FACULTY OF
ENGINEERING AND SURVEYING

HCCI Engine: Numerical and Experimental Approach

A. Aziz Hairuddin
Talal F. Yusaf
Andrew P. Wandel

UNIVERSITY OF SOUTHERN QUEENSLAND

Outline

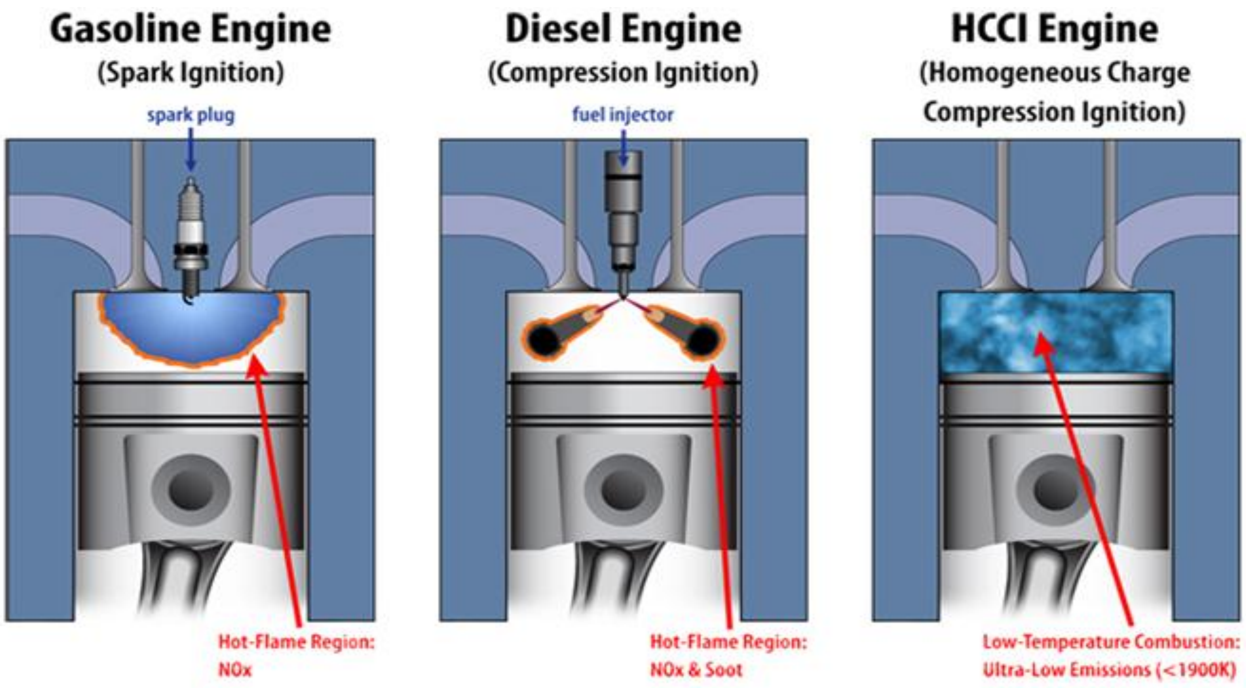
- Introduction
- Numerical Approach
  - Model formulation
  - Results and analysis
- Experimental Approach
  - Engine Diagram
  - Preliminary test
- Conclusion

Introduction

- What is HCCI engine?
  - It stands for Homogeneous Charge Compression Ignition engines.
  - First research was started by Onishi et al. in 1979.
  - This engine has been investigated worldwide as this technology has not matured sufficiently.
  - It could be used in either SI or CI configurations with high compression ratio (CR)
  - In principle, there is no spark plug or injector inside the combustion chamber like SI or CI engines to control the combustion: auto-ignition occurs in multiple spots once the mixture has reached its chemical activation energy.

Introduction

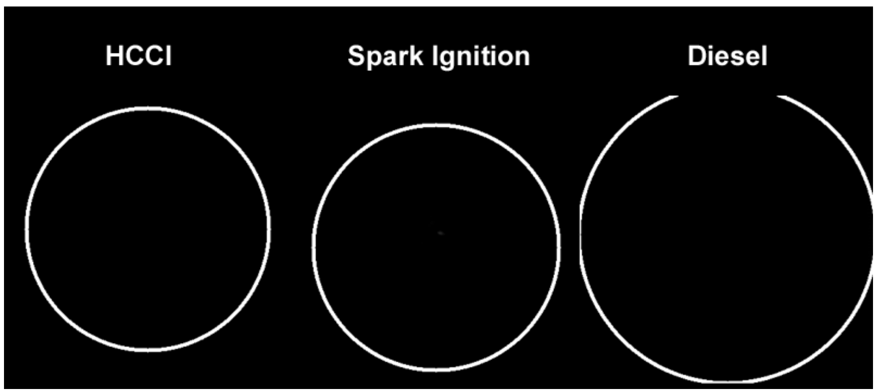
- What is the difference?
  - SI engines: Requires spark plug and low CR
  - CI engines: Requires fuel injector and high CR
  - HCCI engines: Without spark plugs or fuel injectors. Can be configured using CI or SI mode with high CR – leads to high engine efficiency with low emissions level.



Source: Lawrence Livermore National Laboratory, https://www-pls.llnl.gov/?url=science_and_technology-chemistry-combustion

