical CI engine while testing various parameter conditions. We will analyze the engine performance based on different engine properties. We will also do some post-processing and plot our results

- We will analyze the data we get from the engine and Dewesoft using Matlab.
- Most heat engines, such as reciprocating piston engines and rotating turbines, use cyclical processes. The second thermodynamics law states that such engines cannot have perfect conversion of heat transfer into work done => We vary the parameters to see how well the CI engine performs.

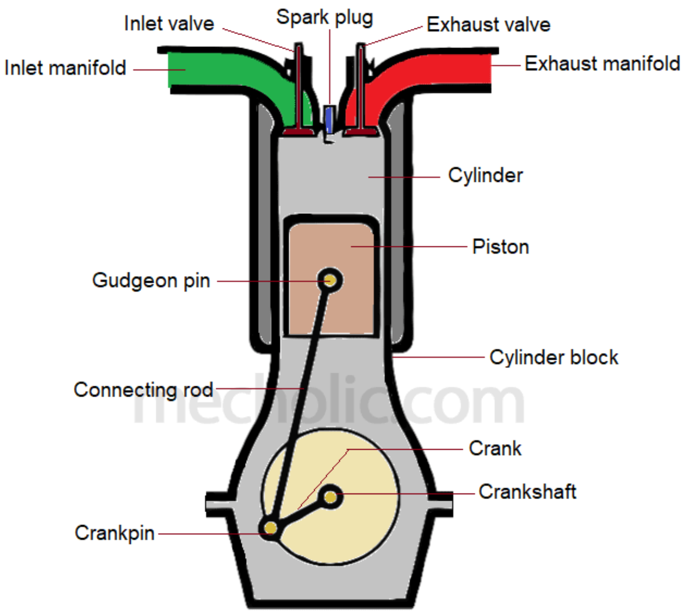
Member contributions:

- Nguyen Xuan Binh: Writing the report, preparing the presentation PPT, presenting tasks 3 and 4 in the presentation and running Matlab codes.
- William Bergman: Gathering data at the lab. Writing base report. Helping in general.
- Jaime Montero de la Plaza: Gathering data at the lab, presenting task 2, attending and scheduling meetings, and working and discussing the presentation.
- Lucas Foley: Gathering data from the engine lab, attending and scheduling meetings, working on powerpoint presentation and discussing the logistics of our project, presenting part of our powerpoint presentation.

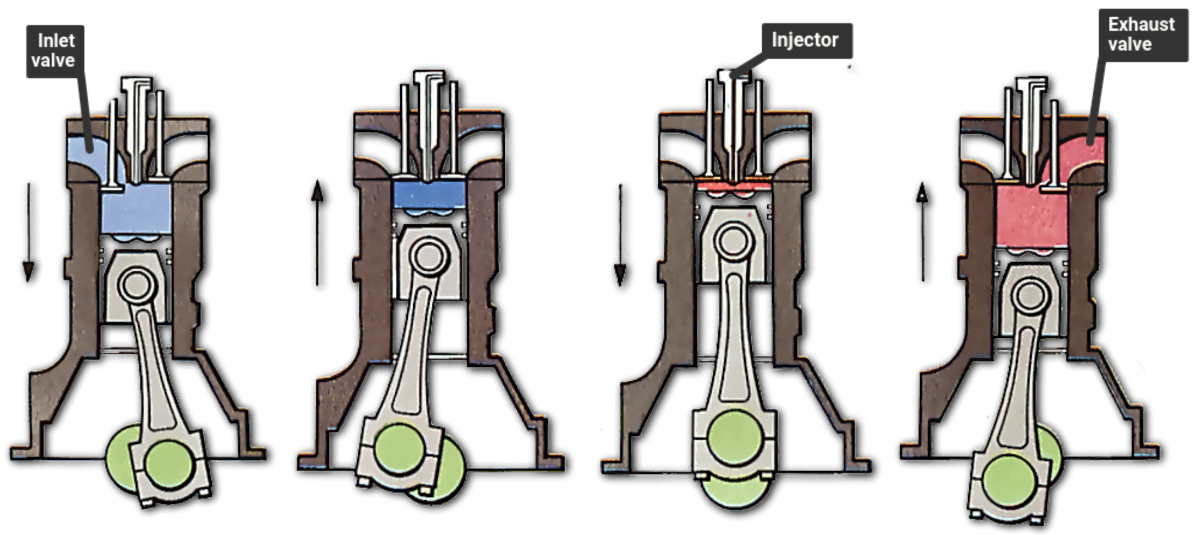
- Niklas Sterpi: Scheduling meetings, contacting advisors and in general making sure that the project runs smoothly. Presenting a part for our powerpoint presentation. Gathering data at the lab.

