The Design Process for a Closed Combustion Chamber Flow Blurring Nozzle

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ABSTRACT

This research outlines a process whereby a flow blurring nozzle is optimized for use in a meso-scale combustion chamber. Flow blurring is defined as the generation of small turbulence scales in a liquid from a singular back-flow pattern of a gas. Flow blurring nozzles are beginning to be adapted in many technical applications, from emission spectrometry of heavy metals in biodiesel, vaporization of high viscosity fuels to meso-scale combustion applications. This nozzle can vaporize liquids at low flow rates efficiently and inexpensively. It uses an air stream to break up the liquid but it operates in a novel flow blurring regime differentiating it from a regular air blast atomizer. There are two issues with using this nozzle for combustion applications. The first is that the air used to vaporize the hydrocarbon in the flow blurring nozzle is insufficient to burn all the hydrocarbon and it is difficult to increase this air supply. The second issue is that the vaporized mixture at the exit of the flow blurring nozzle has a relatively high velocity. The mixture velocity must be decelerated to enable stable combustion without blowoff. This article outlines the design process for solving both these issues. In total, five design iterations were implemented before a satisfactory final design was achieved.

Keywords: Flow blurring nozzle, Stable combustion, Meso scale combustion system, Nozzle design

INTRODUCTION

The goal of this research was to design a nozzle to combust meso-scale quantities of liquid hydrocarbon in a closed combustion system. A meso-scale device is a device of dimension between 1 mm - 10 cm and a power output between 10 W and 1 kW, Agrawal and Sadasivuni [1]. There is a large market potential for power sources within this range, Derek Dunn-Rankin [2]. Moran and Pongvuthithum [3] describe some applications for power systems on this scale. A meso-scale power device with an assumed conversion efficiency of 15% would require a heat source between 1 kW - 4 kW. If regular gasoline, with an energy density of 45 MJ/kg, was selected as the heat source then a continuous volume flow rate of 2 - 8 ml/min is required.

This article describes the design iteration process for a fuel vaporizer capable of atomizing gasoline at these meso-scale flow rates. The vaporizer also has to be capable of delivering sufficient combustion air for the fuel. Sufficient air in this case, is set at 20% excess air over stoichiometric, $\lambda = 1.2$. In the final design, if less air is desired it is easy to reduce the air supply. It will be shown that the reverse is not true, increasing the air supply is difficult. A final design was arrived at, after five iterations. Given this iterative process it was felt that this article would be easier to follow if the designs were presented sequentially, immediately followed by their results.

Atomization

Hede et al. [4] gives a through explanation on two fluid atomization and the industrial processes that use it. There are a variety of atomization technologies but at low liquid flow rates, on the order of milli-liters per minute, standard atomizers are less effective. One way around this is to pulse the flow rate over a small time period as is done in automotive fuel injectors, Nyugen and Rhodes [5]. This is not applicable for applications requiring a steady flow rate. Another method is to use a high electric field to charge and breakup the droplets, Kyritsis et al. [6]. This method requires expensive equipment, is not suited for portable applications and is optimal only at a single fuel flow rate.

Ganan-Calvo [7] presents a nozzle design for low flow rates that satisfies the above issues. It is called a flow blurring (FB) nozzle and is shown in Figure 1. Its operation has been described in many prior publications [3], [1], [8], [9] and therefore only a brief explanation of its operation will follow.

It operates by having a bifurcation back flow pattern which is triggered by a single geometrical parameter, $\Psi = H/D$. Where H is the distance between the liquid exit and the orifice exit and D is the diameter

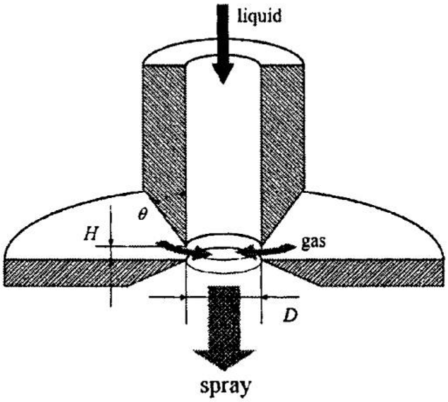

Figure 1: Fuel atomizer of Alfonso Ganan-Calvo [7]

through which the liquid flows. If $\Psi < 0.25$ then the flow changes from a plain jet to a bifurcation or flow blurring pattern.

Meso Scale Applications

There are a variety of applications in the meso-scale area. There are also a myriad of uses within meso-scale which use or which may potentially use a flow blurring nozzle. New applications are being continuously developed as flow blurring diffuses into the mainstream. Some of these applications are described below:

Kroo and Kunz [10] summarized the scaling issues that arose with the initial development of a very small-scale rotorcraft or mesicopters. The size of the craft ranged from 2 to 15 cm, thus falling within the meso-scale regime. They argued that such devices could be used for carrying sensors for atmospheric research or planetary exploration. The initial devices were electrically powered and involved challenges in aerodynamics, control and manufacturing. Many interesting scaling issues arise as one shrinks a flight vehicle down to this size. The biggest challenge for the systems was the power supply. Lithium batteries were too bulky and heavy but an alternative power source was unavailable.

Epstein and Senturia [11] briefly introduced some potential applications for 'micromachines' as they called them. These applications ranged from electrostatic silicon micromotors to applications in micropositioning of optics, miniature heat exchangers, small fluidic devices and meso-scale chemical reaction chambers.

Kaisare and Vlachos [12] gave a very detailed review on microcombustion and microburners and their applications. They define mesoscale devices as any system whose characteristic dimension is greater than ~1 mm. The advantages of meso-scale systems include fast heat and mass transfer, higher efficiency, faster transients which make them suited for portable applications where startup and shutdown are common. The challenges at this scale include thermal and radical quenching, instability, thermal management, and high thermal stresses. In particular they studied applications for potentially powering portable electronics.