Introduction

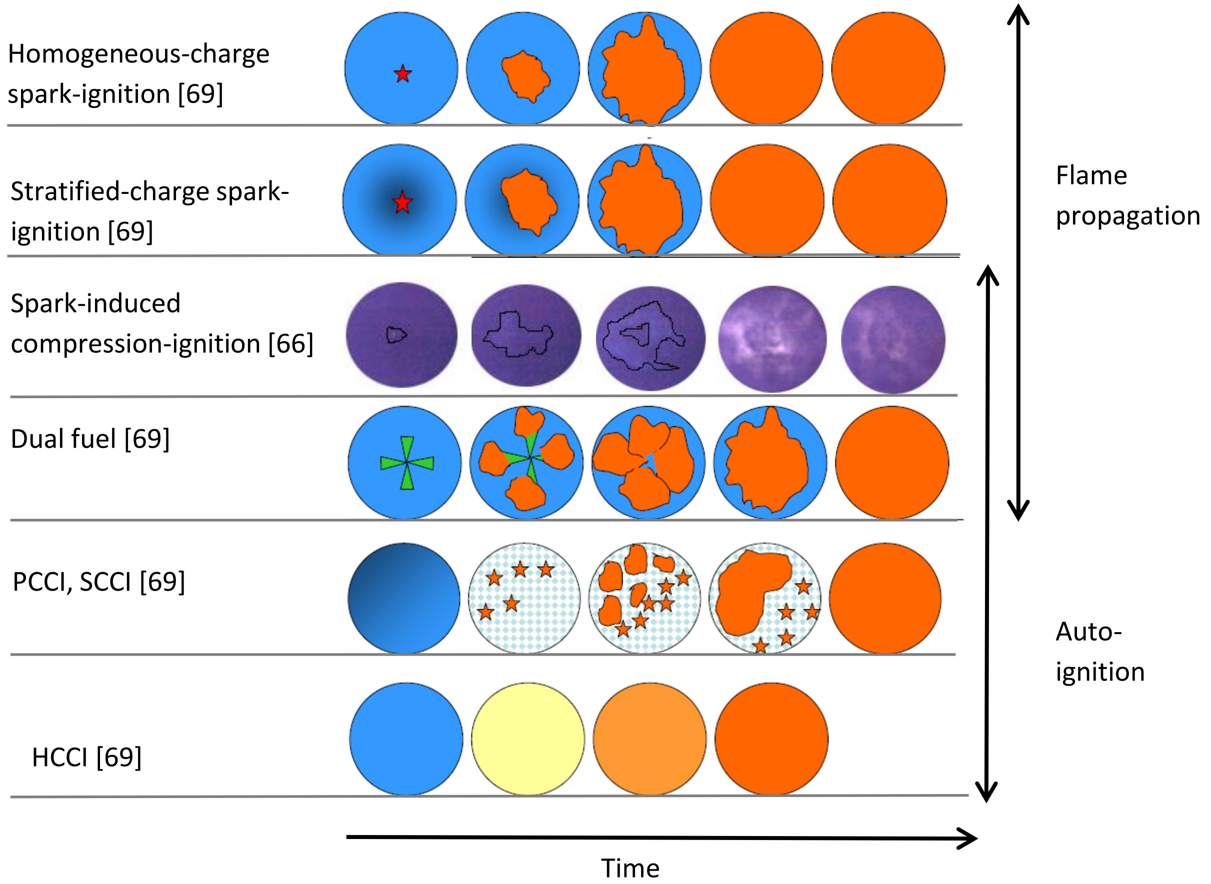
- Combustion behaviour:
  - SI engines: It has flame propagation with longer combustion period
  - CI engines: Auto-ignite when the fuel is injected into hot compressed air
  - HCCI engines: Auto-ignite in multiple spots instantaneously with fast combustion period



Source: Engine Research Centre, University of Wisconsin, http://www.erc.wisc.edu/combustion.php

Introduction

- Homogeneous charge engine types



Introduction

- HCCI engines can operate using any type of fuels as long as the fuel can be vaporized and mixed with air before the ignition.

- Fuel auto-ignition point is important to look at in order to get smooth engine operation: Different fuels will have different auto-ignition points as shown in below figure.

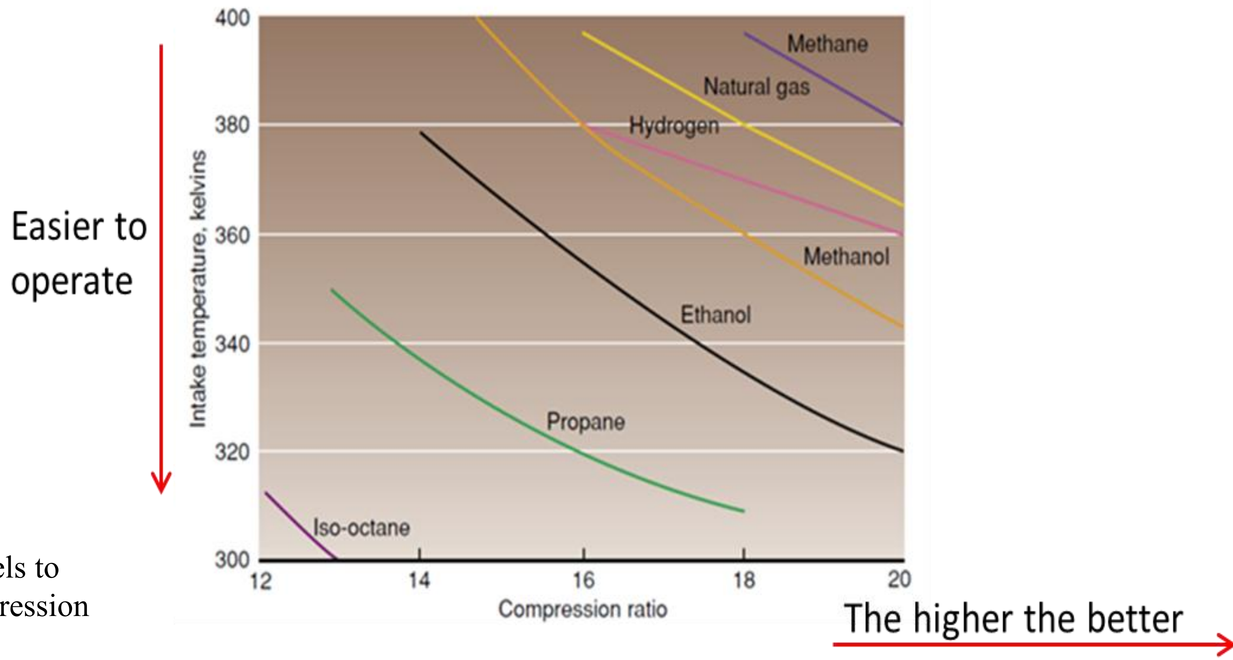


Figure Intake temperatures required for fuels to operate under HCCI mode with various compression ratios (Aceves & Flowers 2004).

Introduction

- **HCCI advantages:**
  - High engine efficiency relative to SI engines by employing high CR and fast combustion [2,3].
  - Ability to operate using a wide range of fuels [4].
  - Can be implemented in any engine configuration: automobile engines, stationary engines, high load engines or small size engines [5,6]
- **HCCI disadvantages:**
  - Difficulties in controlling the auto-ignition and heat release rate at high load operation and achieving cold start [7,8].
  - Knocking due to sudden onset of the combustion behaviour, which reduces engine reliability due to high vibration effects: produces pinging sound which can he heard outside.

Introduction

- **HCCI challenge:**
  - To control the auto-ignition timing of the mixture because there is no spark plug or fuel injector to control the start of the combustion.
  - To achieve cold start.
  - To meet emission standards.
  - To control knock.

