Part II of II

Combustion of Gasoline for Meso Scale Power Applications

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ABSTRACT

Access to the electric power grid in developing countries should not need large-scale infrastructure if clean, inexpensive and efficient individual power devices were available. There is demand for portable power applications that output power in the hundreds of watt range. These systems are referred to as meso-scale systems. Typical applications include non-grid connected homes, remote billboards, automotive auxiliary equipment, military personnel, campsites and human prosthetic devices. High power per unit mass is a very important requirement for these systems which make liquid hydrocarbons an ideal choice for the energy source. The issue with hydrocarbon fuels is that combustion at low flow rates (~ ml/min) is difficult. Injectors or vaporizers, such as those used in automotive engines, typically work at high pressures and relatively high flow rates. Electrostatic injectors can vaporize at low flow rates but they are cumbersome since they require high electric fields and are not suited for portable applications. The use of a flow blurring injector shows promise. A flow blurring injector which vaporizes liquid hydrocarbons at low flow rates has been developed. A system was built at Chiang Mai University, Thailand (CMU) to characterize the parameters effecting the combustibility of a hydrocarbon fuel and to investigate the suitability of this injector for use in meso-scale power systems. The results indicate that it could be used to generate power but care has to be taken to ensure flame stability.

Keywords: Meso Scale Power Systems, Fuel Vaporization, Flow Blurring Injector, Combustion Chamber

RESULTS

Initial Results

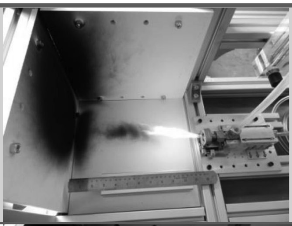
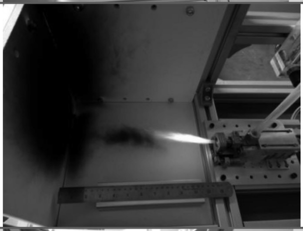
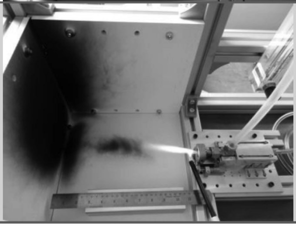
The first issue identified was that at flow rates of approximately 0.5 SCFM or higher the air velocity was just too high from the nozzle to provide any kind of stable flame. This corresponds to a mixture exit velocity of between 25 – 40 m/s, depending on the equivalence ratio, see Figure 5.

Rich Mixtures

In order to get a stable flame, it was necessary to use a much lower air flow rate. An Omega rotameter with a range of 0.1 – 1.2 SCFM was used. Table 2 shows pictures of the flames obtained for some representative air fuel ratios. In all test the air gap height was 350 μm or $\psi = H/D = 0.22$

The majority of the combustion air is drawn by the open flame from the atmosphere. If it entered a closed combustion space there

Table 2: Operating Parameters

Fuel Flow Rate (W)	Air Flow Rate (SCFM)	Equivalence Ratio (λ)	Flame
1500 (34.5 mg/s)	0.15	0.16	
1500 (34.5 mg/s)	0.2	0.21	
1500 (34.5 mg/s)	0.25	0.26	

would be insufficient air for combustion. A series of tests were carried out for **0.125** < ψ < **1.56** with the gasoline flow varying from 34.5 – 92 mg/sec. A summary of the results are shown in Table 3.

Table 3: Results Summary

ψ	Fuel Flow (W)	Air Flow (SCFM)	Equivalence Ratio (λ)	Flame Observations
$0.125 < \psi < 1.56$	1500 – 4000	0.15 – 0.25	$0.06 < \lambda < 0.26$	Within this range there was always a very stable yellow flame
$0.125 < \psi < 1.56$	1500 – 4000	0.3 – 0.35	$0.18 < \lambda < 0.36$	Within this range the flame was mostly yellow with 30%-70% blue mixture. The flame wanted to lift off the nozzle head and was only stable with the help of a flameholder
$0.125 < \psi < 1.56$	1500 – 4000	0.4 – 0.45	$0.15 < \lambda < 0.47$	At this range the flame was always unstable. Even with a flameholder there was liftoff

These are fuel rich mixtures which combust in an open atmospheric flame. The biggest effect on the stability of the flame was the air flow. Changing the gap height and the fuel flow mattered less that the air flow. An approximate layout of the three regions is shown in Figure 7.

