

SIMULATING ENGINE COMBUSTION

The above engine concept relies on oscillatory flow with a catalytic [3] ignition system to maintain near isothermal conditions at the top of the expansion cylinder. As a preliminary investigation to assess the stability of periodic combustion in this type of arrangement, a simulated engine combustion experiment was developed for testing. This section will outline the apparatus used in the combustion experiments.

There are two aspects to supplying the experiment with a controlled gas flow; the first is to supply known amounts of air and fuel to the system. The second is to produce an oscillatory flow to simulate conditions in the engine. Flow supply and mixing was achieved by using MKS mass flow controllers. Two of these devices are used in the test assembly, one for air and the other for fuel. The fuel selected was propane (C_3H_8) supplied at 99.99% purity from a pressurized cylinder. Since the air and fuel will be at the same temperature and pressure (room temperature and atmospheric pressure) when entering the combustion section, a volume rate is equivalent to a molar rate. The equivalence ratio is defined as the actual ratio of fuel-to-air divided by the stoichiometric ratio. In the case when there is not enough fuel to react with the available oxygen, the equivalence ratio is less than one, and the mixture is called lean.

The air mass flow controller was calibrated up to fixed flow rates of 1250 SCCM using a bubble flow tube. A smaller mass flow meter was calibrated and used for propane. To impose a periodic signal on the steady flow coming from the mass flow meters (after the air and propane flows mix), a variable crank mechanism was designed and built where the magnitude and frequency of oscillation could be varied. The variable crank mechanism is shown in Fig. 2. It consisted of a housing which holds a piston cylinder set, and a rotor. The rotor was designed to allow discrete adjustment of crank pin position. The piston-cylinder set was an Airpot series 2K95 which was modified by replacing the normal ball joint with a sleeve bearing to connect to the rotor. The setup consisted of a graphite piston which slides in a borosilicate cylinder. There are no piston rings in this design; the piston relies on a clearance fit for sealing.

Steady State Combustion Experiments

A schematic diagram of the test assembly for steady flow conditions is shown in Fig. 3 where the variable crank mechanism was bypassed. The purpose of this test was to determine the effect of the flow rate and equivalence ratio on the combustion

temperature. The apparatus consisted of the mass flow controllers, thermocouple linearization circuit, a computer data recorder, a current limiting power supply to preheat the combustor, and the combustor itself. The latter component is a 4 mm ID quartz tube with an Omega FRX-164116 four-hole alumina tube inside. The alumina tube had three of four holes dedicated to Ni-Cr heater wire, with the fourth being used for the thermocouple. The heater tube was wrapped on its outside with three wraps of 8 mm x 8 mm, 100 mesh platinum gauze strips resulting in a snug fit with the ID of the quartz tube. The platinum gauze acted as the catalytic element for the combustor. To measure the temperature, the thermocouple was placed inside the alumina tube such that the junction was 1 mm downstream of the leading edge of the platinum screen.

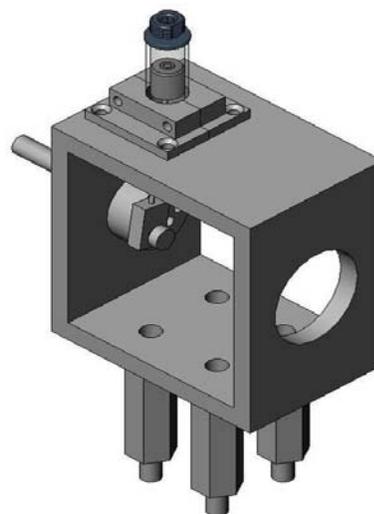


Fig. 2: Variable crank mechanism for creating an oscillatory flow from the flow controller outlet.

For the steady state benchmark tests, air flow rates from 500 to 1250 sccm were established through the combustor with the propane flow set to varying levels to provide differences in stoichiometry. Results for the steady state experiments are shown in Fig. 4. Each curve represents a different overall flow rate where the equivalence ratio varied from a low of approximately 0.4 to a high of 1.5.

From the results shown in Fig. 4, the measured thermocouple temperatures varied from approximately 600 °C to values approaching 1200 °C. It should be emphasized that this temperature is an indicator of combustion; it is not a measure of a quantity such as adiabatic flame temperature since there is considerable heat loss from the system. This data represents baseline results for later comparison.