Numerical Approach

- **Zero-Dimensional Model without Turbulence and Mixing Models**

Model Formulation

- **Conservation of mass:**
  - $\frac{dm}{dt} = \sum_j \dot{m}_j$
- **Conservation of species:**
  - An n-heptane reduced chemical reaction mechanism was used [13].
  - The properties are similar to conventional diesel (e.g. cetane number)
  - Consists of 160 species and 770 elementary reactions
  - $\frac{dY_i}{dt} = \frac{\dot{\omega}_i W_i}{\rho}, i = 1, \ldots, n$
- **Gas exchange process:**
  - A gas exchange process takes place when inlet or exhaust valve is open.
  - One-dimensional, steady state, isentropic flow is used to model the process [16].

Model Formulation

- **Conservation of energy:**
  - The equation was derived from the first law of thermodynamics for an open system to get the change in temperature.
  - $\frac{dT}{dt} =$
    $$\frac{1}{Cp-\frac{Pv}{T}}\left[-\left(\sum H_i - \frac{Pv\sum_i {}^{Ru}/_{W}}{{}^{Ru}/_{\overline{W}}}\right)\frac{dY_i}{dt} - \frac{\dot{m}}{m}\left(h_j - Pv\right) + \frac{1}{m}\left(\sum \dot{m}_j h_j - P\frac{dV}{dt} + \frac{dQ}{dt}\right)\right]$$
  - Where the pressure was calculated using the ideal gas law equation:
  - $P = \rho T \frac{R_u}{\overline{W}}$

- **Heat transfer:**
  - Heat is transferred to the wall through convection and radiation.
  - Radiation heat transfer on HCCI engines is neglected because the effect is very small, due to low soot and low temperature combustion [14,15]
  - The modified Woschni equation by Chang et al. [14] was used.

Results and Analysis

- Validation
  - The model was validated against numerical and experimental data from Guo et al. [17]: the fuel was injected at inlet manifold.
  - To account for mixing effects: the effective intake temperature was set 20°C higher than the intake temperature [17].

Table 1 Engine parameter used in the simulation [17]

Cylinder bore	82.55 mm
Stroke	114.3 mm
Connecting rod length	254 mm
Compression ratio	10
Engine speed	900 rpm
Inlet valve open (IVO)	10° CA ATDC
Inlet valve closed (IVC)	36° CA ABDC
Exhaust valve open (EVO)	40° CA BBDC
Exhaust valve closed (EVC)	5° CA ATDC

Results and Analysis

- Validation
  - The comparison between experimental and numerical data from Guo et al. [17] with the zero-dimensional model. The combustion phasing is in good agreement with the experimental data.

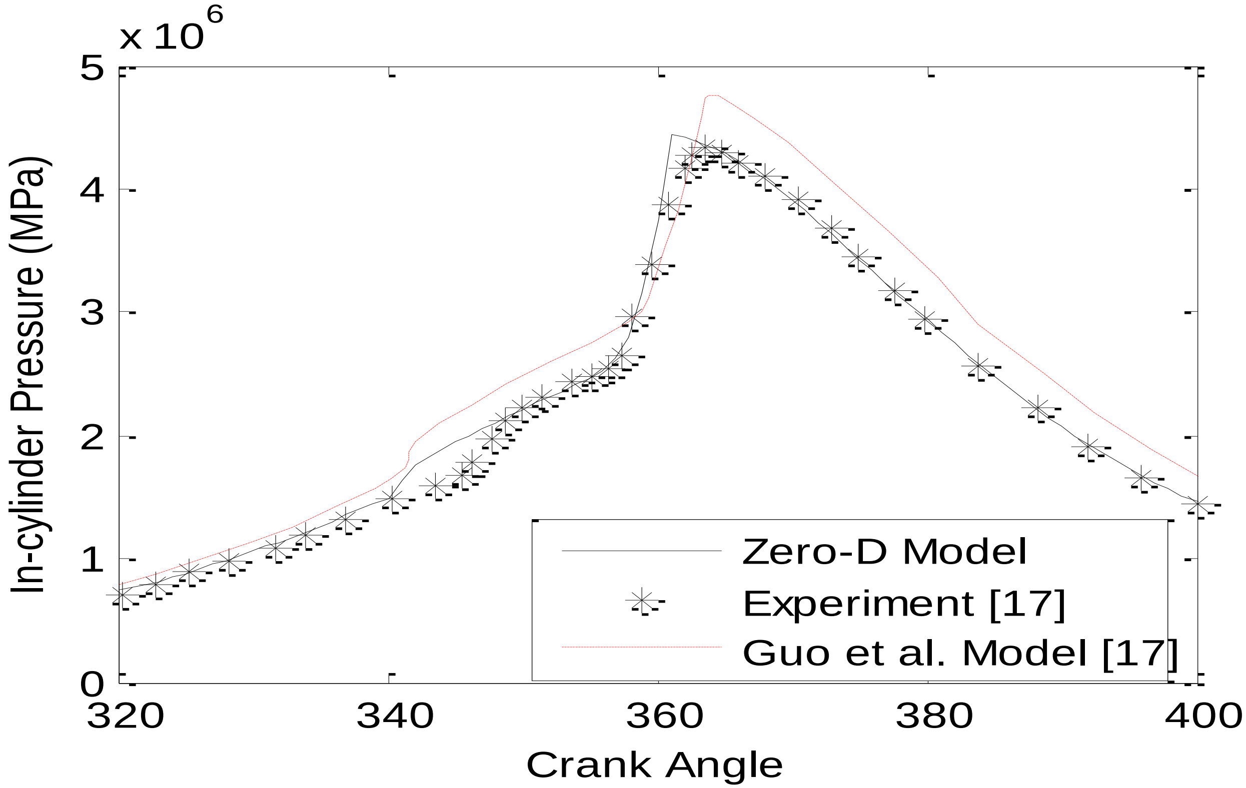
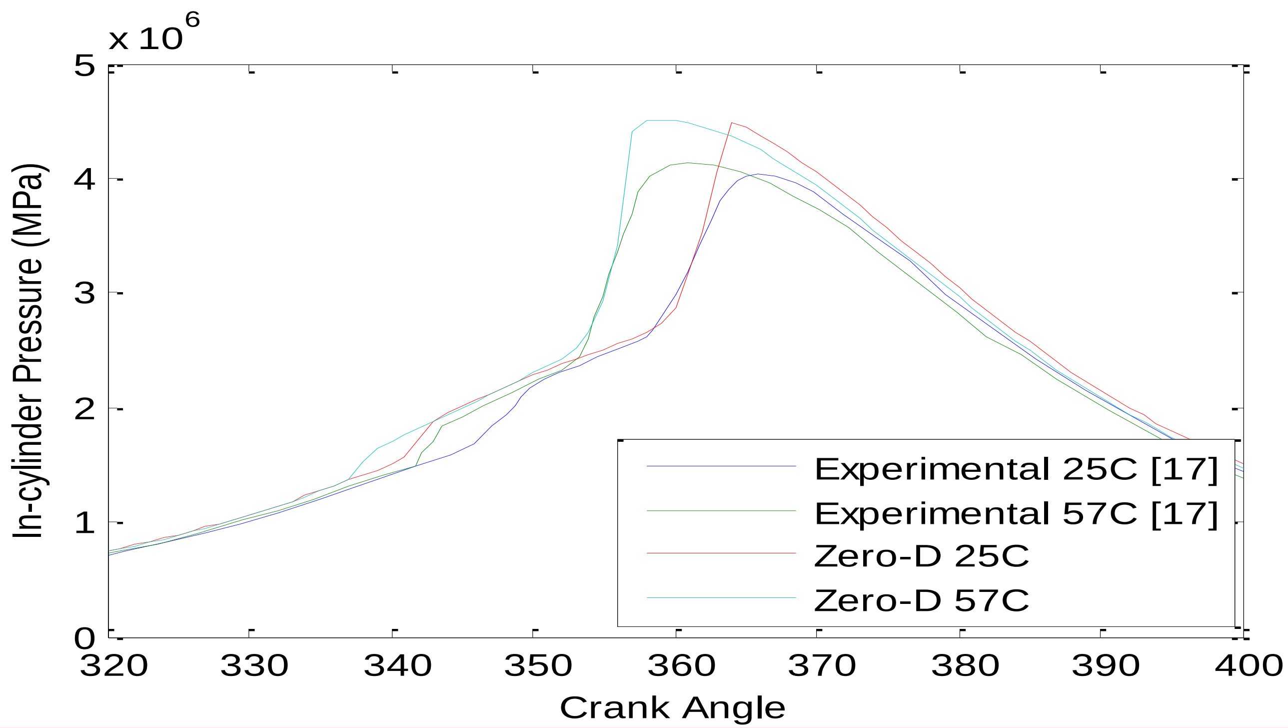