Dunn-Rankine et al. [2] gave a thorough review of future personal power systems. These are systems such as communication devices and mobile robotic devices which operate autonomously for hours. They aid individuals so their power sources need to have a similar operational range as humans, which means energy densities between 1.8 - 18 MJ/kg and power density requirements from 10 to 1000 W/kg. These power sources are within the meso-scale. They describe a huge variety of potential power sources, thermochemical, biological and electrochemical and outline the challenges of scaling these to the meso-scale.

Gomez et al. [13] used a free piston Stirling engine to achieve meso-scale electric power. The energy density of the power system, 3.6 - 7.2 MJ/kg fell within the range suggested by Dunn-Rankine [2] for portable individual power systems.

Shirsat and Gupta [14] examined meso-scale combustion inside heat-recirculating Swiss-Roll combustors. An overview of meso-scale power systems for use in both propulsion and electric power generation was given.

All of these studies have a common theme. They are all interested in utilizing the high energy densities of hydrocarbon fuels at the meso-scale. The main difficulty in thermal applications with scaling down is combustion instability. This article hopes to contribute by providing a potential solution to this challenge.

Project Goals

Take a reasonably large meso-scale power system outputting power between 150 - 600W. Assuming a thermodynamic efficiency of 15% and using a heat source from liquid hydrocarbon combustion implies a heat output between 1 - 4kW. Therefore, the goal of this project is to design a flow blurring nozzle to completely combust a liquid hydrocarbon with a heat output of 1 - 4 kW with 20% excess air in a clean, stable manner. For gasoline (gasohol 91), this heat output corresponds to a flow rate between 2 - 8 ml/min. To combust this fuel in a closed system, an air-fuel equivalence ratio, of 1.2 was selected. The actual air/fuel flow rates for gasoline and air is shown in Figure 2 for three different equivalence ratios.

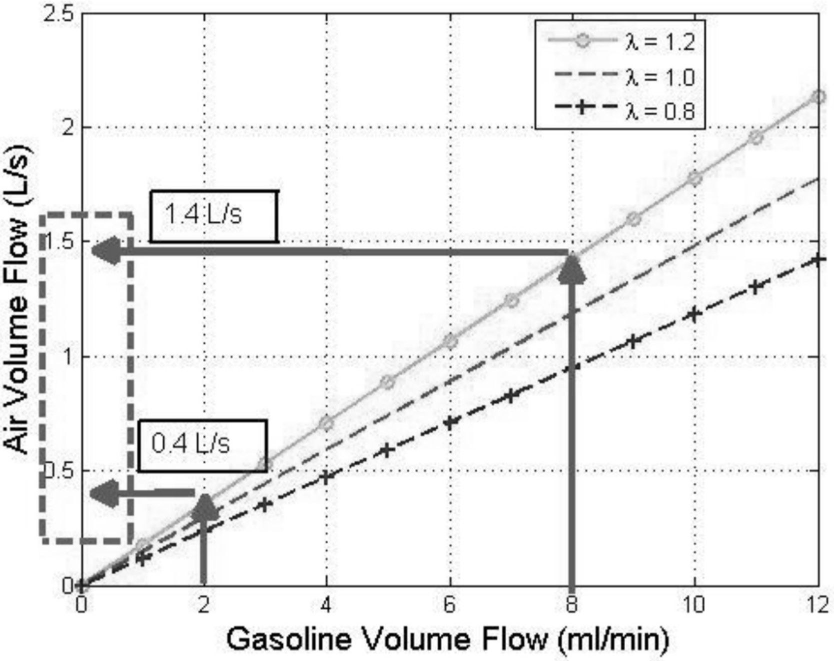

Figure 2. Air/Gasoline flow rates for different stoichiometric ratios

EXPERIMENTAL SETUP

The basic outline of the combustion system is shown in Figure 3. The air is supplied via a BOGE air compressor. It has a maximum air flow rate of 700 L/min and a maximum pressure of 1 MPa. The air is then filtered and dried before entering the nozzle.

The fuel delivery system was a screw pump. This had the advantages of providing the required flow rate with small flow fluctuation, any fuel type is allowed and the fuel delivery rate (1 - 50 ml/min) is independent of the air pressure inside the nozzle. However the disadvantage is that there is only a finite amount of fuel that can be delivered before the supply tube needed refilling. Together the fuel and air combine in the flow blurring nozzle and produce the vaporized droplet cloud. The distance 'H' in the flow blurring nozzle can be varied with an XCRS40 Linear X-stage, which has a travel distance of +/- 6.5 mm and a resolution of 10 μm. Two tube diameters, 'D' were used throughout these experiments, 1.6 mm and 0.87 mm.

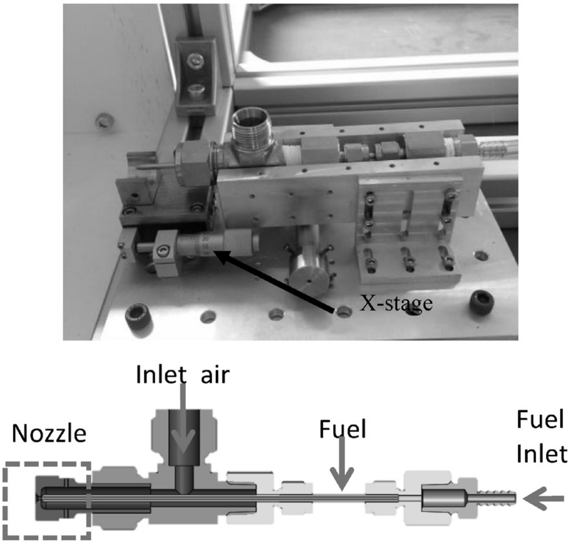

Figure 3: The nozzle head (a) finished component showing linear X-stage (b) Cross Section

First Nozzle Design

The first design attempted was the original flow blurring nozzle as shown in Figure 4. Allowing the fuel flow rate to vary between 2 - 8 ml/min gives a required airflow of 0.4 - 1.4 L/s, for a equivalence ratio of 1.2 as can be seen in Figure 2.