## II. CI Engine - How it works

The main components of the CI engine are illustrated in the picture below:




How a Single Cylinder Compression Ignition Engine works:




| Stroke 1: Induction | Stroke 2: Compression | Stroke 3: Combustion | Stroke 4: Exhaust |
|---|---|---|---|
| As the piston begins to move down the bore, the inlet valve opens and air is sucked in | The inlet valve closes at the bottom of the stroke. The piston then rises up to compress the sucked-in air | Fuel is injected in at the top of the stroke. It ignites and forces the piston down, generating power | On the piston's upward travel, the exhaust valve opens and the burned gas is expelled out. |

The specifications of the CI engine that we experiments on are:

| | |
|---|---|
| **Cylinder bore (mm)** | **111** |
| **Stroke (mm)** | 145 |
| **Total Displacement- 6-cylinder (L)** | 8.42 |
| **Displacement 1-cylinder (L)** | 1.4 |
| **Compression ratio** | 16.5:1 |
| **Diesel pilot injection** | Bosch CRIN3-20 Common rail, direct |
| **Methane injection** | Port injection with 2 Hana injectors |
| **Engine control** | Custom made in LabVIEW environment, uses NI DRIVVEN and other NI modules |

# III. What we have measured

- Injection pressure: It is the pressure of the fuel being injected into the engine during the ignition stroke. Compression ratio (CR) and fuel injection pressure (FIP) strongly affect the performance characteristics of the CI engine.

- Injection timing: It is the moment when diesel fuel enters the cylinder during the combustion phase. When we adjust the timing, we can alter when the engine injects the fuel, therefore changing when combustion occurs. In the project, it is called start of injection (SOI). It is the time at which injection of fuel into the combustion chamber begins. It is expressed in crank angle degrees (CAD) before TDC (top dead center) of the compression stroke.

- Injection duration: The period of time at which the diesel fuel injected into the combustion chamber from the injector is known as injection duration, is the time taken between start of injection and end of injection and is associated with the fuel mass. The injection duration is measured in milliseconds.

- Fuel properties

| Fuels | Diesel(EN590) | Methane | Hydrogen | Ethane | n-dodecane | HVO | RME | n-heptane |
|---|---|---|---|---|---|---|---|---|
| Chemical Formula | CnH1,8n | CH4 | H2 | C2H6 | C12H26 | CnH2n+2 | C21H38O2 | C7H16 |
| Density(kg/m3) | 835 | 0.725 | 0.09 | 1.212 | 752.1 | 780 | 880 | 680 |
| Lower Heating Value (LHVf)(MJ/kg | 42.7 | 50 | 120 | 47.8 | 44.17 | 44 | 36,7–40,5 | 44.6 |
| Cetane Number | 53 | 0 | | | 87 | 80-99 | 54.4 | 56 |
| Stoichiometric fuel-air ratio (F/A)s | 0.069 | 0.058 | 0.029 | 0.0621 | 0.10227 | 0.06711 | 0.0793 | 0.06589 |
| Stoichiometric air-fuel ratio (A/F)s | 14.49275362 | 17.24137931 | 34.48275862 | 16.1031 | 9.778038525 | 14.9009 | 12.6103 | 15.1768 |
| Autoignition Temperature/ oC | 250 | 650 | 585 | 472 | 410 | 204 | 240 | 223 |
| Molecular Weight (g/mol) | | 16.043 | 2.016 | 30.07 | 170.34 | | 306.534 | 100.205 |

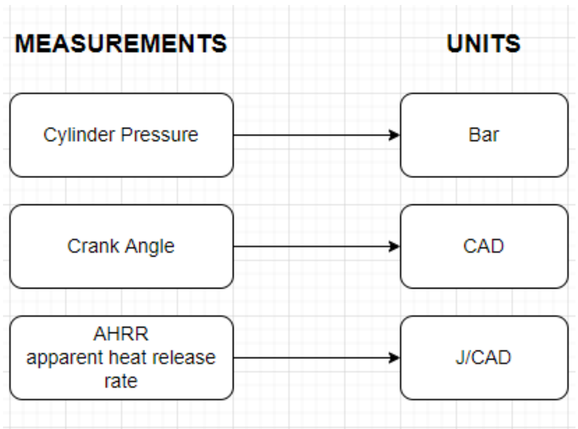
- Fuel mass: how much fuel is injected into the engine during the combustion stroke

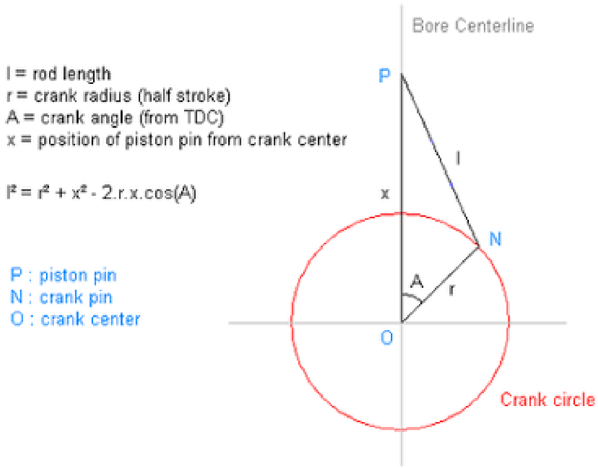
- Fuel Heating Value: heating value is the amount of heat obtained when fuel or some other substance of a specific unit quantity is combusted. The lower heating value (net) is the difference between combustion and latent heat of vaporization of the water vapors formed from combustion.

