Part I 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

INTRODUCTION

This article introduces hydrocarbon combustion for meso scale power systems which provide power in the range of several hundred

Watts [1]. High power per unit mass is a very important requirement for these systems. Figure 1 shows some energy densities of high level power sources available today.

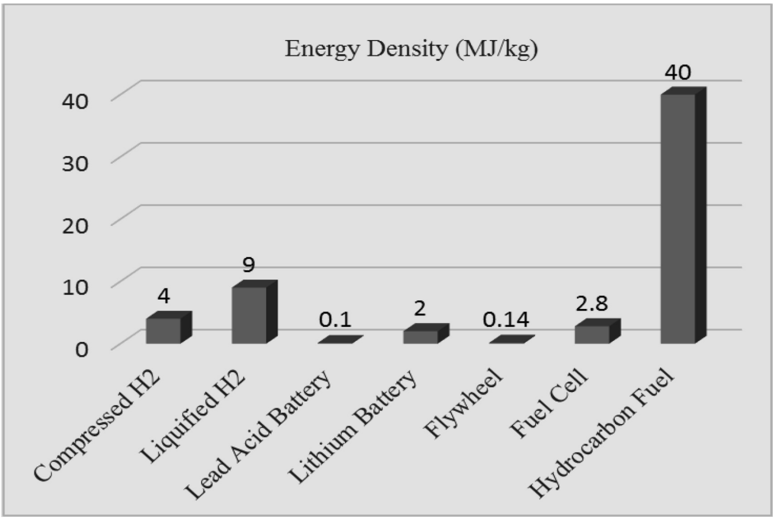


Figure 1: Energy Densities

Figure 1 is a little misleading since a battery or fuel cell is a complete power system, while hydrocarbon fuel needs to be converted to produce useful power. Nonetheless, it does show the potential of hydrocarbon fuels if suitable conversion devices existed.

Power from hydrocarbon fuel

A meso scale power system that falls within our scope of interest would deliver electric power in a range of 75W – 450W. This power system can be any machine that takes as its input the heat produced from hydrocarbon combustion and converts this heat into electric energy. Smaller scale engines are generally less efficient than larger ones due to larger losses from the larger surface to volume ratio. For example, taking an efficiency of 15% would require 500 – 3000W of heat via hydrocarbon combustion as shown in Figure 2. Assuming the device was portable and suitable for indoor use then there are many applications for such a device as listed in the abstract. The focus of this article is not the device that converts the heat to electricity but rather the method of heat production.

The primary source of this power will initially be gasoline but a flexible system should be capable of using any liquid fuel, including bio fuels. The combustion should be continuous and not intermittent, resulting in fewer pollutants than an automotive engine and thus be suitable for indoor use. In order to produce 500W – 3000W of useful heat, a mass flow rate of gasoline of 10 – 70 mg/sec (0.8 – 6 ml/min) is required.

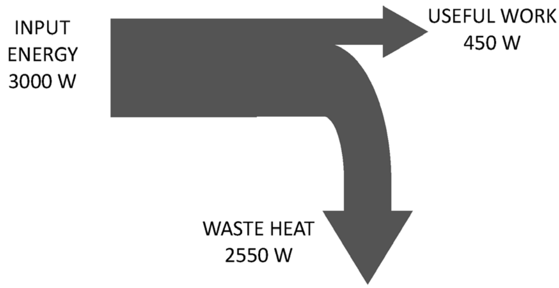


Figure 2: Energy Flow from a 15% efficient conversion device Literature review

The issue with hydrocarbon fuels is that combustion at low flow rates (< 10 ml/min) is difficult. Ultrasonic and electrostatic atomization devices have been developed and employed to vaporize liquid fuels with a relatively small drop size. However, the results achieved with such systems have been mixed and such systems are complex to build and operate. Kyritsis et al. [2] used electrostatic injectors which could vaporize at low flow rates but they are cumbersome since they require high electric fields and are not ideally suited for portable applications. In addition the droplet size in an electrospray increases with increasing fuel flow rate which severely limits the turn-down ratio of the injector. A solution to this problem is to have many electrosprays in parallel to give the correct droplet size and flow rate. This technique is called multiplexing and adds to the complexity of the system. Gomez et al. [3], implemented a multiplexed electrospray-catalytic combustor-heat recuperator system with a Stirling engine to produce 42.4 W of electric power at fuel to electric efficiency of 22%.

Whelan et al. [4] modeled injectors, such as those used in automotive engines. They typically work at high pressures and relatively high flow rates. Figure 3 shows the gasoline flow rate for a Bosch injector for a GDI vehicle. The flow rate in Figure 3 is approximately 1600 ml/min and flows for 4 milli-seconds at a supply pressure of 10MPa. These pressures and flow rates are two orders of magnitude higher than required for meso scale systems.