The range of parameter tested is shown in Table 1.

Results: First Nozzle Design

It was possible to get a flame with this nozzle design as shown in Figure 5. However the conditions under which a stable flame was found were very specific. Varying the parameter, did not have a significant impact. At the conditions in the picture the air/fuel ratio is

$$\frac{\dot{m}_{air}}{\dot{m}_{fuel}} = 1.2$$

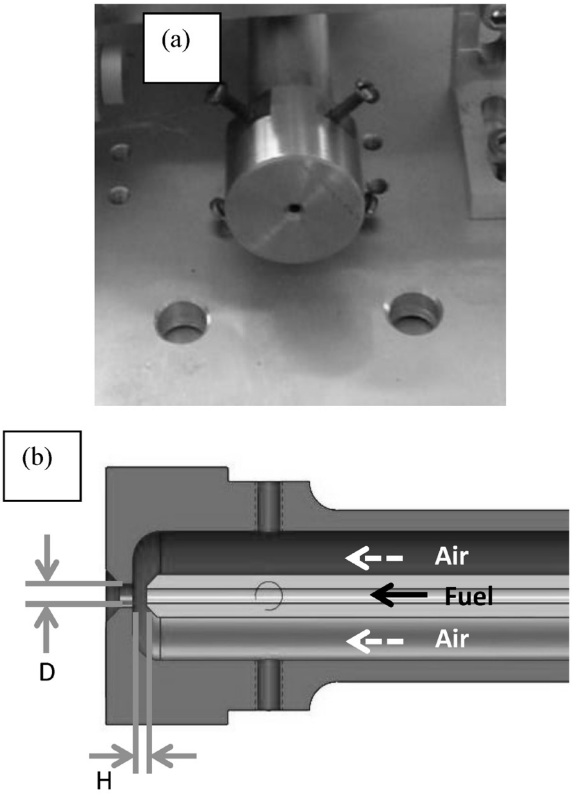

Figure 4: (a) The original flow blurring nozzle, (b) Cross sectional view inside nozzle

Table 1: Test conditions for Nozzle Design #1

Ψ (-)	Fuel flow rate (ml/min)	Max. Air flow rate (L/s)	Tube Diameter (mm)
0.06 – 0.62	4	0.09	1.6
0.06 – 0.62	6	0.14	1.6
0.06 – 0.62	8	0.14	1.6

which means the equivalence ratio is, $\lambda = 0.08$. Increasing the equivalence ratio by increasing the air supply leads to an unstable condition known as blow off. This is where the mixture velocity is higher than the laminar flame speed. The range of equivalence ratios where a somewhat stable flame could be observed was narrow. Figure 7 shows a graph of the stability range for this nozzle. The red straight lines correspond to the stability limits, where a flame was observed. There is no data at 2 ml/min because a stable flame did not exist there at any air flow.

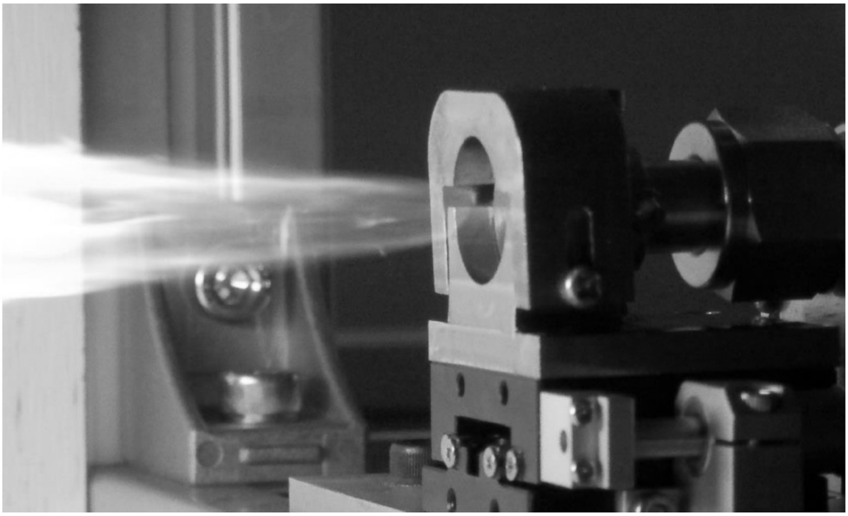

Figure 5: Plain nozzle with a 1.6 mm diameter exit orifice, H = 700 μm., Fuel flow rate 8 mL/min, air flow rate 0.095 L/s

This air fuel equivalence ratio, shown in Figure 6 is not remotely close the desired goal of λ = 1.2. If used in a closed system the flame would immediately extinguish, from a lack of sufficient oxygen. The flame is orange in color implying a rich mixture, see Figure 5.

Second Nozzle Design

No amount of tweaking the basic design could ever produce a stable flame with sufficiently high air flow. The mixture velocities are too fast. The diameters of the nozzle and fuel supply tube could be increased but this reduces the effectiveness of the flow blurring nozzle since a larger diameter produces larger droplets. Smaller droplets are produced with smaller diameters.

The approach taken is shown in Figure 7. The air flow is divided into two. A primary air supply whose function is to produce the droplets and a secondary air supply whose function is to provide sufficient air for combustion. The secondary air is added 2 cm downstream from the FB nozzle head through 6, 3 mm sized holes around the pipe circumference.