- Pilot ratio: It is the ratio between diesel fuel and pilot fuel according to the formula, where LHV is the lower heat value of the fuel. Pilot fuel helps achieve stable ignition of natural gas mixed with air.

$$P_R = \frac{\dot{m}_{PF} \times LHV_{PF}}{\dot{m}_{PF} \times LHV_{PF} + \dot{m}_{CH4} \times LHV_{CH4}}$$

1. Unit Block Diagram and crank angle degree (CAD)




2. Assumptions

- Stable operating conditions for CI engine
- Correctly calibrated sensors that give accurate data
- Right type of fuel
- The environment parameters are fixed. Air temperature is 25°C, mass air flow is 80kg/h and the engine operates at 1200 RPM

3. Boundary Conditions

- No other parameters will be changed then the desired ones
- CI engine has to be operated at safe conditions, which means no potentially dangerous parameter changes that could cause harm to the operators or the engine

# IV. CI Engine performance based on measurements

We are going to see how well the CI engine performs based on several factors. They are:
- Heat release rate (J/CA): the rate of heat generation by the combustion per crank angle

$$\mathrm{HRR} = \frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta}$$

- Cumulative Heat Release: It is the integral of the HRR with respect to the crank angle

$$\mathrm{AccQ} = \int \frac{dQ}{d\theta} d\theta$$

- dP/dθ: rate of change of pressure with respect to crank angles. It is in the formula of HRR
- Indicated efficiency: $E_{\text{indicative work}}$ is calculated using the formula:

$$E_{inidcated\quad work} = \frac{gIMEP \times V_{displacement}}{TFE} \times 100$$

where gIMEP is gross indicated mean effective pressures, $V_{\text{displacement}}$ is the volume of displacement and TFE is total effective energy.

There are 5 tasks of varying parameters in which we will measure the engine performance:

Task 1: (Single-injection) Difference in Injection Pressure

Task 2: (Single-injection) Difference in Start of Injection 1 measured in Crank angles before top-dead center

Task 3: (Dual-injection) Difference in SOI 1 measured in CAD bTDC for the first fuel. Same injection pressure, fuel mass for both fuels

Task 4: (Dual-injection) Difference in the fuel mass and the injection duration for two fuels

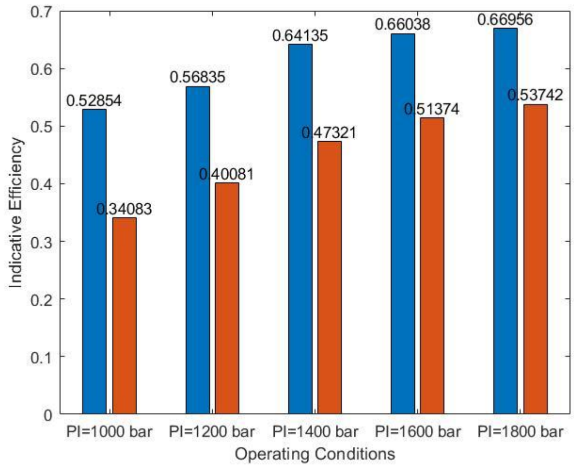
Task 5: (Single-injection) Difference in the fuel mass and the injection duration

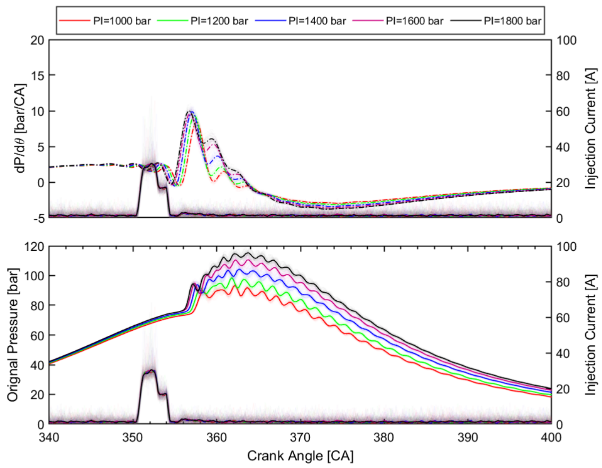
The tasks can be summarized in this table below

