The Fourth International Workshop on
Micro and Nanotechnology for Power Generation
and Energy Conversion Applications
PowerMEMS 2004
November 28 - 30, 2004
Kyoto, Japan

Effect of Initial Pressure, Temperature, and Chamber Size on Pressure Rise in Reduced Scale IC Engine Combustion Chambers

Yoshifumi Tsuji, Bennett Sprague,* David Walther,* Albert Pisano* and Carlos Fernandez-Pello*
School of Engineering, University of Tokyo
Hongo 7-3-1, Bunkyo, Tokyo, 113-8656, Japan
Tel +81-3-5841-6623, Fax +81-3-5841-6623, E-mail yosifumi@thermo.t.u-tokyo.ac.jp
*Mechanical Engineering, University of California, Berkeley
Berkeley, CA 94720 USA

Abstract

The ignition and subsequent combustion event in reactors designed to simulate engine of small scale has been examined to understand the limits of combustion when the size of the chamber is small and the ignition energy is limited. Three parameters; pressure, temperature and chamber size, are parametrically varied and the resulting pressure pulse is recorded. The experimental data were compared with a 0-dimensional model results using Cantera and the chemical conversion efficiency within the combustion chamber has been quantitatively estimated. The results of model match quite well the experimental observations.

Keywords: IC engine, constant volume combustion

1. INTRODUCTION

In order to better understand the combustion process that occurs in engines of small scale, the ignition and subsequent combustion event has been independently examined to mitigate the effects of engine processes (such as sealing, compression ratio, spark timing, oil contamination, etc.) on the ignition and combustion event. As a first step, the geometry of a 1.0 kW Wankel engine, which has a displacement of 5.0 cm^3, has been chosen and a static closed combustion chamber which mimics the combustion process at the top dead center (TDC) position has been built. The system is instrumented with pressure transducers and an optical imaging system.

The objective of this study is to understand the limits of combustion when the size of the chamber is small and the ignition energy is limited. Three parameters; pressure, temperature and chamber size, are parametrically varied and the resulting pressure pulse is recorded. Initial pressure is varied to determine the impact of compression ratio on performance. Initial chamber temperature is varied to examine the effect of heat losses on the combustion process, simulating compression heating of the compressed intake charge. The ignition energy has been fixed to minimize the amount of parasitic power drawn from the engine, while still consistently igniting the mixture.

In the experiments, the unsteady pressure inside the chamber was measured to determine whether ignition has occurred and to obtain the resulting pressure rise and to obtain the resulting pressure rise from which useful work may be extracted. The results have important implications toward MEMS scale engine development.

Along with the pressure measurements, a zero-dimensional model using Cantera has been developed to estimate the resulting pressure rise based upon chemical conversion efficiency within the combustion chamber. In this model, a complete set of chemical kinetics for butane/air mixture was used. The data obtained within this fully-closed system model match quite well the experimental observations. Similar trends are observed in terms of pressure and temperature dependences between the experimental and model data.

2. EXPERIMENTAL SET UP

A static combustion chamber was developed to obtain fundamental understanding of a combustion event that occurs in millimeter sized chamber over a range of temperatures and pressures. The static combustion chamber was designed to duplicate the geometry of the Wankel engine. Figure 1 shows the engine as it goes through the standard four stroke cycle of intake, compression, expansion, and exhaust. The rotor has a combustion pocket to increase the size of the combustion chamber.

The static combustion chamber mimics the geometry of the combustion pocket at top dead center (TDC), the minimum chamber volume at which combustion is initi-

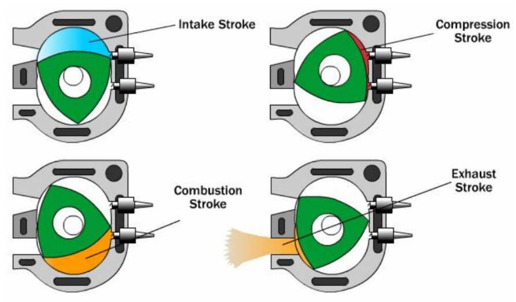


Figure 1. Four-stroke cycle of Wankel engine.

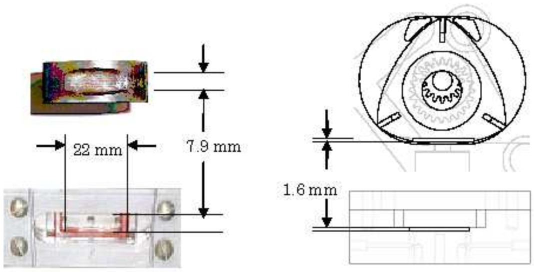


Figure 2. Dimensions of a Wankel engine combustion chamber.

ated. Figure 2 shows side and cross-sectional views of the Wankel engine at TDC and our static test chamber.