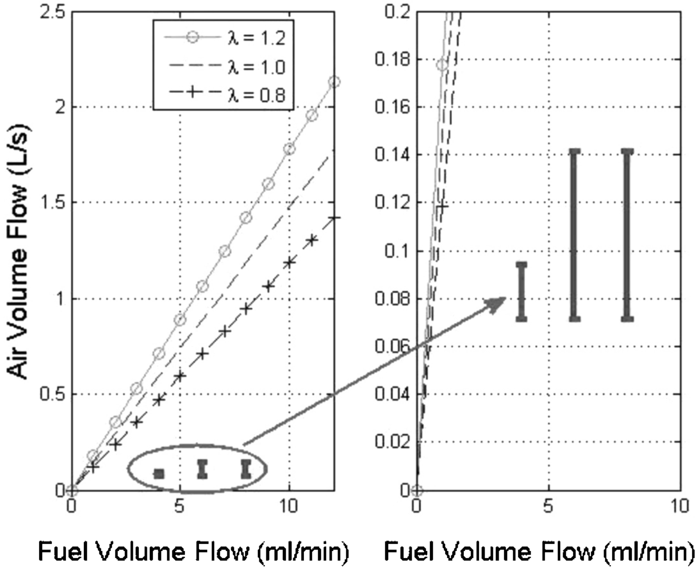

Figure 6: Stability range for the first nozzle design

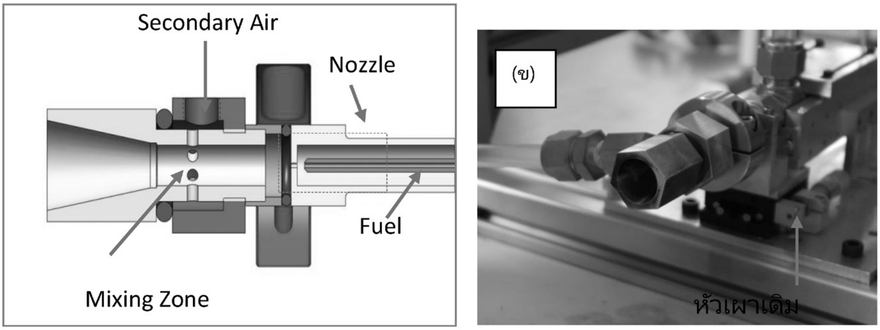

Figure 7: The second nozzle design (a) cross section (b) completed design

The conditions tested with this nozzle are shown in Table 2.

Table 2: Test conditions for Nozzle Design #2

Ψ (-)	Fuel flow rate (mL/min)	Primary air (L/s)	Max. Secondary air (L/s)
0.12 – 0.62	4	0.07	0.26
0.12 – 0.62	6	0.09	0.62
0.12 – 0.62	8	0.14	0.66

Results: Second Nozzle Design

Figure 8 shows a typical flame from the second nozzle. It is a lot bluer in color than the flame from the first nozzle. This is a sign of a less rich mixture. At its trailing edge the color still contains a lot of yellow/orange. Fuel flow rates of 4, 6 and 8 ml/min were tested. This time, two orifice diameters were used, 0.87 mm and 1.6 mm with slightly bluer color flames observed from the 0.87 mm orifice. Again varying the parameter did not have a significant impact.

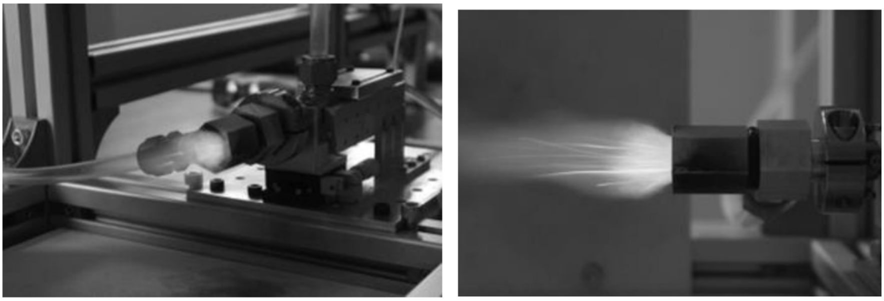

Figure 8: Flame from nozzle #2 with an orifice diameter of 0.87 mm, H = 300 μm., Fuel flow rate 6 mL/min, Primary Air 0.118 L/s, Secondary air 0.47 L/s

The flames from the second nozzle were more stable and didn't require a flameholder under the conditions specified. A flameholder is a device such as a lighter or candle needed to constantly anchor the flame. However there still was insufficient air (Primary + Secondary Air) getting to the nozzle head as shown in Figure 9. The red lines show the conditions under which combustion was observed. At a fuel flow of 6 ml/min the maximum equivalence ratio achievable is 0.8. If enough air was supplied for a equivalence ratio of 1.0, the flame would extinguish from blowoff.

Another issue was that large droplets were seen in the flame, see Figure 8. At large secondary air flow rates, the gasoline in liquid form was observed flowing out of the nozzle. One explanation for this is that the secondary air was striking the vapor cloud at a 90° angle and causing the atomized gasoline to condense on the walls of the nozzle as shown in Figure 10. This effect was more noticeable the higher the secondary air, > 0.47 L/s.