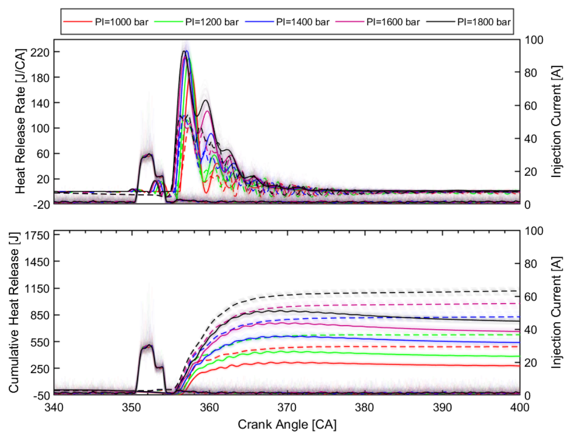
| | CAD: Crank Angle Degree | | | SOI: start of injection | | | bTDC: before top-dead center | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Task | Test Point | $T_{air}$ °C | $m_{air}$ (kg/h) | RPM | SOI1, CAD bTDC | Dur1, ms | SOI2, CAD bTDC | Dur2, ms | Injection Pressure | Injection 1 Fuel Mass, mg | Injection 2 Fuel Mass, mg | Energy1 | Energy 2 | Total Energy ,J |
| | 1 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1000 | 21.89 | 0 | 934.7 | 0 | 934.7 |
| | 2 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 3 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1400 | 30.26 | 0 | 1292.1 | 0 | 1292.1 |
| | 4 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1600 | 34.7 | 0 | 1481.7 | 0 | 1481.7 |
| Task1 | 5 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1800 | 39.13 | 0 | 1670.9 | 0 | 1670.9 |
| | 6 | 25 | 80 | 1200 | 0 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 7 | 25 | 80 | 1200 | 2 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 8 | 25 | 80 | 1200 | 4 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 9 | 25 | 80 | 1200 | 6 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| Task2 | 10 | 25 | 80 | 1200 | 8 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 11 | 25 | 80 | 1200 | 0 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 12 | 25 | 80 | 1200 | 2 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 13 | 25 | 80 | 1200 | 4 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 14 | 25 | 80 | 1200 | 6 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| Task3 | 15 | 25 | 80 | 1200 | 8 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 16 | 25 | 80 | 1200 | 3 | 0.32 | 40 | 0.4 | 1200 | 15.7 | 20.63 | 670.39 | 880.901 | 1551.3 |
| | 17 | 25 | 80 | 1200 | 3 | 0.34 | 40 | 0.38 | 1200 | 17.24 | 19.82 | 736.15 | 846.314 | 1582.5 |
| | 18 | 25 | 80 | 1200 | 3 | 0.36 | 40 | 0.36 | 1200 | 18.45 | 18.45 | 787.82 | 787.815 | 1575.6 |
| | 19 | 25 | 80 | 1200 | 3 | 0.38 | 40 | 0.34 | 1200 | 19.82 | 17.24 | 846.31 | 736.148 | 1582.5 |
| Task4 | 20 | 25 | 80 | 1200 | 3 | 0.4 | 40 | 0.32 | 1200 | 20.63 | 15.7 | 880.9 | 670.39 | 1551.3 |
| | 21 | 25 | 80 | 1200 | 5 | 0.3 | NaN | NaN | 1200 | 7.96 | 0 | 339.89 | 0 | 339.89 |
| | 22 | 25 | 80 | 1200 | 5 | 0.4 | NaN | NaN | 1200 | 20.63 | 0 | 880.9 | 0 | 880.9 |
| | 23 | 25 | 80 | 1200 | 5 | 0.5 | NaN | NaN | 1200 | 31.81 | 0 | 1358.3 | 0 | 1358.3 |
| | 24 | 25 | 80 | 1200 | 5 | 0.6 | NaN | NaN | 1200 | 48.95 | 0 | 2090.2 | 0 | 2090.2 |
| Task5 | 25 | 25 | 80 | 1200 | 5 | 0.7 | NaN | NaN | 1200 | 66.36 | 0 | 2833.6 | 0 | 2833.6 |

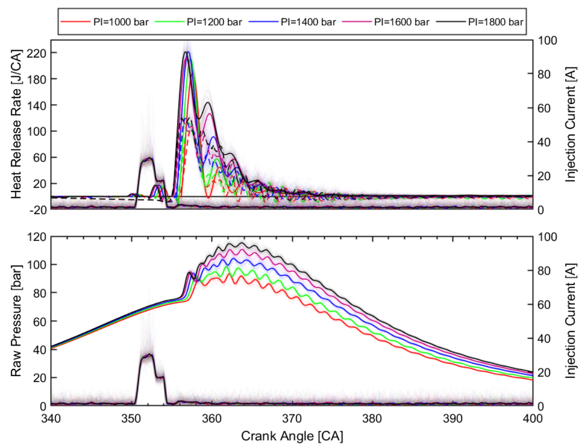
## 1. Task 1: (Single-injection) Difference in Injection Pressure

| Task | Test Point | $T_{air}$ °C | $m_{air}$ (kg/h) | RPM | SOI1, CAD bTDC | Dur1, ms | SOI2, CAD bTDC | Dur2, ms | Injection Pressure | Injection 1 Fuel Mass, mg | Injection 2 Fuel Mass, mg | Energy1 | Energy 2 | Total Energy ,J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1000 | 21.89 | 0 | 934.7 | 0 | 934.7 |
| | 2 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 3 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1400 | 30.26 | 0 | 1292.1 | 0 | 1292.1 |
| | 4 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1600 | 34.7 | 0 | 1481.7 | 0 | 1481.7 |
| Task1 | 5 | 25 | 80 | 1200 | 7 | 0.5 | NaN | NaN | 1800 | 39.13 | 0 | 1670.9 | 0 | 1670.9 |



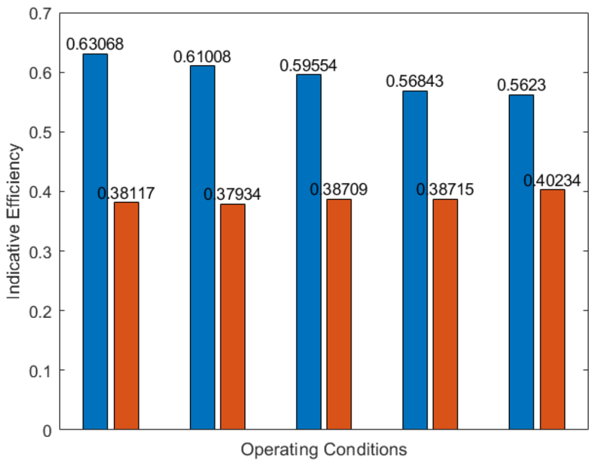

In the first task, we have varying injection pressure.