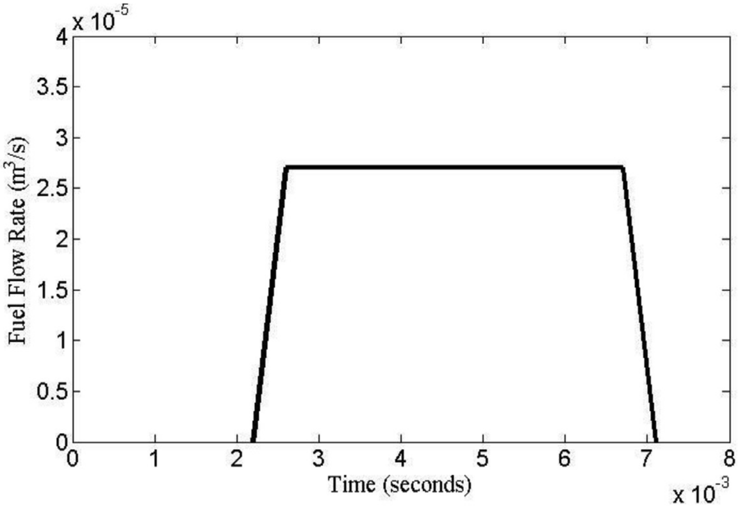


Figure 3: Fuel Flow in Automotive Injector (from [4])

In Internal Combustion (IC) engines, fuel injector efficiencies are still limited by the size of the drops that form the injector spray. For example, the spray/atomization characteristics of today's fuel injectors are still insufficient to allow for the use of low vapor pressure fuels, such as kerosene. Methane combustion is easier to accomplish than gasoline since there is no vaporization requirement. Sahota et al. [5] designed a backward facing step meso combustor that ran on methane air mixtures. The flame stability limits were broadened significantly by the use of active swirl.

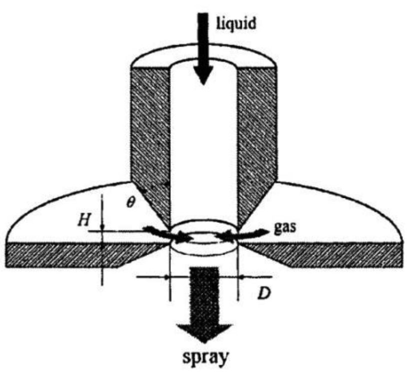


Figure 4: Fuel atomizer of Alfonso Ganan-Calvo [6]

A flow blurring injector which promises complete vaporization at low flow rates has been developed by Alfonso Ganan-Calvo [6]. The structure of the nozzle is shown in Figure 4. Liquid fuel is passed through an inner tube, at the exit it mixes with air flow before both exit an orifice together. The vaporization works by setting up a recirculation region inside a capillary tube which causes the fuel to breakup into small droplets. The nature of the air and fuel mixing causes the fuel to break up into small droplets creating five to fifty times more fuel surface area than a plain jet air-blast atomizer. He derived a parameter ψ which is the distance of the tube to the nozzle exit, H divided by the tube diameter, D. Flow blurring is supposed to occur so long as, $\psi = H/D \leq 0.25$. The flow rate reported was 20 ml/min and the droplet diameters ranged from 0.4 – 90μm.

Vijaykant et al. [7] has independently verified the functioning of this injector and has built a small combustion system around this technology. They used kerosene as the fuel as it is the most difficult to vaporize. Their reported power densities ranged from 30 – 90MW/m^3 with no coking or soot issues. In another paper Vijaykant et al. [8] presents a specific meso scale combustor design that uses kerosene. Data was only presented for one fuel flow rate, 11mg/sec, but the results indicated that the fuel was combusted cleanly and efficiently. Jiang and Taylor [9] used time-resolved Particle Image Velocimetry (PIV) to measure the mean diameter of glycerol emitted from the FB injector. They discovered fine streaks and droplets with thicknesses less than 40μm at the immediate exit.

A dual fuel nozzle, based on the flow blurring concept, capable of supplying either methane or liquid fuel is presented in [10]. The goal was to use methane combustion to provide heat feedback which allows glycerol to be combusted. The heat feedback lowers glycerol's kinematic viscosity and until its own combustion provides this heat. Secondary combustion air is swirled around the flow blurring nozzle. The volume flow rate of the secondary air is six times that of the atomizing air. Carlos Fernandez-Pello [11] provides a nice summary on the state of the art of micro power generation using micro combustion. There are even non-combustion related used for this injector. It was used as a nebulizer for analyzing samples with an inductively coupled plasma optical emission spectrometer in Orozco et al. [12] and Pereira et al. [13].

Problem Statement

An issue that arises concerns flame stability. The nozzle exit diameters as reported in the literature have varied between 0.5 – 1.5mm.