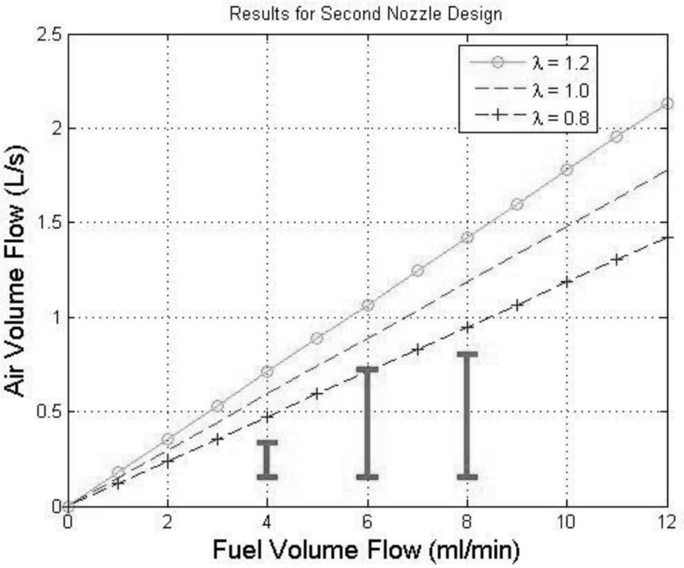

Figure 9: Stability range for the second nozzle design

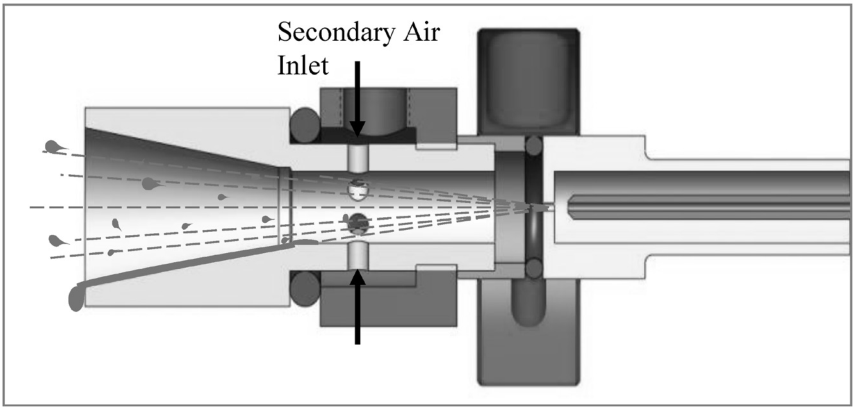

Figure 10: Issues with the second nozzle design, coalescence

Third Nozzle Design

To reduce the impact from the secondary air, it was decided to introduce the secondary air at an inclination. This was carried out in the third nozzle design. This had the secondary air entering at a 10° angle to the horizontal to an angular arrangement of 6, 3mm holes. Through this mixing arrangement it was hoped that this would prevent the vapor cloud from impacting the nozzle walls. The design of this nozzle can be seen in Figure 11.

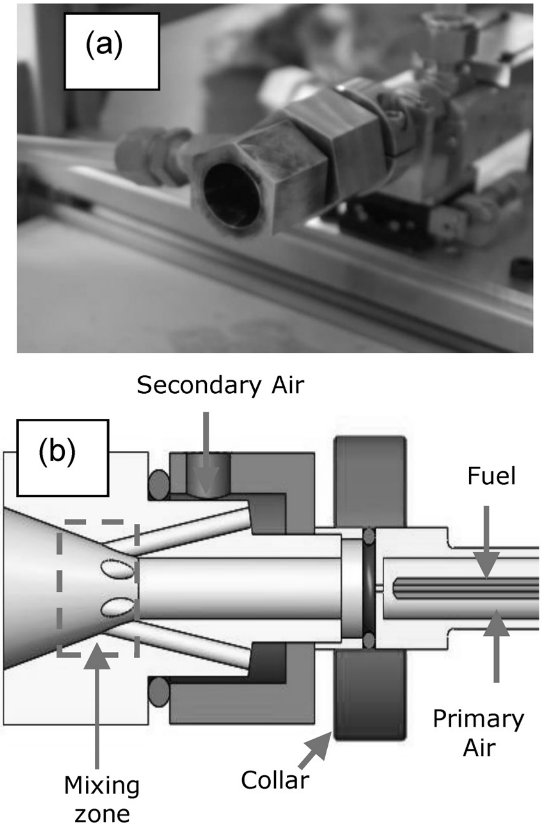

Figure 11. The third design (a) actual design (b) cross

Results: Third Nozzle Design

Figure 12 shows a typical flame from this nozzle design. It looks very similar to that of the second design. There was noticeably less large droplets or gasoline leakage. However the stability range of this flame was worse than the second design, as shown in Figure 13. The airflow on the y-axis is the total airflow from both the primary and secondary air supplies. The initial flame color is blue and then due to insufficient air it becomes more yellow/orange in color. Again if the total airflow was set at a stoichiometric ratio of 1.0, the flame would extinguish. Another issue in addition to the insufficient total air was that the flame was unbalanced. It did not occupy the entire nozzle exit area. There was also the some liquid coalescence and agglomeration problem, although not as severe as the second nozzle.

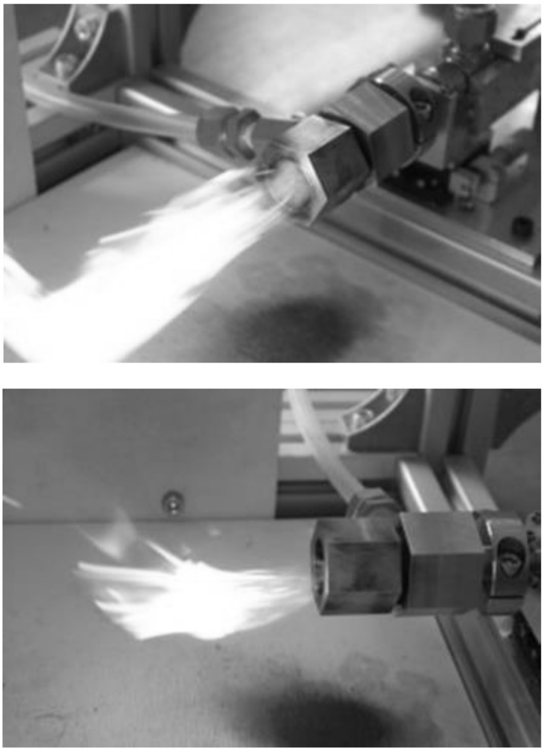

Figure 12: Flame from third nozzle with an orifice diameter of 0.87 mm, H = 300 μm, Fuel flow rate 6 mL/min, Primary air 0.118 L/s, Secondary air 0.31 L/s

Fourth Nozzle Design

The secondary airflow interfered too much with the vapor plume. One option was to make the nozzle very long so as to allow time for the streams to thoroughly mix. However a large nozzle does not fit with the small meso scale design desired. As an alternative it was decided to feed the secondary air from behind the plume as shown in Figure 14. The air did not flow through discrete holes but through an annulus arranged at a 30° angle to the horizontal. The intention was that the angular uniformity of the secondary air will have less negative effects over the plume.