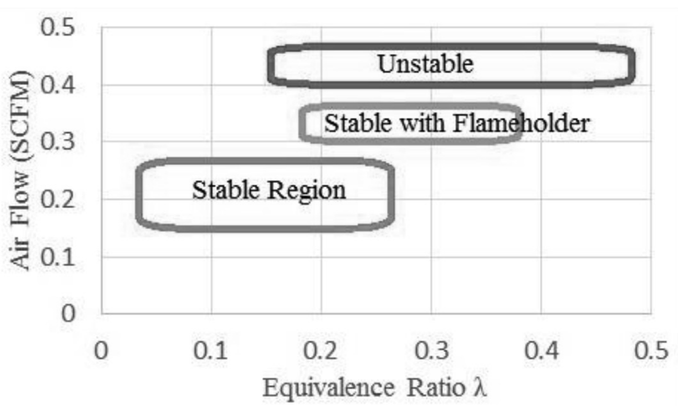


Figure 7: Approximate transition from stable to unstable flame

ANALYSIS

Stoichiometric Analysis

Taking the air flow rate which produced a stable flame, 0.2 – 0.25 SCFM for a fuel flow rate of 1500 – 4000 W. The Air/Fuel ratio is defined as AF = $\frac{\dot{m}_{air}}{\dot{m}_{fue}}$ and taking the high and low value for these ranges gives a ratio of (1.2 < ALR < 4). This ALR or Air-to-Liquid Ratio $\left(\Phi = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}\right)$ is only the air flow through the nozzle, not the actual air in the reaction. This nozzle could not be used in a closed system witho[illegible]ir supply. Four times the air flow would be needed to have [illegible] air for stoichiometric combustion. This is a problem as the ultimate aim for this research is to be able to use this nozzle for such closed power systems as Stirling engines or Tesla Turbines. It was not possible with the present nozzle to increase the air flow as this resulted in extinguishing the flame and an unstable or non-existent reaction.

Mean diameter estimation

Ganan-Calvo [16] developed a correlation to estimate the dimensionless droplet mass median diameter which is defined as δ ≡ MMD/D. The correlation was as follows:

$$\delta = 0.42 W_{eD}^{-0.6} (1 + 180 h_D)(1 + ALR^{-1})^{1.2} \qquad \text{Eq. 1}$$

Where ALR is the Air to Liquid ratio or $\left(\phi = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}\right)$, the Weber number is defined as $We_D = \frac{\rho_{air} U_{air}^2 D}{2\sigma}$ and the Ohnesorge number $Oh_D = \frac{u_{fuel}}{\rho_{fuel}\sigma D}$. Using the following properties for gasoline (Table 4).

Equation 1 predicts a small droplet size for a higher air velocity. At the extremes of this testing, for ALRs between 1.2 – 4 the predicted droplet mass median diameters ranged from 170μm to 80μm as shown in Figure 8. This was the stable region of the tests where the air flow

Property	Gasoline
Specific Heat Capacity (kJ/kg.K)	2.22
Heat of Vaporization (kJ/kg)	348.8
Boiling Point (°C)	40-200
Density @20°C (kg/m^3)	701
Viscosity @20°C ($N.s/m^2$)	$6x10^{-4}$
Viscosity Gasoline Vapor @150°C ($N.s/m^2$)	$1.5x10^{-5}$
$R_{gasoline}$ (J/kg.K)	92.3
σ (mN/m)	22

Table 4: Gasoline Properties

was between 0.2 – 0.25 SCFM. Unfortunately, the predicted lower diameters all occurred at the higher velocities, where the flames were bluer and cleaner but were unstable, suffering from liftoff. At the stoichiometric ALR of 18.2 the predicted droplet size would be in the 10 - 15μm and should result in increased combustion efficiency. However, Jiang et al. [18] found that this correlation did not apply for diesel or vegetable oil since it predicted higher droplet diameters than were actually measured.

Ganan-Calvo [16] also provides a correlated set of data points showing the atomization efficiency of the flow blurring nozzle over the plain jet air blast atomizer. Increase in atomization efficiencies of over

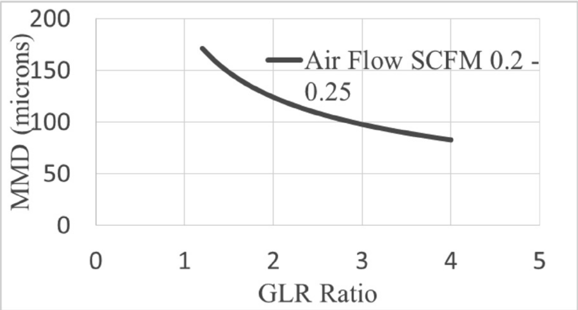


Figure 8: Estimate of droplet mass median diameter as a function of the GLR

600% are reported but these are for high air/fuel ratios. At our values of A/F from 1.2 – 4 the increase in efficiency is lower, varying from a 10% increase to a 100% increase. It is possible that without measuring the droplet sizes that the small efficiency increase may not be observable by just combustion alone in this experiment.