As an initial testing device, the curved surfaces have been approximated as planes, keeping the overall dimensions the same. The dimensions of the static chamber are 22 mm × 7.9 mm × 1.6 mm with a volume of 278 mm^3.

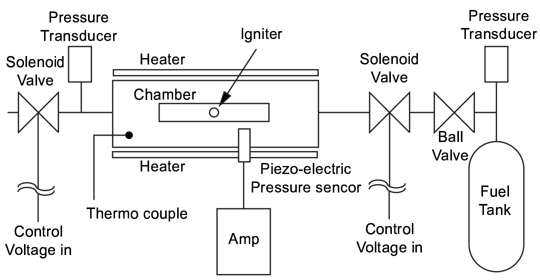


Figure 3. Schematic of experimental setup.

Pressure measurements were performed with a stoichiometric mixture of butane and air over a range of initial pressures from 1 atm to 6 atm and at four initial temperatures (25 °C, 50 °C, 100 °C) with three different size of chamber (see table 1.)

The auxiliary equipment (figure 3) included a 2.25 ℓ mixing chamber (Whitey 304 ℓ SS DOT-3A 1800) that contained the fuel and air at a specific stoichiometry. The stoichiometry was obtained by filling the tank with air to atmospheric pressure, then adding the fuel to a calculated partial pressure, and finally adding air to the final pressure. Two solenoid valves (Asco 8225B-006V) and a 0-200 PSIG Omega pressure transducer (model # PX176-200S5V) were used to fill the chamber to a set pressure. A 3" × 1" 50 W strip heater and a temperature controller (Watlow model S1A3JP1 and 96A1-CKAR) controlled the temperature. A 100 μF capacitor was charged to 28.3 volts and discharged through both an ignition coil with a 100:1 turns ratio (MSD Blaster part # 8223) and a custom tungsten electrode to ignite the mixture at 40 mJ. It should be noted that the energy measured is the energy that is discharged from the capacitor, not what is delivered to the fuel-air mixture, as there are certain losses in the ignition system. For high data rate pressure measurements, an aluminum plate and a Kistler 601B pressure transducer was mounted with a Type 222P needle adaptor over the combustion chamber.

The test procedure was to set the chamber to a given temperature and then to fill the chamber with a fuel-air mixture to a set pressure. The mixture was allowed to thermally equilibrate for ten seconds and then an attempt was made to ignite the mixture by discharging a capacitor with a fixed amount of stored energy.

3. EXPERIMENTAL RESULTS

After the capacitor is discharged through the electrode into a mixture at a known temperature, initial pressure, and stoichiometry, dynamic pressure is measured to determine whether ignition has occurred and to obtain the resulting pressure rise. A pressure pulse was detected inside the test section for all test conditions as tabulated in table 1, including 1 atm and 25 °C. Note that the narrow cross section of our test chamber is 1.6 mm, and half of the quenching distance, 3.0 mm, of a stoichiometric butane-air mixture at 1 atm and 25 °C quoted in the literature [1].

Figure 5 shows the data obtained for each size of chamber, 8 mm, 6 mm, and 4 mm width with different initial conditions. First, the initial pressure, P_{in}, is determined by averaging the pressure outside the chamber before ignition. Then, the peak of dynamic pressure inside the chamber was extracted from piezo-electric pressure transducer data and was used for equilibrium pressure, P_{eq}, inside the chamber. The two values were used to calculate the pressure ratio, *PR*, and plotted against initial pressure P_{in} as shown in the figure 5.

$$PR = \frac{P_{eq}}{P_{in}} \qquad (1)$$

From the figures 5, it can be seen that the pressure ratio, *PR*, is slightly dependent on initial pressure for all size chambers, with a slight decrease at higher initial pressures.

Table 1. Range of experimental parameters

Size (mm)	8, 6, 4
Pressure (psi)	0, . . . , 100
Temperature (°C)	25, 50, 75, 100

This could be due to more leakage from the chamber at higher absolute pressures.

For each chamber size, the lower initial temperature results the higher pressure ratio. This is due to the higher density of the fuel/air mixture at lower temperatures. The additional fuel and air mixture burns to produce a higher pressure ratio.

The data also shows that as the size of chamber deceases, the pressure ratio obtained at the same initial temperature decreases. This can be attributed to the fact that in a smaller chamber, the heat loss to the wall becomes proportionally larger, thereby reducing the pressure ratio.

4. ZERO-DIMENSIONAL MODEL RESULTS

Using a Cantera code[2] pressure ratio was obtained. The model condition is schematically shown in figure 4. For thermal property a data was taken from Livermore national lab LLNL Database[3].