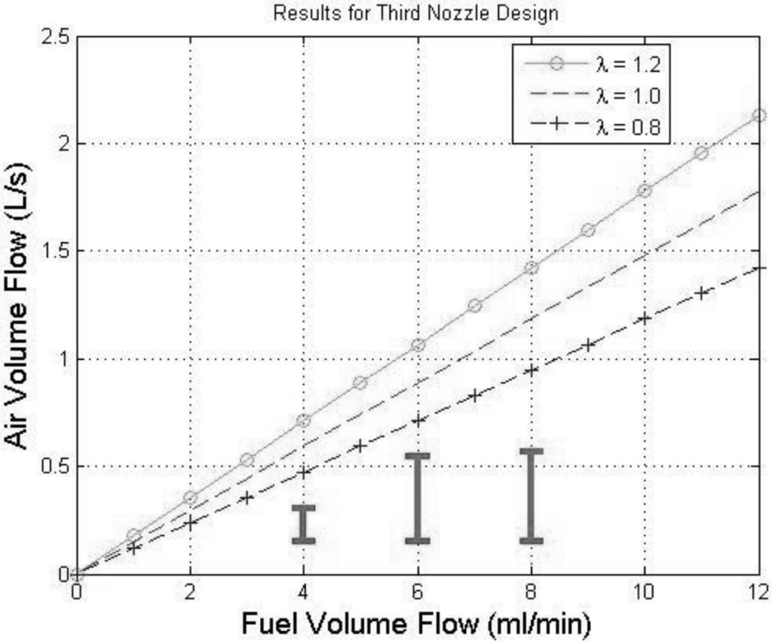

Figure 13: Stability range for the third nozzle design

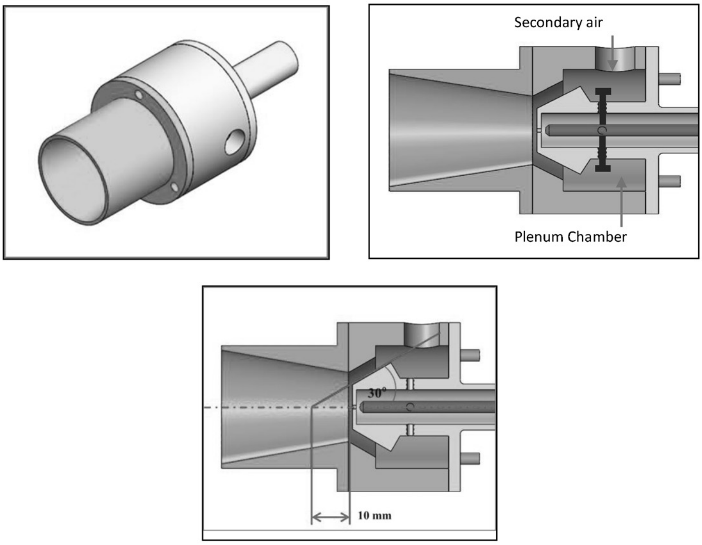

Figure 14: The fourth nozzle design

Results: Fourth Nozzle Design

A typical flame under the tests conditions is shown in Figure 15. The flame is very yellow, it does not expand to cover the entire diffuser exit area but exits as a jet. The exit divergent nozzle is not influencing the flow. Increasing the airflow led to an unstable flame. Its stability range is worse than that of the second and third nozzles as shown in Figure 16. One positive outcome was the droplet coalescing problem was less apparent.

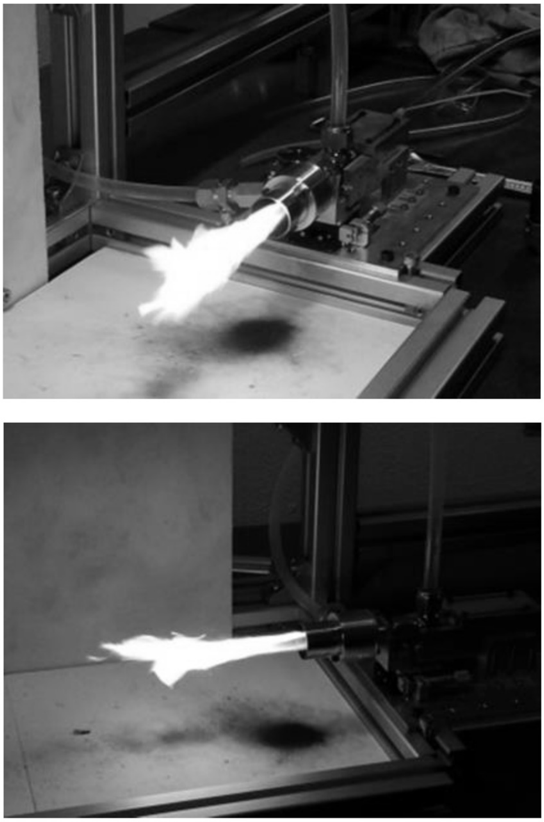

Figure 15: Flame from the fourth nozzle with an orifice diameter of 0.87 mm, H = 600 μm, Fuel flow rate 6 mL/min, Primary air less than 0.05 L/s, Secondary air 0.15 L/s