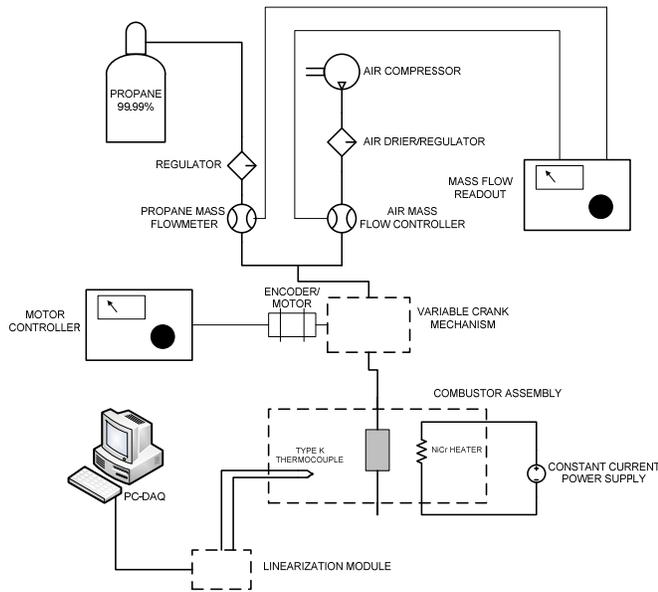


Fig. 3: Schematic diagram of the experimental setup for steady state and in-line oscillatory flow combustion.

In-line Oscillatory Combustion Experiments

The in-line oscillatory flow experiments used the apparatus as shown in Fig. 3 where the flow now passed through the cylinder of the variable crank mechanism. It is important to define a criterion for the amount of oscillation imposed on the steady flow. The limits would be steady flow on the one hand and flow that reverses itself and has various levels of this reversed flow. However, the mean flow would always be set by the fact that the mass flow controllers produce a steady mean flow downstream so that any oscillatory flow would be superposed on this.

We define the parameter R' to describe this oscillatory flow such that:

$$R' = 1 - \frac{\dot{V}_{\min \text{ flow}}}{\dot{V}_{\max \text{ flow}}} = 1 - \frac{\dot{V}_{\text{steady}} - \dot{V}_{\max \text{ oscillation}}}{\dot{V}_{\text{steady}} + \dot{V}_{\max \text{ oscillation}}}$$

In the experiments reported here, the crank speed was adjusted between 600 and 1200 RPM at various inlet flow rates of the mixture. The flow variable R' was changed by altering the crank position and/or the crank speed between the allowed positions. The combinations produce values of R' from 1.040 to 1.678, each of which is tested at equivalence ratios from 0.5 to 1.125. The variable crank mechanism and the motor used to drive it were limiting factors in the ability to test a larger range. The assembly could not

attain a rotational rate above 1800 RPM, and the rotation rate was not stable below 500 RPM. This limited the potential fixed flow rates and R' values which could be used in testing the combustor for the inline oscillatory flow case.

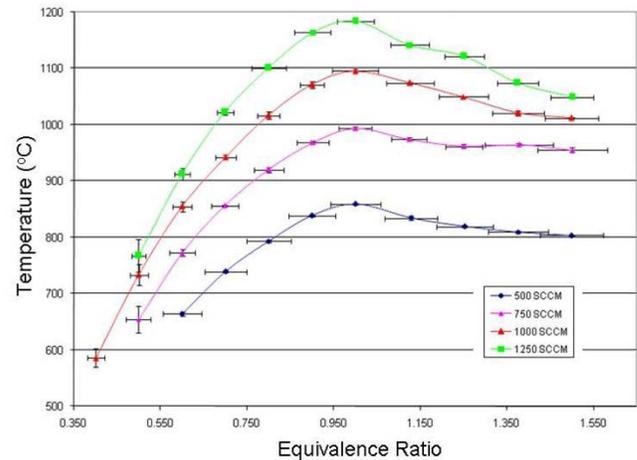


Fig. 4: Experimental results for the steady state combustion flow experiments.

The case of R' equal to zero is when the crank mechanism is not spinning. For operating crank conditions when the oscillations do not produce a flow reversal, R' is less than 1. When the flow starts to reverse direction for a small portion of the cycle, in this case the minimum flow is negative, so R' takes a value of greater than one. If the flow were to reach zero velocity at the minimum flow rate, R' would have a value of one. Notice that R' does depend upon the steady state flow rate in that it is used to determine the maximum and minimum flow rates from the oscillation values. Fig. 5 shows the results for the in-line oscillatory experiments. The results are quite close to the steady flow experiments even when reverse flow take place. It appears there is a larger divergence from the steady state experiments at low equivalence ratios but this divergence is within the experimental error for equivalence ratios near 1.

Pure Oscillatory Combustion Experiments

The pure oscillatory flow experimental configuration is shown in Fig. 6 where the combustible flow mixture passes through a straight tube and is periodically drawn into and exhausted from a transverse side tube. Provisions are made for the platinum screen wraps and the ignition tube assembly (with thermocouple) in the side branching tube.