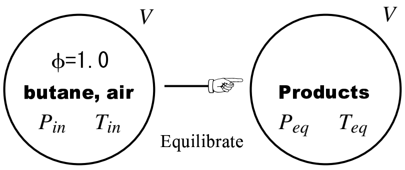


Figure 4. Schematic of constant volume combustion bomb model.

Simulations were carried out for the same range of initial pressure and temperature as the experiment (table 1.) For ideal adiabatic conditions with stoichiometric butane and air mixture, the results show a pressure ratio of 9 to 10 for the temperature and pressure range from 25 °C to 100 °C and from 10 psi to 100 psi. The pressure ratios decreases very slightly as the initial pressure increases. The Cantera results also show that as initial temperature is increased, the pressure ratio decreases. This agrees qualitatively with experimental data, but the absolute number is much higher. In order to quantitatively estimate the effective combustion efficiency in different size channel, a portion of initial butane was replaced with argon to simulate unburned butane inside the chamber. The right bottom plot of figure 5 shows the result of this calculation. The number in the figure indicates the percentage of butane that remains in the chamber.

5. DISCUSSION

From the conservation of energy, the energy change per mass is expressed using PR as;

$$(PR - 1)\, C_v T_{in} = Q_s - \frac{Q_{loss}}{\rho V}. \qquad (2)$$

C_v is the specific heat capacity for constant volume and Q_s, and Q_{loss} are specific heat release by reaction and total heat loss from the system. V is the chamber volume.

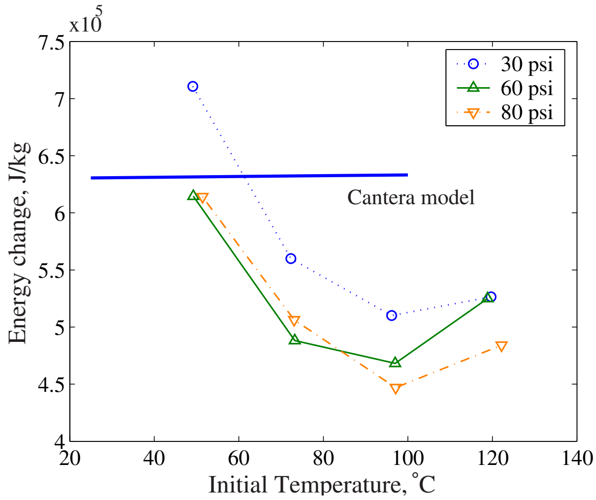


Figure 6. Energy change vs temperature for 8 mm chamber.

Note that the heat loss is not proportional to the density, whereas the heat release from combustion is. The specific energy change of the system, $(PR - 1)\, C_v T_{in}$, was calculated from the experimental data and plotted in figure 6.