Figure 1 Comparison between single-zone zero-dimensional model with experiment and another single-zone model using modified Woschni heat transfer model [17]. CR=10.0, N=900 rpm, T_{in}=40°C, P_{in}=95 kPa, AFR=50.

Results and Analysis: Effect of intake temperature

- Auto-ignition can be advanced once the intake temperature is increased.

- Results from the current simulation were compared with experimental results [17] in Fig. 2(a) to validate the model over different operating temperatures: The results agreed well as did in Fig. 1.

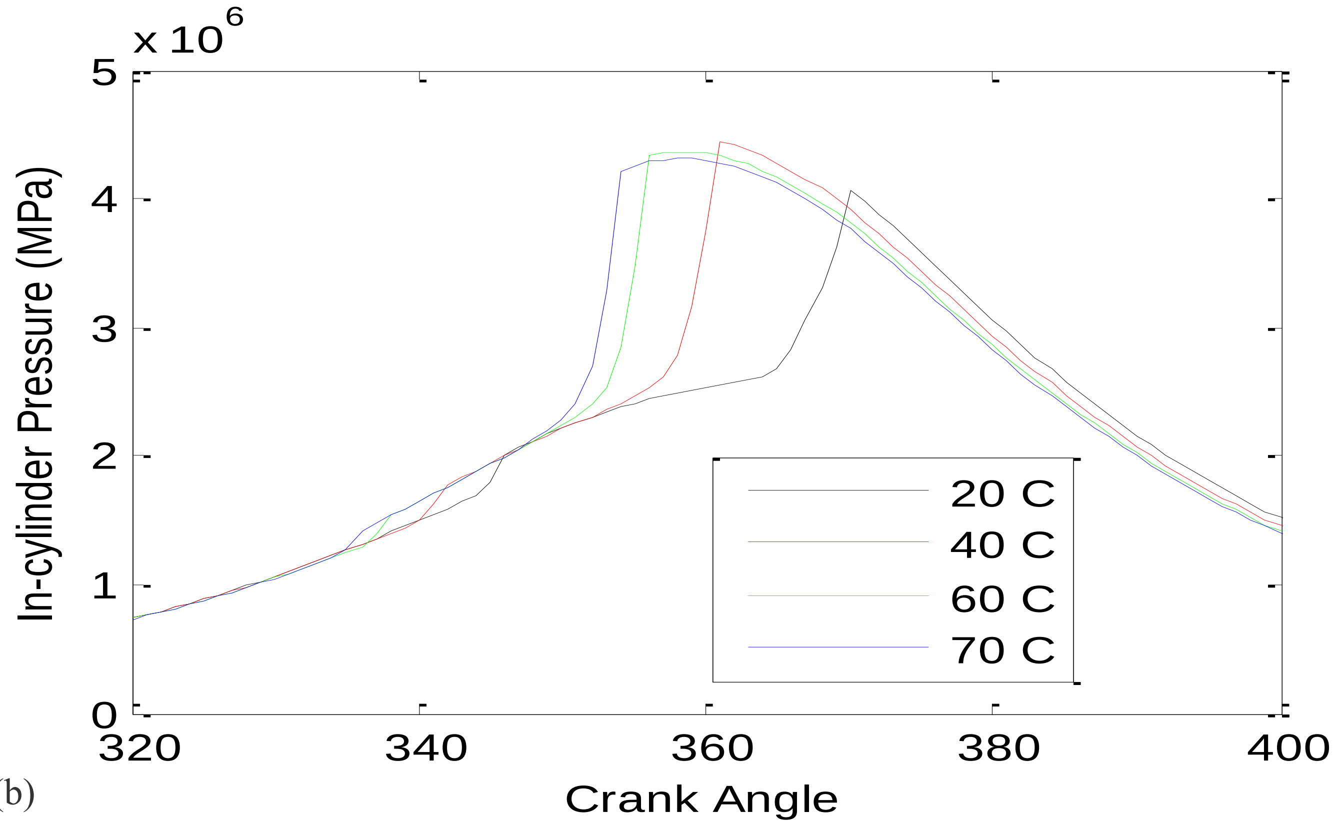


(a)

Figure 2 Effect of intake temperature on the in-cylinder pressure: CR=10.0, N=900 rpm, P_{in}=95 kPa, AFR=50 (a) Validated varying intake temperature.

Results and Analysis: Effect of intake temperature

- The predicted in-cylinder peak pressure starts to decrease even though the auto-ignition is advanced (Fig 2b).