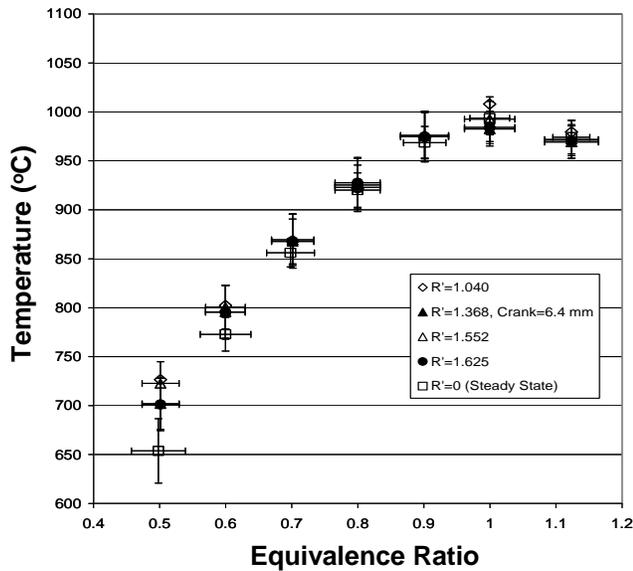


Fig. 5: Experimental results the oscillatory in-line combustion flow experiments.

For the purely oscillatory flow case, two parameters are defined to describe the magnitude of the flow passing into, and then being exhausted from, the entry section of the side branch. First, the definition for R is:

$$R = \frac{\dot{V}_{average}(S, \omega)}{\dot{V}_{air}}$$

This variable normalizes the averaged oscillatory flow rate through the combustor to the steady cross stream flow rate generated by the flow controllers. The second parameter is S; defined by,

$$S = \frac{A_{bore} * crank}{A_{bore} * D_{bore}} = \frac{crank}{D_{bore}}$$

S is a normalized value of the square cylinder, which has a bore equal to the stroke. It denotes the approximate volume that is drawn into the combustor at the rate of R. It should be noted that R is a function of S, but that S is not dependent upon R. With these two parameters, experimental data for temperature can be plotted and trends can be inferred from the trend lines. One such plot is shown in Fig. 7. The plotted data show, for an equivalence ratio of 1, that both higher R and S values result in higher measured temperatures. Although these trends only represent a small set of collected data, qualitative observations demonstrated that the purely oscillatory flow configuration was a robust combustion system easily

ignited and operated throughout a relatively large equivalence ratio and flow rate range.

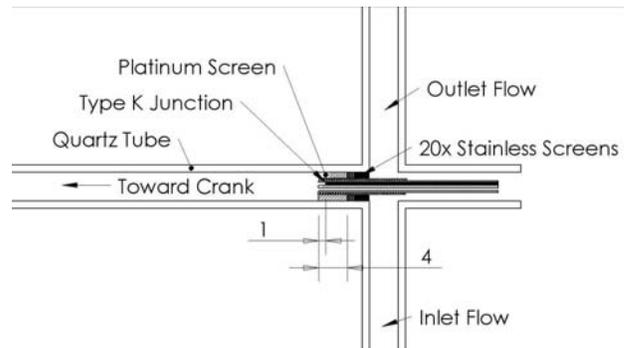


Fig. 6: Experimental configuration for the purely oscillatory combustion flow experiments.

CONCLUDING REMARKS

The descriptions provided here of oscillatory flow combustion experiments provide support that catalytic combustion will be a reliable and effective means of powering micro engines having separate compression and expansion cylinders. Further work will involve proving this out in a small-scale engine.

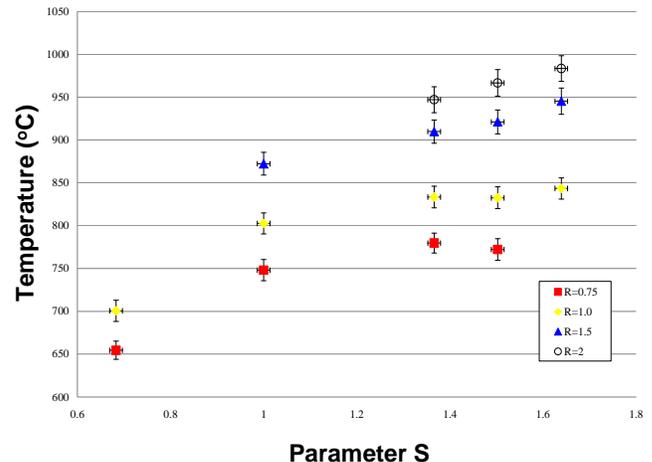


Fig. 7: Experimental results for the pure oscillatory combustion flow case at an equivalence ratio of 1.

REFERENCES

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