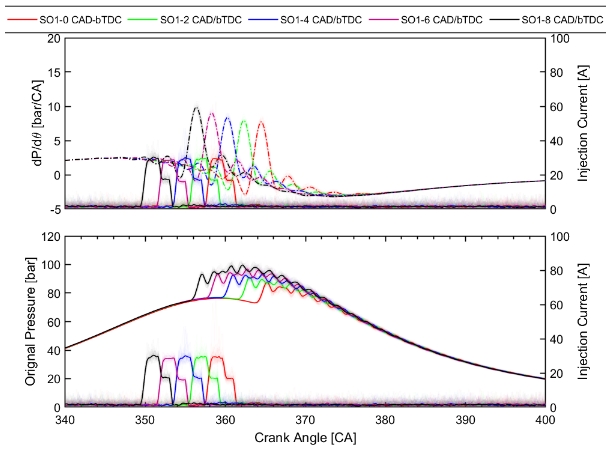
- Indicative Efficiency: As we can see, the more pressure the fuel is injected, the more efficient the CI engine performs
- Raw pressure: The pressure from 1000 to 1800 bar are plotted during the start of combustion stroke
- Pressure change w.r.t CAD: The start of injection occurs at the same time for five tests, resulting a spike in the graph
- Heat Release Rate: The higher the injection pressure, the more heat is released
- Cumulative Heat Release: Less heat is accumulated for lower injection pressure

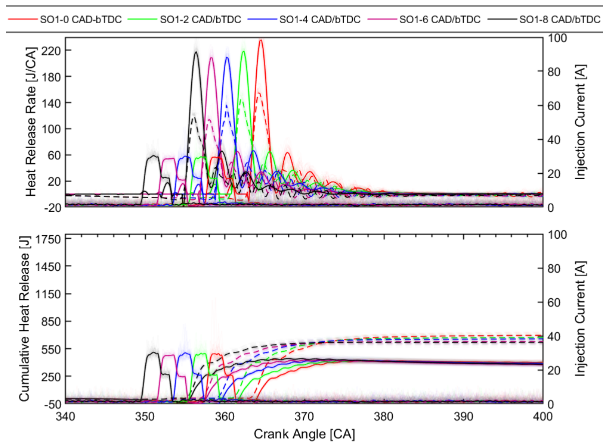
## 2. Task 2: (Single-injection) Difference in Start of Injection 1 measured in Crank angles before top-dead center

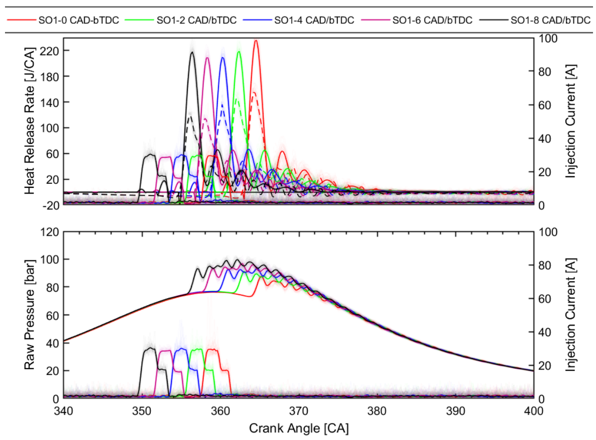
In the second task, SOI of the fuel varies

| Task | Test Point | $T_{air}$ °C | $m_{air}$ (kg/h) | RPM | SOI1, CAD bTDC | Dur1, ms | SOI2, CAD bTDC | Dur2, ms | Injection Pressure | Injection 1 Fuel Mass, mg | Injection 2 Fuel Mass, mg | Energy1 | Energy 2 | Total Energy ,J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6 | 25 | 80 | 1200 | 0 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 7 | 25 | 80 | 1200 | 2 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 8 | 25 | 80 | 1200 | 4 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| | 9 | 25 | 80 | 1200 | 6 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |
| Task2 | 10 | 25 | 80 | 1200 | 8 | 0.5 | NaN | NaN | 1200 | 25.83 | 0 | 1102.9 | 0 | 1102.9 |