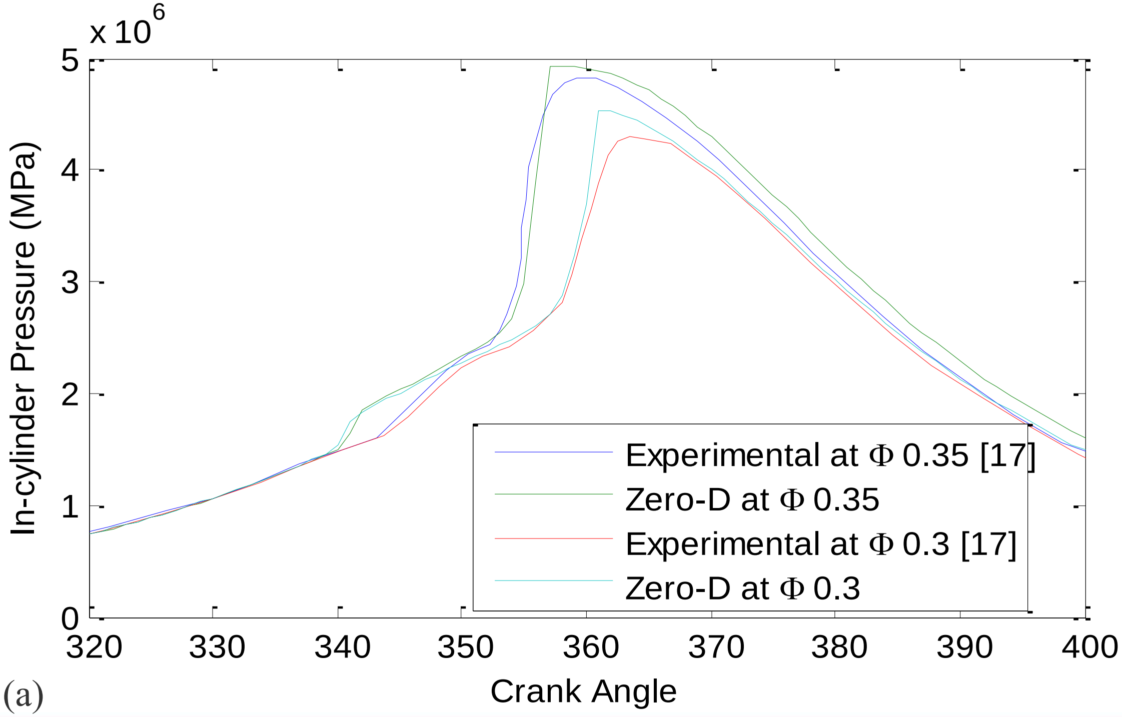
(b)

Figure 2 Effect of intake temperature on the in-cylinder pressure: CR=10.0, N=900 rpm, P_{in}=95 kPa, AFR=50 (b) Predicted in-cylinder pressure trend.

Results and Analysis: Effect of equivalence ratio

- The equivalence ratio (Φ) is a measure of how much fuel and air is being consumed in the combustion chamber.

- Figure 3(a) shows validated result of different equivalence ratios compared to the experiment, again showing good agreement.

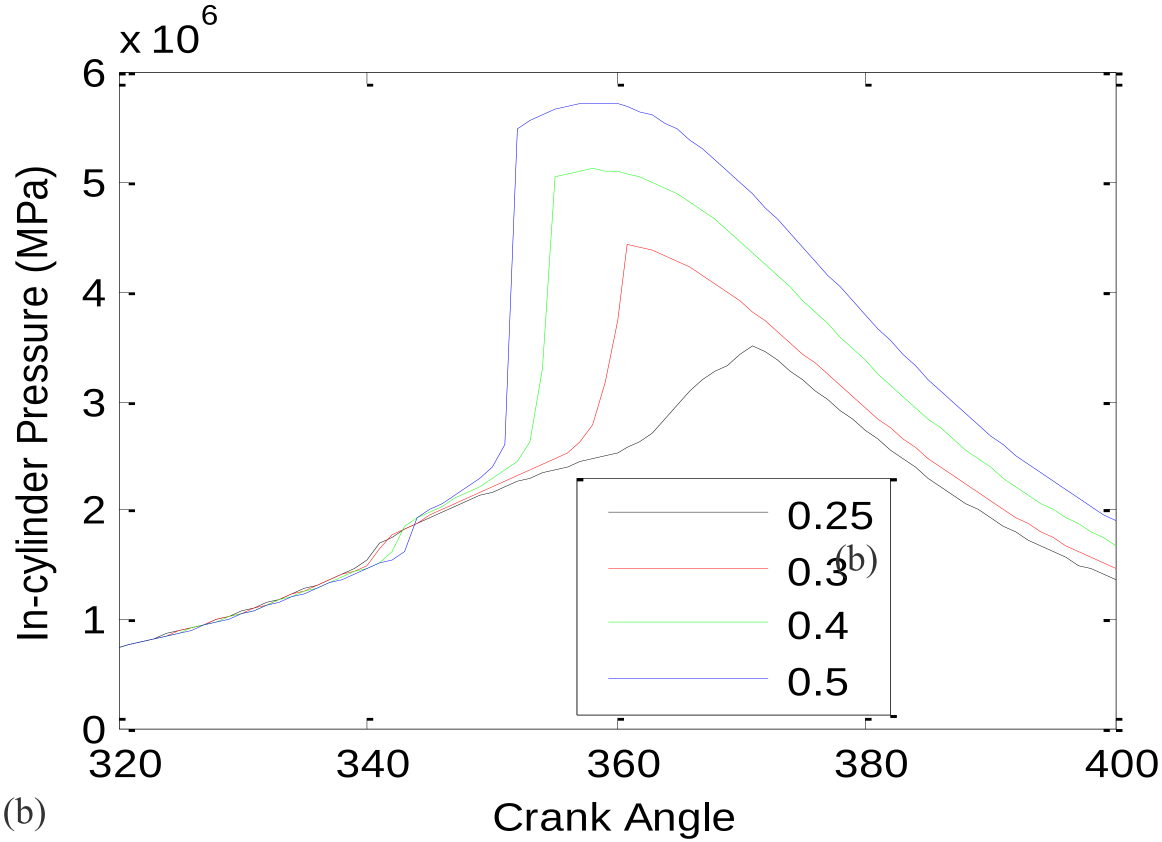


(a)

Figure 3 Effect of equivalence ratio on the in-cylinder pressure: CR=10.0, N=900 rpm, T_{in}=40°C, P_{in}=95 kPa (a) Validated varying equivalence ratio.

Results and Analysis: Effect of equivalence ratio

- The in-cylinder peak pressure trend keeps increasing with increasing equivalence ratio: will create knocking.