Fifth Nozzle Design

The exit diffuser in the fourth design was ineffective. The mixture exit velocity was not reduced in the diffuser. Only a small portion of the

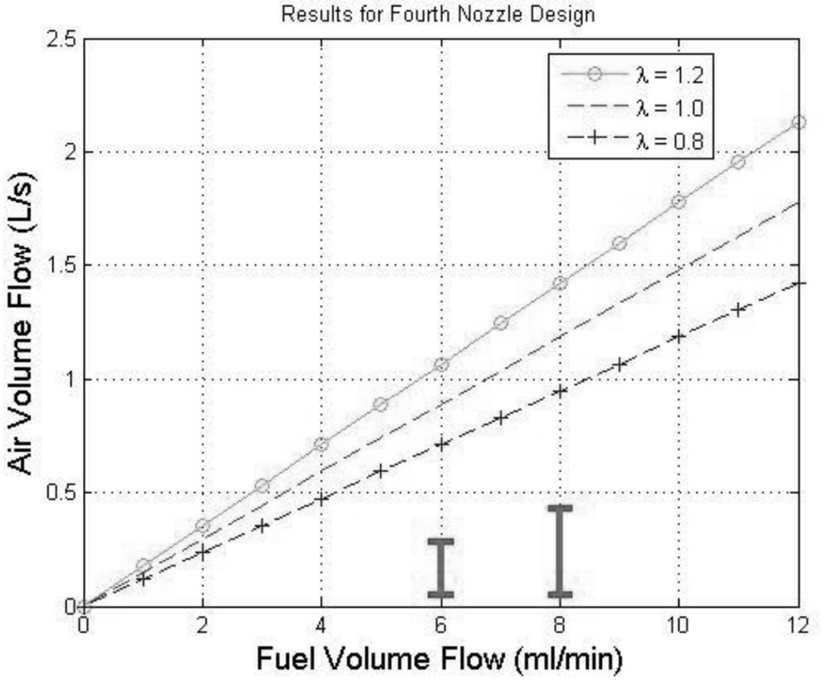

Figure 16: Stability range for the fourth nozzle design

final exit area was used. The fifth iteration, shown in Figure 17, is not so much a separate design as an extension of the fourth. An insert is put in the path of the vapor flow. The goal is to force the flow over a wider area. The intention is to decrease the exit velocity.

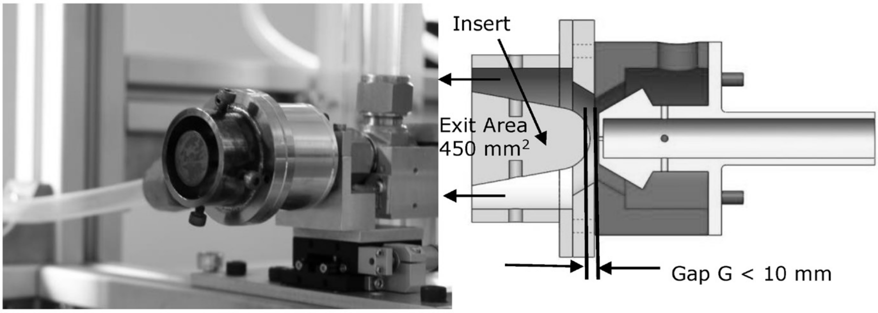

Figure 17. The fifth nozzle design

Results: Fifth Nozzle Design

A typical flame from nozzle 5 under the listed conditions is shown in Figure 18. As can be seen it is a blue flame with no orange present. There is more than sufficient air to burn the available fuel. The total air supplied is equal to or greater than the 20% excess air requirement. This is the only nozzle that satisfies this criteria. Its stability range, along with the rest of the nozzles, is shown in Figure 19. All fuel flow rates, 2, 4, 6, 8 ml/min are the same for each nozzle but on this plot they have been offset so that they are visible. As can be seen the final nozzle functioned as intended with a very stable continuous blue flame across all flow rates.

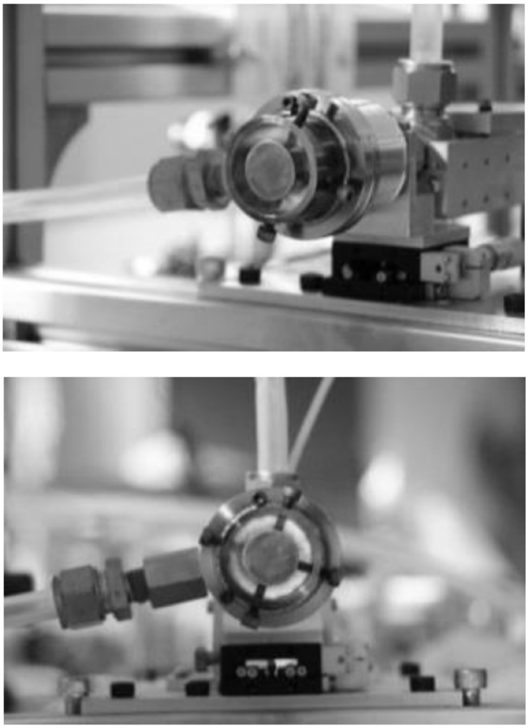

Figure 18. Flame from the fifth nozzle design with an orifice diameter of 0.87 mm, H = 300 μm, Fuel flow rate 4 mL/min, Primary air 0.118 L/s, Secondary air 0.63 L/s

Another way to present the data for each nozzle is shown in Figure 20. The x-axis shows the heat output from the gasoline supply from 4 to 8 mL/min which corresponds to a range of 2,000 W to 4,000 W. Nozzle