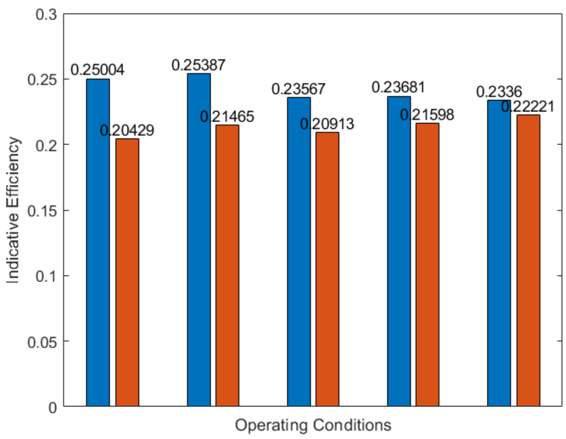



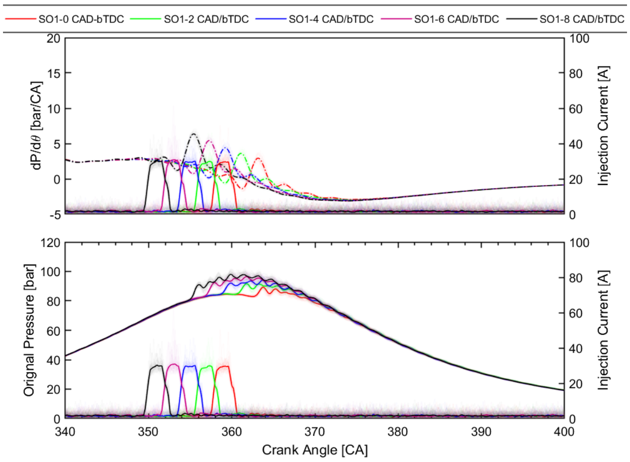

- Indicative Efficiency: from the bar chart, we can tell that the closer the pistol to the top-dead center (fewer CAD bTDC) when fuel is injected, the more efficient the CI engine performs
- Raw pressure: The raw pressure doesn't change between the test cases, they are only shifted by 2 crank angle degree due to different SOI.
- Pressure change w.r.t CAD: The pressure changes are shifted by 2 CAD due to different SOI of the test cases.
- Heat Release Rate: the engine slightly releases heat more with lower CAD bTDC
- Cumulative Heat Release: Accumulated heat is nearly similar for the 5 test cases.

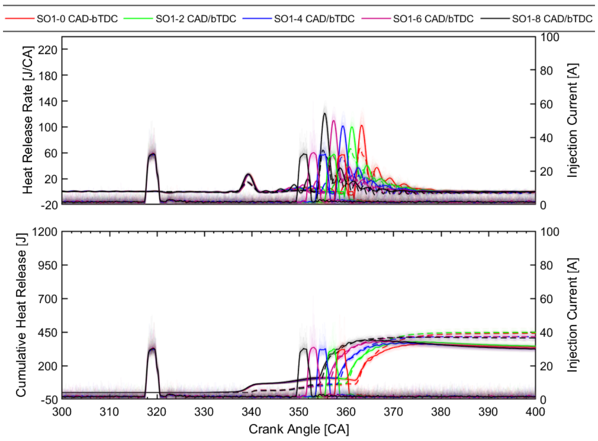
3. **Task 3: (Dual-injection) Difference in SOI 1 measured in CAD bTDC for the first fuel. Same injection pressure, fuel mass for both fuels**

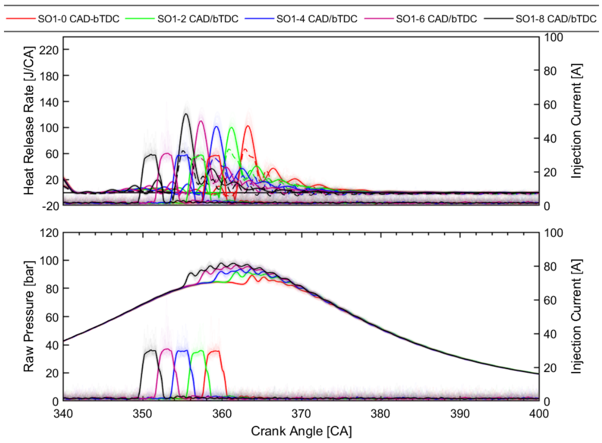
The Dual engine has different SOI1 but the same SOI2

| Task | Test Point | $T_{air}$ °C | $m_{air}$ (kg/h) | RPM | SOI1, CAD bTDC | Dur1, ms | SOI2, CAD bTDC | Dur2, ms | Injection Pressure | Injection 1 Fuel Mass, mg | Injection 2 Fuel Mass, mg | Energy1 | Energy 2 | Total Energy ,J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 11 | 25 | 80 | 1200 | 0 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 12 | 25 | 80 | 1200 | 2 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 13 | 25 | 80 | 1200 | 4 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| | 14 | 25 | 80 | 1200 | 6 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |
| Task3 | 15 | 25 | 80 | 1200 | 8 | 0.4 | 40 | 0.4 | 1200 | 20.63 | 20.63 | 880.9 | 880.901 | 1761.8 |