Assuming that all of the combustion air also flows through this nozzle the exit velocity gets to be quite large as seen in Figure 5. For 2000W heat input and an (fuel-air) equivalence ratio* $\lambda = 1.0$ the exit velocity of the air fuel mixture is greater than 70 m/s. The stability of combustion as these speeds is a concern.

The purpose of this work is to quantify the limits of the combustion reaction. It is one thing to say that complete vaporization of a liquid has occurred but that does not mean combustion is possible. Under what circumstances does flame lift off occur and at what equivalence ratio does it occur. This information will be of help to designers of flow blurring nozzles in designing for stable combustion.

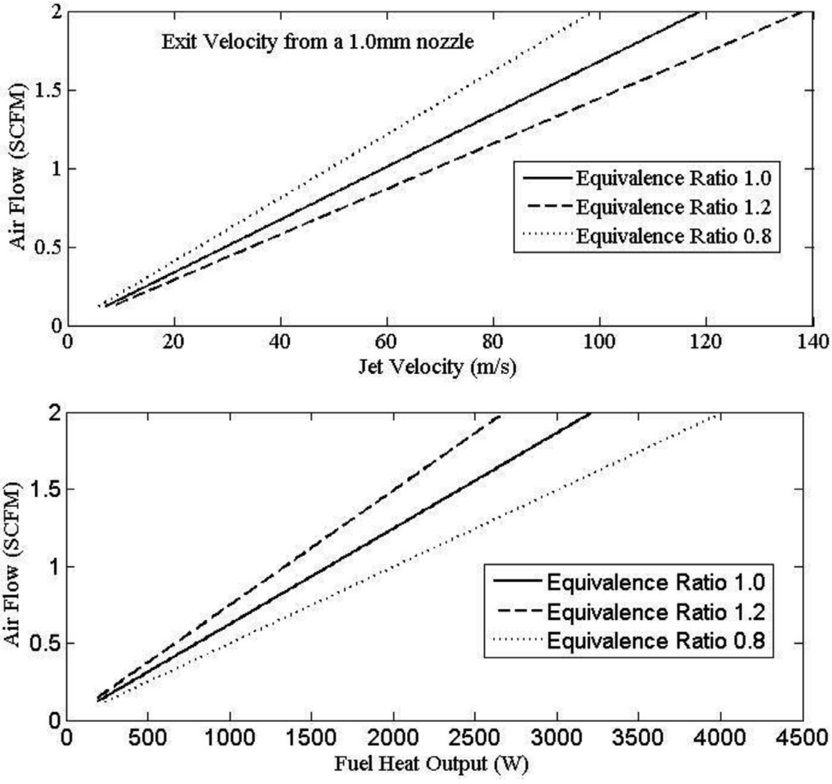


Figure 5: Air Flow v Exit Nozzle Velocity (a) and Air flow v Fuel Heat Output (b) for different equivalence ratios and a nozzle diameter of 1mm.

**The fuel–air equivalence ratio of a system is defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio.*

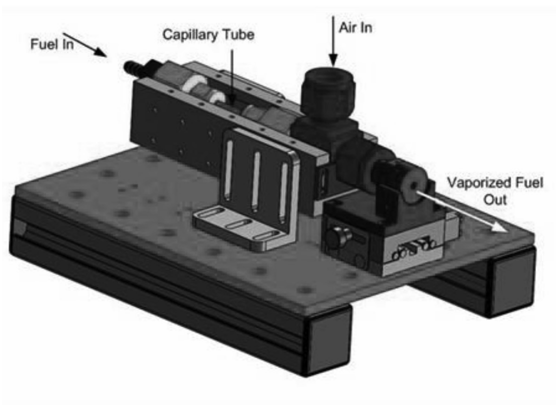
An important parameter controlling the combustion behavior of fuel is the laminar burning velocity (S_L). A flame is reported to be stable when there is a balance between the reactants velocity and the laminar burning velocity. When an imbalance between both velocities occurs, phenomena such as blowoff and flashback appear. When using in high flow rate, if the laminar burning velocity is lower than the speed of the incoming unburned reactants, the flame may detach from the burner (known as blowoff) [14]. A low laminar burning velocity means that small combustible mixture flow rates are necessary to achieve stability. In this case, a flame would blow off when the turbulent flame speed is everywhere less than the local flow velocity, $S_T < U_{REF,}$ where S_T denotes the turbulent flame speed. It is difficult to measure local flame speeds. Griebel et al. [15] reported stable turbulent flames at a bulk velocity between 30 – 60m/s. They measured turbulent flame speeds between 1.1 – 2.25 m/s. However this was for high pressure and temperature mixtures of methane.