(b)

Figure 3 Effect of equivalence ratio on the in-cylinder pressure: CR=10.0, N=900 rpm, T_{in}=40°C, P_{in}=95 kPa (b) Predicted in-cylinder pressure trend.

Results and Analysis: Effect of hydrogen addition

- Effective way to reduce ignition delay and improves engine efficiency [19].
- Too much hydrogen will create knocking: the energy ratio should be less than 15% [20].
- The auto-ignition point is advanced significantly with 1% hydrogen and the in-cylinder peak pressure keeps increasing with increasing hydrogen content.

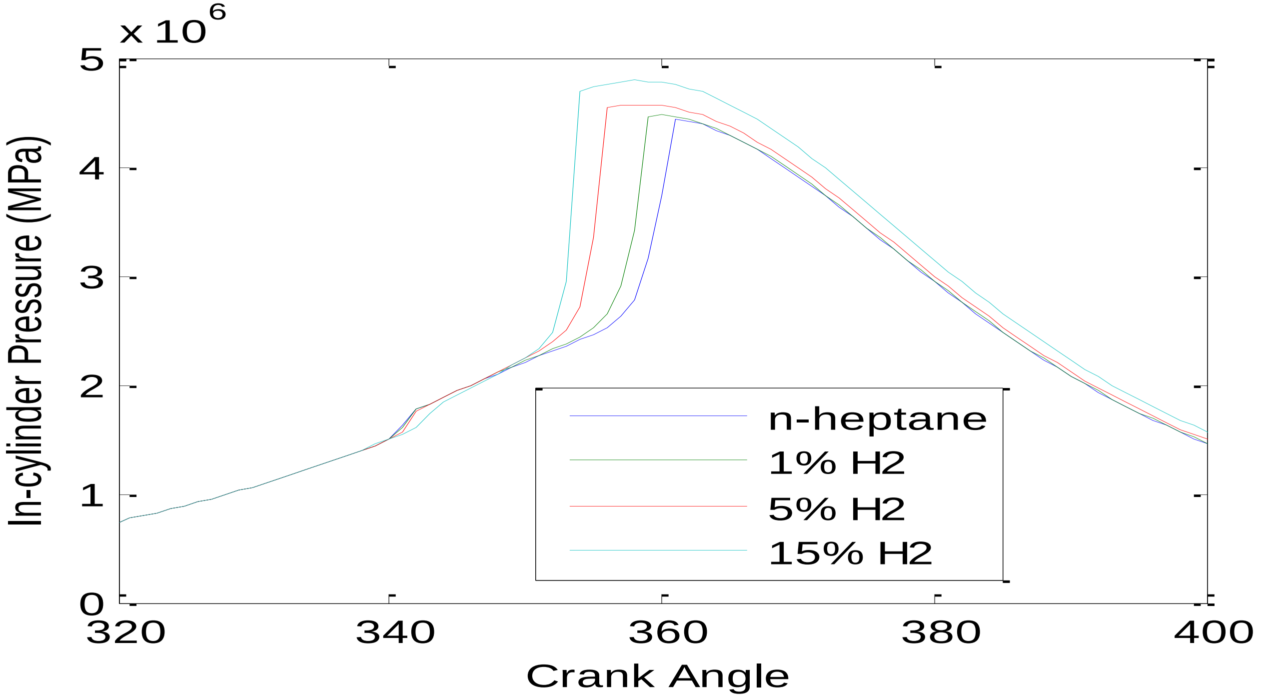


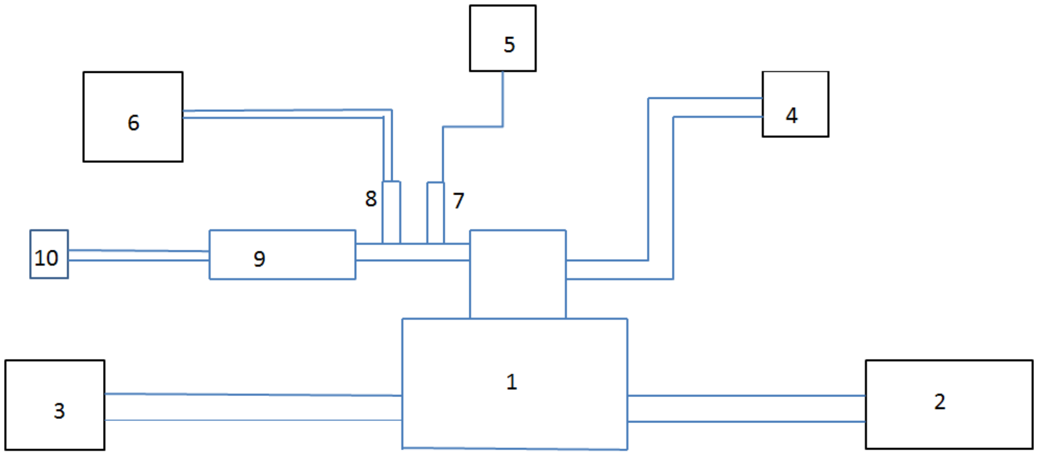
Figure 4 Predicted effect of hydrogen addition on the in-cylinder pressure for fixed n-heptane injection: CR=10.0, N=900 rpm, T_{in}=40°C, P_{in}=95 kPa

Experimental Approach

- Engine: Single cylinder SI engine to be converted to HCCI engine
- External heater to be installed on the intake air manifold
- Hydrogen will be added later on: if the time like us!