DISCUSSION

To summarize these results:

- The flow blurring nozzle can produce a flame within the meso-flow regime that is of interest
- The flame is stable and constant within a certain air flow range and gap size
- Only rich air/fuel mixtures combusted with our system

Several issues have arisen and are as follows:

1. The special "flow blurring" regime was not observed, directly from the combustion alone. There was no discernable difference in the flame from $0.125 < \psi < 1.56$. Flow blurring is supposed to only occur at $\psi < 0.4$.
2. The air flow rate was necessarily low for flame stability. It was so low that the nozzle, in its present form, cannot be used in a closed combustion system without additional secondary air supply or a flame stabilization mechanism.
3. The stable flames produced were yellow in color. They also had some soot visible at the flame ends. This usually signifies insufficient oxygen for a complete combustion reaction as expected from a rich mixture.

There are three or more possible explanations for not directly observing a change in the combustion pattern when the nozzle operates in the flow blurring regime:

a. At these low air flow rates the efficiency improvement in the FB nozzle is not observable
b. Even if the efficiency improvement was higher it may still not be possible to observe it by looking only at the combustion flame

c. Flow blurring may only occur at the higher air flow rates that produce liftoff and flame instability

FURTHER RESEARCH

Further research will be carried out on combustion stabilization techniques. This is to prevent liftoff when sufficient combustion air is supplied for closed system operation. A swirl stabilized injector has been designed and is under construction. Other techniques such as backward facing steps and flow arresters will also be considered. The aim is to provide enough combustion air to the flame without extinguishing it. In this way the heat can be used in a closed system. A closed system is needed to power the energy conversion system since an open flame will lose most of its energy to its surroundings.

Once a method to stabilize the flame is achieved the second step is to design and build a closed combustion system. This will be a small combustion chamber that powers the energy conversion device. It will be well thermally insulated and have an integrated recuperator to recover the heat.

Finally the third step will be to design and construct the energy conversion device. At the moment the specific type of energy device is undefined. As previously mentioned in the abstract, the uses for a meso scale power system include non-grid connected homes, remote billboards, automotive auxiliary equipment, military personnel, campsites and human prosthetic devices. In order to satisfy these applications some requirements include, a) Portability b) Good Efficiency c) Reasonable Cost d) Lightweight e) Robust. Of course many of these requirements are subjective. However making it lightweight and portable excludes any heat recovery or CHP mode of operation. Unless a specific application for say, domestic heat and power were desired then a standalone unit could be designed but then the portability requirement would not be met.

CONCLUSIONS

In this article, a new injector concept has been investigated with the intention of using it in the design of meso-scale power systems to provide up to 4000 W of thermal power. Assuming moderate efficiency levels this should output between 75W - 450W of electric power. The novelty in the injector stems from its ability to combust small quantities of any liquid hydrocarbon simply and efficiently.

With this end in mind a flow blurring injector was designed with a 1.6 mm tube and orifice. It was tested under a variety of air/fuel flow rates and gap sizes. The stable range is shown in Figure 7 and discussed in section 0. If it is desired to use the flow blurring injector in a meso scale power system then more work needs to be done on different designs and operating parameters to get a fully functional flow blurring nozzle. Papers on flow blurring injectors previously either did not involve combustion [6], [17] or used fuel in extremely small quantities [7]. Researcher's combusting fuels in meso scale applications needed a secondary air supply [18] and [10]. This research has shown that using a flow blurring injector for meso scale applications needs a secondary air supply or else a mechanism to slow down the mixture velocity at the nozzle exit. To summarize issues that arise when trying to use a FB injector in a closed chamber include:

I. If a meso scale combustion chamber is to be built around the FB injector then a secondary air stream is needed. One low flow rate stream is for the vaporization and the second stream provides the combustion air.
II. Alternatively, a flow stabilization mechanism can be used which slows down the mixture velocity to stable flame levels. The mixture velocity could be slowed down in a diffuser before entering the combustion chamber.
III. For the range of air flow that provides stable open flame combustion the FB injector does not operate in the injector's most efficient region.

Eventually the goal of this particular research is to build a meso scale combustion system used to power an energy conversion device such as a Stirling engine and/or Tesla turbine.

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