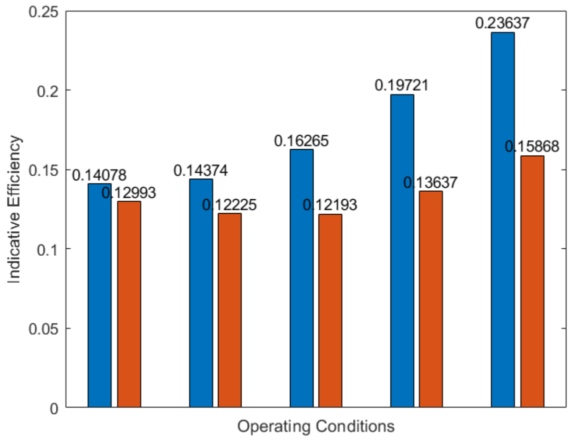



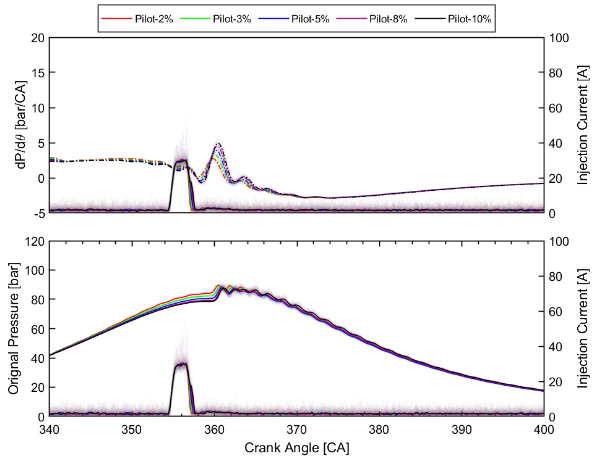

- Indicative Efficiency: The efficiency does not change much for the five test cases. However it appears that the engine performs better with fewer CAD bTDC
- Raw pressure: Stay constant for the same five tests, shifted by 2 CAD
- Pressure change w.r.t CAD: Stay constant for the same five tests, shifted by 2 CAD
- Heat Release Rate: The engine releases more heat when it starts fuel injection earlier or with higher CAD bTDC
- Cumulative Heat Release: The 5 test cases nearly accumulate nearly the same heat, but it appears that higher CAD bTDC will generates more heat

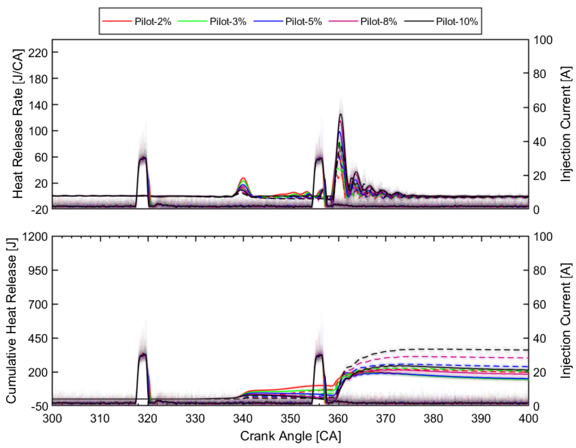
## 4. Task 4: (Dual-injection) Difference in both fuel mass and injection duration

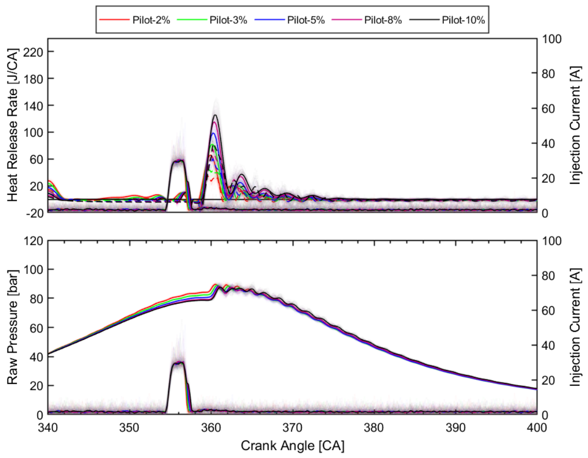
SOI 1 and SOI 2 stay the same. The diesel fuel and pilot fuel varies in their mass and injection duration. The longer the fuel duration, the more fuel mass injected. In the 5 test cases, the diesel fuel and the pilot fuel are in inverse proportion.

| Task | Test Point | $T_{air}$ °C | $m_{air}$ (kg/h) | RPM | SOI1, CAD bTDC | Dur1, ms | SOI2, CAD bTDC | Dur2, ms | Injection Pressure | Injection 1 Fuel Mass, mg | Injection 2 Fuel Mass, mg | Energy1 | Energy 2 | Total Energy ,J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 16 | 25 | 80 | 1200 | 3 | 0.32 | 40 | 0.4 | 1200 | 15.7 | 20.63 | 670.39 | 880.901 | 1551.3 |
| | 17 | 25 | 80 | 1200 | 3 | 0.34 | 40 | 0.38 | 1200 | 17.24 | 19.82 | 736.15 | 846.314 | 1582.5 |
| | 18 | 25 | 80 | 1200 | 3 | 0.36 | 40 | 0.36 | 1200 | 18.45 | 18.45 | 787.82 | 787.815 | 1575.6 |
| | 19 | 25 | 80 | 1200 | 3 | 0.38 | 40 | 0.34 | 1200 | 19.82 | 17.24 | 846.31 | 736.148 | 1582.5 |
| Task4 | 20 | 25 | 80 | 1200 | 3 | 0.4 | 40 | 0.32 | 1200 | 20.63 | 15.7 | 880.9 | 670.39 | 1551.3 |




- Indicative Efficiency: The efficiency of the engine increases noticeably as we inject more diesel fuel and less pilot fuel. The raw pressure stays constant for 5 tests

- Pressure change w.r.t CAD: Higher pilot ratio will cause higher pressure rate of change in the combustion stroke