Experimental Approach

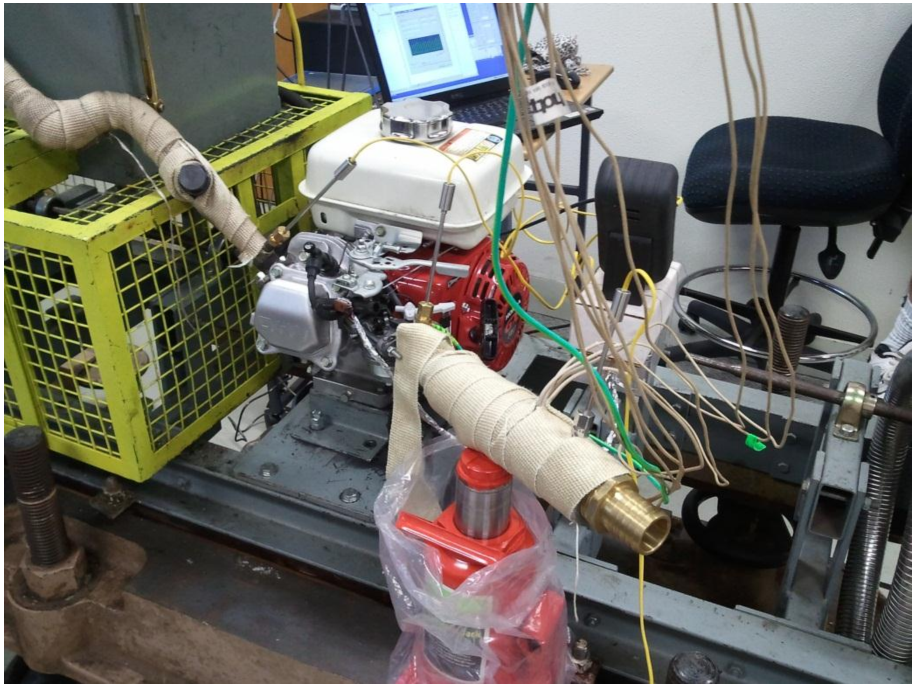
- Engine diagram

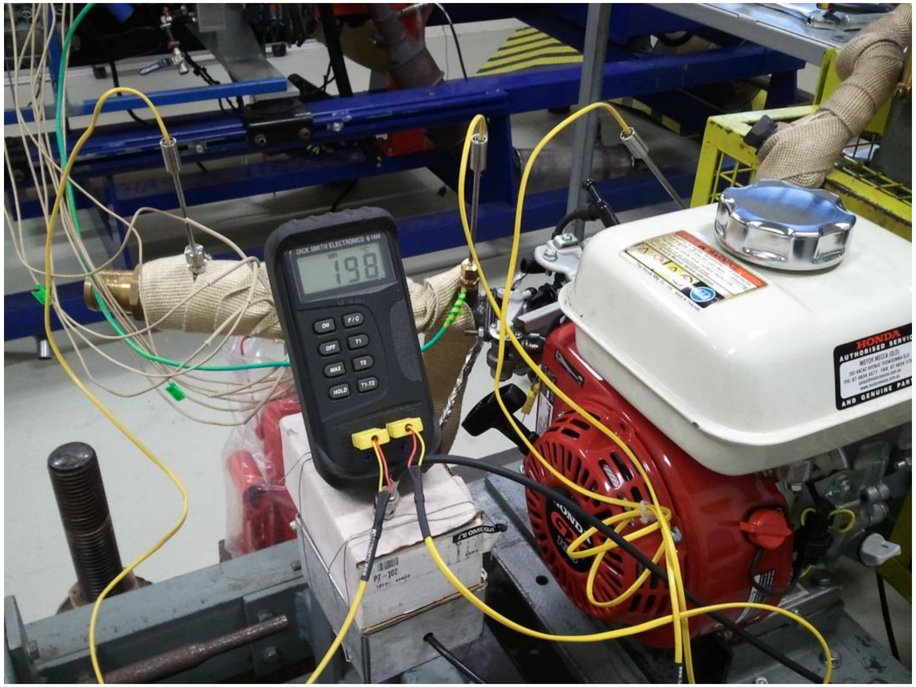


1 Engine	6 Hydrogen electrolyser
2 Dynamometer	7 Fuel injector
3 Data logger	8 Hydrogen injector
4 Fuel tank	9 Air intake heater
5 ECU	10 Airflow meter