Ganan-Calvo [16] in his seminal paper used a Gas to Liquid Ratio = $\frac{\dot{m}_{air}}{\dot{m}_{liquid}} = 10$, with water flowing at 20ml/min. Both water and ethanol were used as the liquid but nothing was combusted. Benjamin et al. [17] used a flow blurring injector with an airflow of 40 standard liters per minute, water flow of 50 ml/min and a nozzle diameter of 1.5mm which gave an approximate mixture velocity of 1.5 m/s. The mass flow rate of the liquid in this case is very high, almost the same as the air mass flow rate. Again there was no combustion here either. Sadasivuni et al. [8] used an air flow rate of 420 g/hr with kerosene which when coupled to their nozzle diameter (0.9 mm) approximately yields a mixture exit velocity of 25 m/s. This mixture then enters a relatively wide (1 cm) porous medium combustion chamber where it actually combusts at a much lower velocity. Jiang at al. [18] used a 1.5mm nozzle. They ran glycerol at 11.3 ml/min and a rich equivalence ratio of 0.77. They ensured complete combustion by having a secondary air flow located around the FB nozzle. It should be noted that Sadasivuni et al. and Jiang et al. were the only groups using fuel and having an actual combustion reaction.

Table 1 gives a summary of the previous research on this topic. ALR stands for the air to liquid ratio. For this project it is desired to have an air/liquid (fuel) ratio greater than 16 (stoichiometric) and a maximum fuel flow rate of magnitude 10ml/min.

Table 1: Summary of Previous Research

Researchers	Nozzle Type	Combustion (Yes/No)	Fuel Flow Rate (ml/min)	Air/Liquid Ratio
Sadasivuni et al. [8]	Flow Blurring	Yes	0.3	16 < ALR < 21
Kyritsis et al. [19]	Electrostatic	Yes	0.23	5 < ALR < 11
Ganan-Calvo [16]	Flow Blurring	No	20	0.5 < ALR < 90
Benjamin et al. [17]	Flow Blurring	No	50	1 < ALR < 4
Nguyen et al. [20]	Air Blast	No	0.6	0.25 < ALR < 1.5
Jiang et al. [18]	Flow Blurring	Yes	11.3	ALR < 3 (Secondary Air Added)
This Project	Flow Blurring	Yes	10	1 < ALR < 4



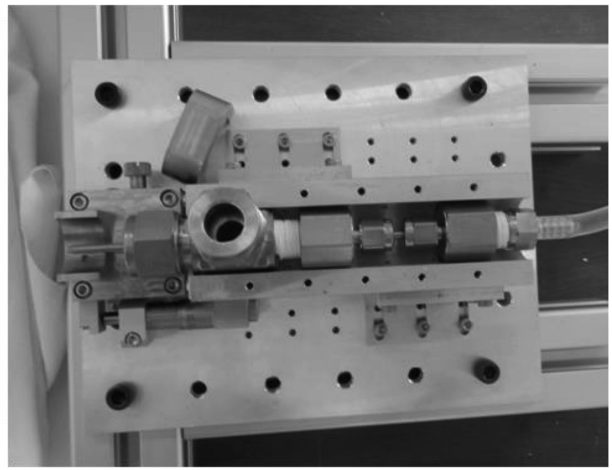


Figure 6: Fuel Vaporization System in Development

MATERIALS AND METHODS

A system, presented in Figure 6, was built at CMU to verify the combustibility of hydrocarbon fuel in a flow blurring injector.

To power an energy conversion device with 500W – 3000W of heat requires roughly between 10 – 70 mg/s of gasoline. Assuming an equivalence ratio of 1.2 is used (20% excess air) which gives an airflow range in between 0.4 – 2.4 SCFM. An Omega acrylic rotameter with a range from 0 - 20 SCFM was purchased. The compressor used for the air supply was a 4kW BOGE compressor capable of supplying 700 l/min at 1000kPa.

The nozzle head assembly contains the fuel vaporizer and the ability to control the gap height, H using a micrometer table. An XCRS40 Linear X-stage, with a travel distance of +/- 6.5mm and a resolution of 10 μm was used to mount the nozzle head. A 1.6mm inner diameter, stainless tube was used to deliver the fuel. The nozzle exit diameter was designed to be the same diameter as the fuel delivery tube, 1.6mm.

Experimental Setup

The initial test plan was to map out the range of the nozzle's usability. The parameter ψ will be set to the value of 0.25, since $D = 1.6mm$ this means that $H = 400\ \mu m$. Gasoline and air will be piped through to give the flow blurring pattern. If successful then the gasoline should burn in a clean stable manner. Although the exact droplet diameter size is not measured direct therefore clean combustion is a subjective term. It was proposed to map out the regions of air flow, fuel flow and ψ where the nozzle is most effective.

To be continued: The second part of this article will be published in the next issue of the *DG&AE Journal*, Vol. 32, No. 1.