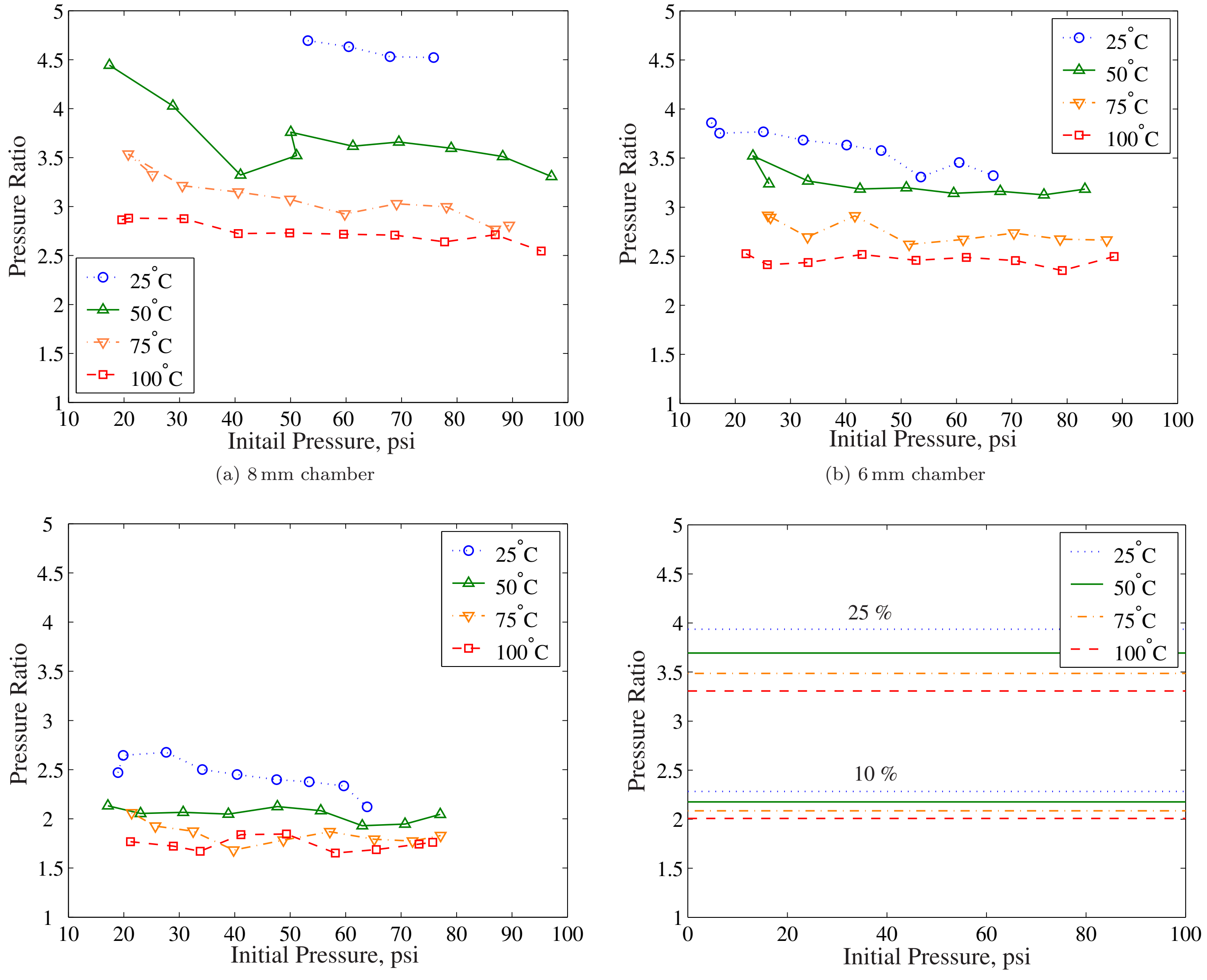
The effect of temperature on the pressure ratio is due to two competing effects on heat loss. At high temperatures, there is less fuel/air mixture due to density. This has the effect of more surface area for a given amount of fuel. This effect can be seen in the negative slope of the energy change in figure 6 from 25 °C to 100 °C. However, at higher temperatures, there is also less heat loss due to the higher temperature of the chamber walls. This has the effect of increasing the energy change, and can be seen in figure 6 for temperature above 100 °C. The increase of heat release due to higher reaction rate is negligible, as can be seen from the straight line given by the Cantera model in the figure 6.

The effect of initial pressure on the pressure ratio is very small under the conditions that were tested. There is, however, a slight drop in the pressure ratio that is larger than that predicted by the zero- dimensional model. This is most likely due to leakage from the combustion chamber at higher absolute pressures.

By comparing the pressure ratio from the experiment to that calculated from the model, the effective combustion efficiency was estimated for each chamber, neglecting mass loss due to leakage (See Table 2.) The efficiency drops as the size decreases. This implies that the relative increase in heat loss in smaller chambers reduces combustion efficiency. Gas sampling will be used in future work to verify that the measured combustion efficiency agrees with the calculations.

6. CONCLUSION

In the present work, a static chamber of millimeter scale has been built to investigate the combustion characteristics inside small IC engines. Initial pressure and tem-



(a) 8 mm chamber (b) 6 mm chamber (c) 4 mm chamber (d) Cantera model results

Figure 5. Pressure ratio against the initial pressure.

perature were controlled to simulate the engine operating conditions. The dynamic pressure inside the chamber was measured during the experiment and was used to calculate the ratio of equilibrium pressure to initial pressure. The pressure ratio is almost independent on initial pressure. However the ratio decreases as the initial temperature is increased, which implies that the impact of decreased amount of initial gas at higher temperatures was greater than the effect of decreased heat loss.

A zero-dimensional Cantera model was developed and the results were compared with the experimental data. The results agreed with data qualitatively. Furthermore, the model has estimated the combustion efficiency to be approximately 25 % to 10 %. Care should be taken in relating results from the static chamber to a working engine, due to differences including moving wall boundaries, compressive heating, and the effect of exhaust scavenging.

Table 2. Estimated combustion efficiency

size	Efficiency
8 mm	25 %
6 mm	20 %
4 mm	10 %

Future work will include testing of smaller chambers to further understand the effects of high surface area to volume ratio chambers on combustion. More work is ongoing to determine the impact of critical chamber dimension on ignition, including gas sampling to verify efficiency calculations, but these results clearly indicate that combustion can be controlled at the small scale and is not a fundamental combustion limit.

References

[1]Kanury, A., *Introduction to Combustion Phenomena*, Gordon and Breach Science Publishers, New York, 1975.

[2]http://www.cantera.org.

[3]http://www-cms.llnl.gov/combustion/combustion2.html.