Experimental Approach

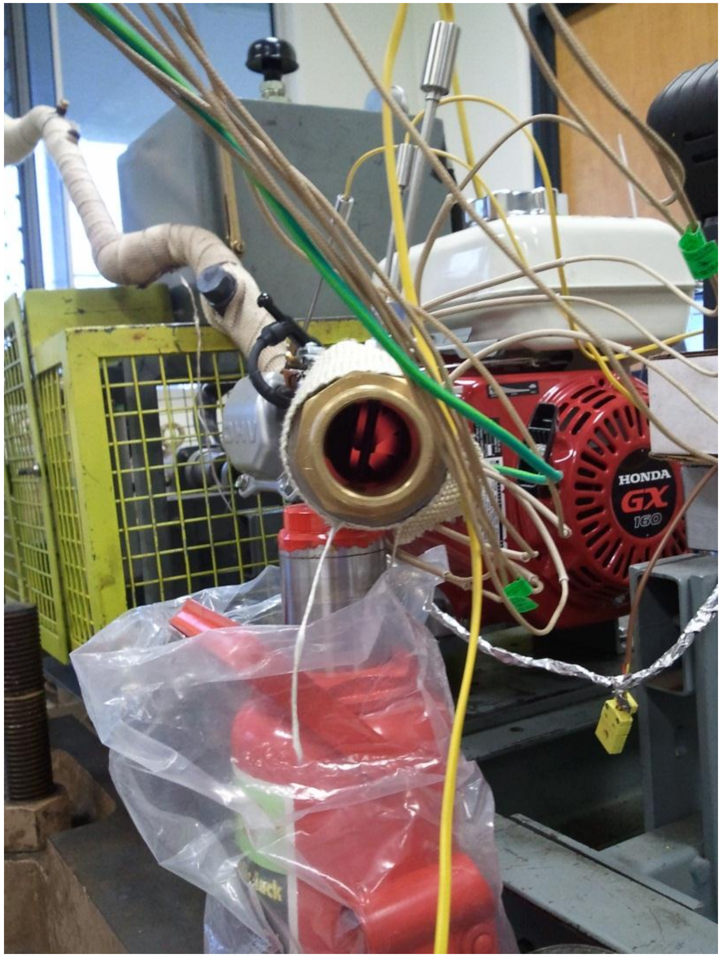
- Preliminary test

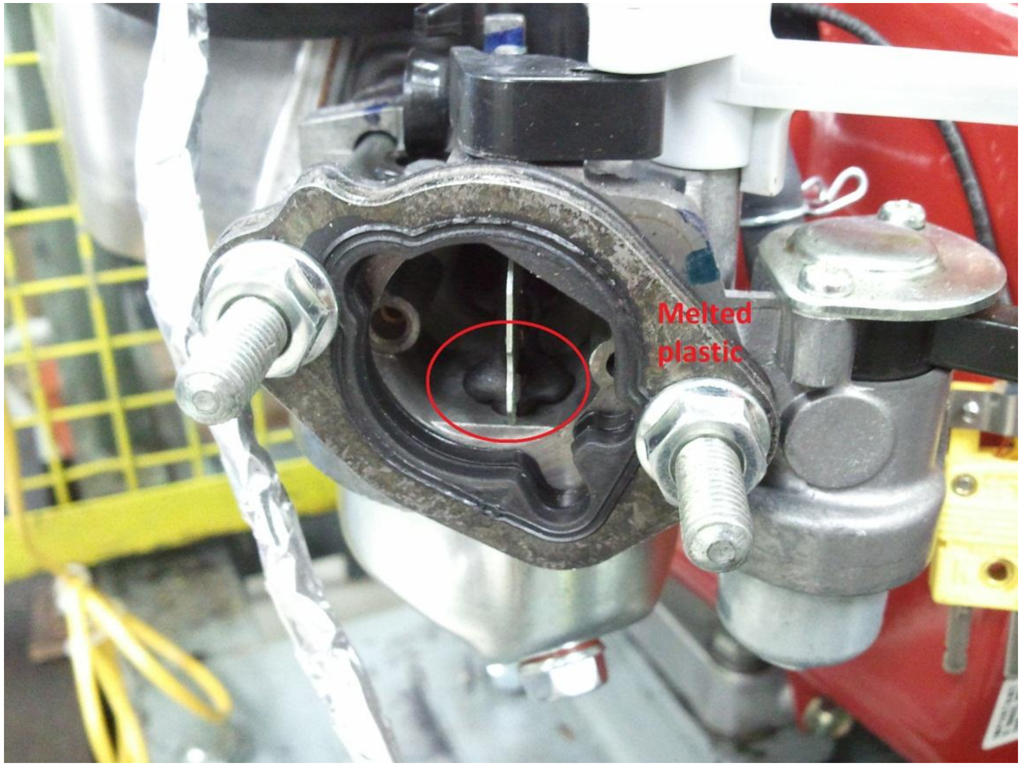




Experimental Approach

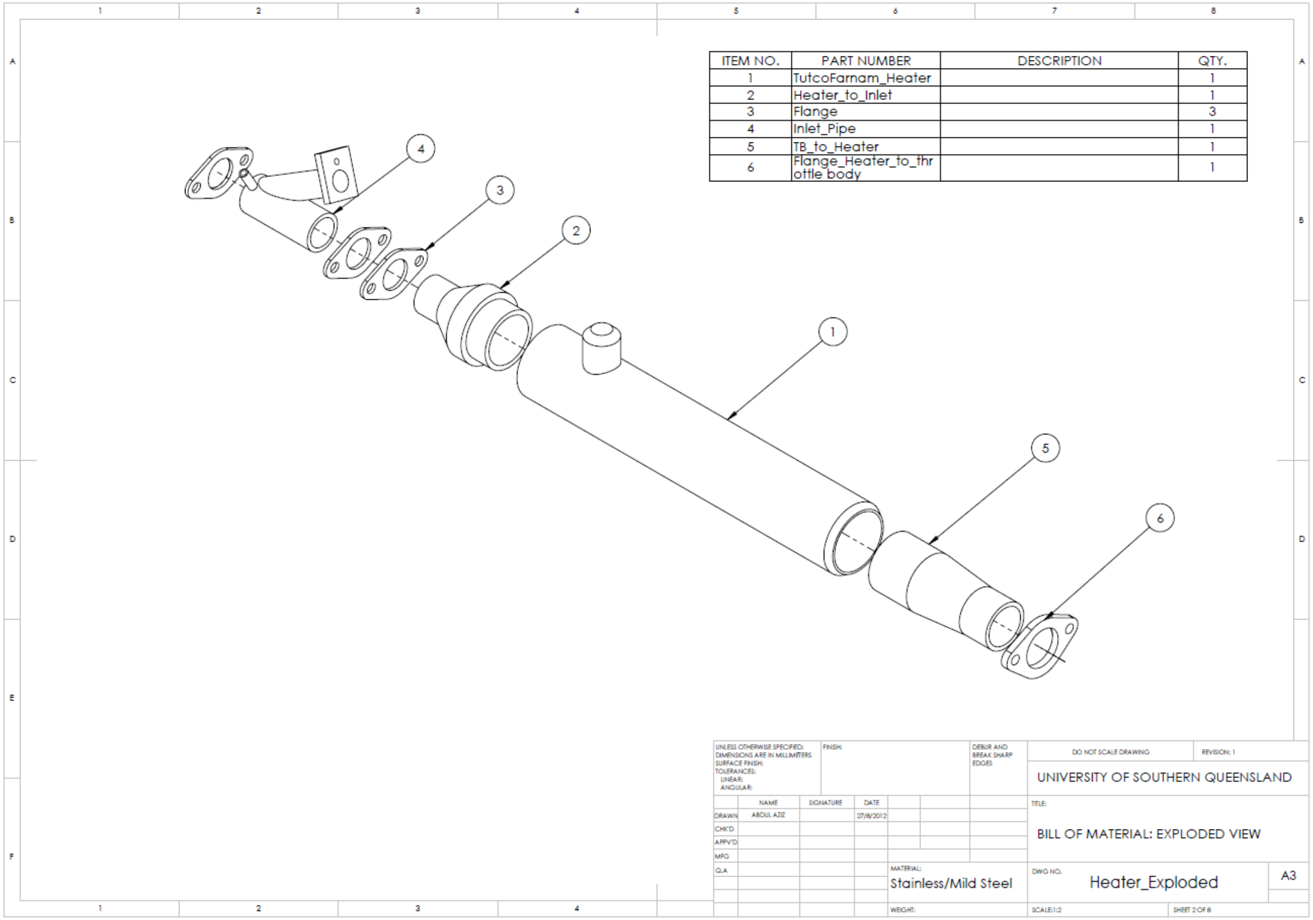
- Preliminary test: Problem





Experimental Approach

- Next modification:



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	TutcoFarnam_Heater		1
2	Heater_to_Inlet		1
3	Flange		3
4	Inlet_Pipe		1
5	TB_to_Heater		1
6	Flange_Heater_to_throttle body		1

Experimental Approach

- Next modification:
  - Carburetor system replaced by injector system
  - New 2kW heater installed before the injector
  - Wideband lambda sensor will be used

Conclusion

- HCCI: high combustion efficiency, low emissions levels, can use any fuels
- Numerical:
  - Once the intake temperature is increased above a certain threshold, the in-cylinder peak pressure will decrease with increasing intake temperature.
  - The in-cylinder peak pressure keeps increasing with increasing equivalence ratio: will create knocking.
  - Increasing the hydrogen content will also increase the in-cylinder peak pressure: should be no more than 20%
  - In summary, the combustion phasing is advanced by increasing all the parameters (intake temperature, equivalence ratio and energy ratio).
- Experimental:
  - Engine setup has to be completed as soon as possible: workshop work for a new heater is pending. ETA in 2 - 4 weeks!
- Future work: Investigation of all these factors on HCCI engines' performance.