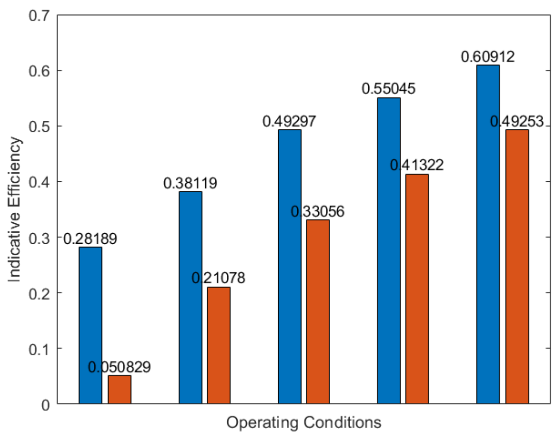
- Heat Release Rate: We can observe that a higher pilot ratio will release much more heat. As we know, losing more heat will mean less efficiency => The engine performs better when we injects more diesel fuel and in longer time than pilot fuel

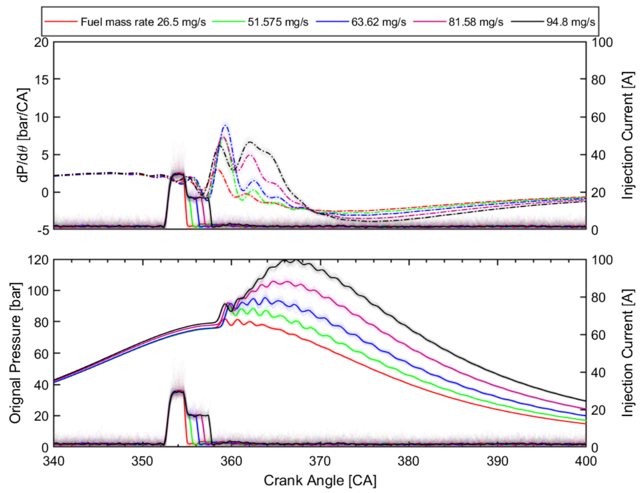
- Cumulative Heat Release: A lower pilot ratio yields less total heat release and is more efficient

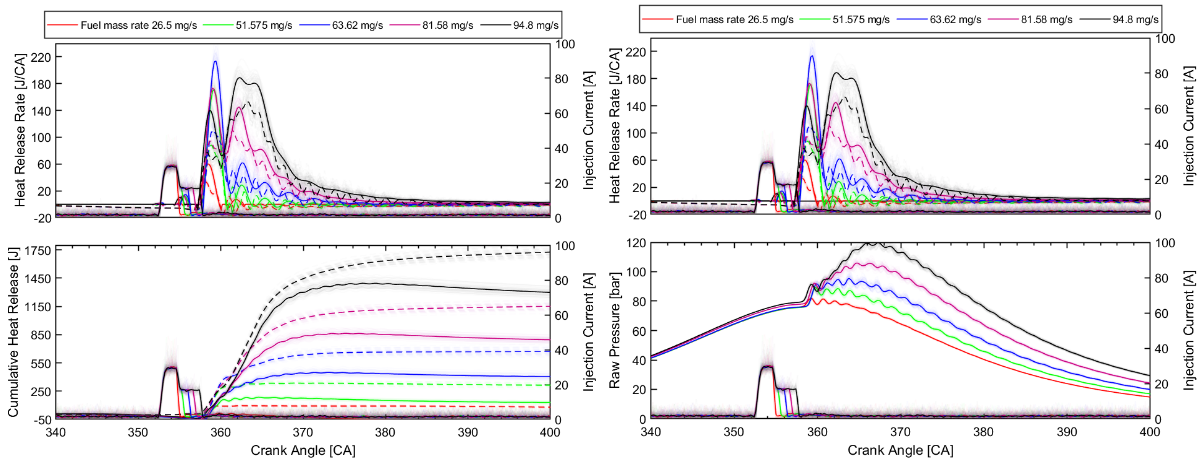
## 5. Task 5:(Single-injection) Difference in single fuel mass and injection duration

Dur1 and Injection 1 Fuel Mass varies between the test cases

| Task | Test Point | $T_{air}$ °C | $m_{air}$ (kg/h) | RPM | SOI1, CAD bTDC | Dur1, ms | SOI2, CAD bTDC | Dur2, ms | Injection Pressure | Injection 1 Fuel Mass, mg | Injection 2 Fuel Mass, mg | Energy1 | Energy 2 | Total Energy ,J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 21 | 25 | 80 | 1200 | 5 | 0.3 | NaN | NaN | 1200 | 7.96 | 0 | 339.89 | 0 | 339.89 |
| | 22 | 25 | 80 | 1200 | 5 | 0.4 | NaN | NaN | 1200 | 20.63 | 0 | 880.9 | 0 | 880.9 |
| | 23 | 25 | 80 | 1200 | 5 | 0.5 | NaN | NaN | 1200 | 31.81 | 0 | 1358.3 | 0 | 1358.3 |
| | 24 | 25 | 80 | 1200 | 5 | 0.6 | NaN | NaN | 1200 | 48.95 | 0 | 2090.2 | 0 | 2090.2 |
| Task5 | 25 | 25 | 80 | 1200 | 5 | 0.7 | NaN | NaN | 1200 | 66.36 | 0 | 2833.6 | 0 | 2833.6 |




- Indicative Efficiency: The more and longer the fuel injected, the better the efficiency
- Pressure change w.r.t CAD: Since raw pressure is higher for more fuel, it also means higher pressure change. There are two spikes in the pressure change between the second and third strokes
- Heat Release Rate: More fuel will release more heat and vice versa
- Cumulative Heat Release: More fuel will accumulate more heat and vice versa