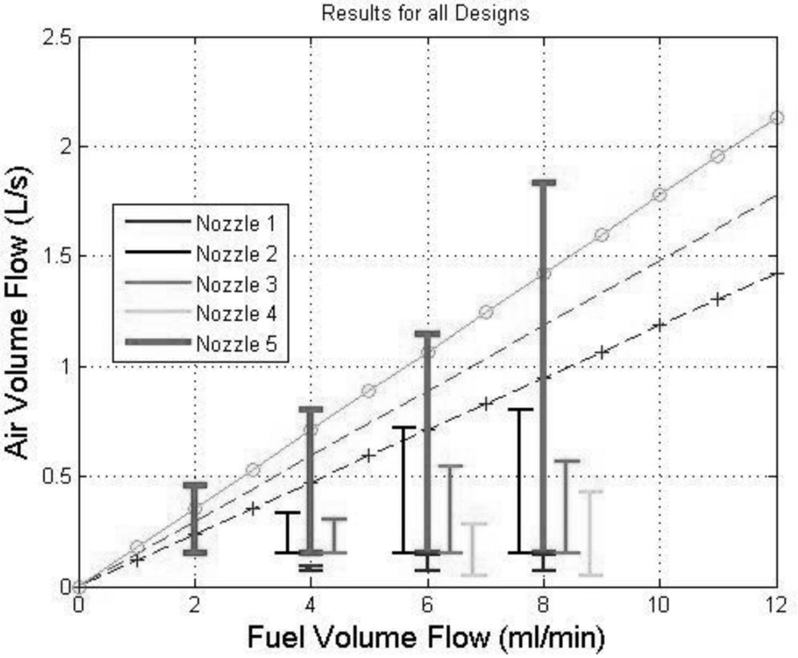

Figure 19: Stability range for the all nozzle designs

1 is not shown as it was never stable over a reasonable time period. Nozzles 2 and 3 could only burn fuel from 4 - 8 ml/min. The air fuel ratio is plotted on the y-axis. Horizontal lines representing stoichiometric air flow rates and 120% of stoichiometric are shown for reference. Under the graph is a picture of each nozzle design. Nozzle 5 gave the best performance by far and satisfied the initial design requirements.

DISCUSSION

This article presents a design process for a flow blurring nozzle used for combustion. The original flow blurring nozzles produces vaporized droplets efficiently using an air stream to break up the liquid. For complete combustion enough air must be supplied. This increases the mixture exit velocity from the nozzle and causes the flame to extinguish. To supply sufficient air, the mixture exit velocity must be reduced or else a secondary source of air introduced. The latter was chosen for this research.

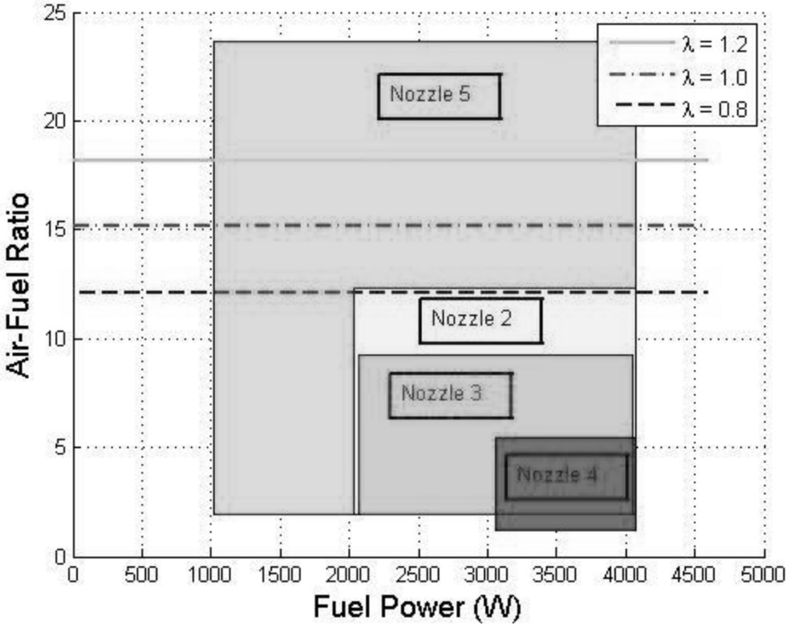

Figure 20: Flame stability range for each nozzle

Counting the original flow blurring nozzle, the design cycle took a total of five design iterations. This article describes each design and the thought process behind it. The flame stability range for each design was presented and the limitations of each design was used to try and improve the next iteration. The challenge was to combine all the flow streams, such that a stable flame was obtained at stoichiometric ratios sufficient for a closed system.

The second design introduced a secondary air stream which increased the overall stability range. However, this increased range was not broad enough and there were issues with droplet agglomeration and coalescence. The third and fourth design iterations both tried to alter the angle and structure which the secondary air was mixed with the primary streams. Their stability range was less than the second nozzle, however the agglomeration was resolved.

The fifth and final design used an insert to force the streams out into the diffuser area. The forced the mixture velocity down and ended providing the stability range required. For all gasoline flow rates, which ranged from 1 - 4 kW, equivalence ration of 1.2 were obtained. The flames were blue in color with no signs of orange or the streaks from liquid fuel.

Two different diameter pipes were used to supply the gasoline, 1.6 mm and 0.87 mm. The exit nozzle orifice was always matched with the diameter of the fuel supply pipe. At lower fuel flow rates, 2 ml/min, the smaller diameter had a more stable flame. At fuel flow rates above 4 ml/min there was little to distinguish the flames for either diameter.

A clean, stable flame was also obtained for values of the parameter, $\Psi = H/D$, between $0.2 \leq \Psi < 0.6$. A difference in the flame was noticed for $\Psi > 0.6$. The exit plume contained large droplets and was very streaky with lots of pockets of orange/yellow flames. Ψ was kept at a value of 0.35 for the majority of the tests presented here.

The next step of for this research is to design and build a meso scale combustion chamber. The final nozzle design presented here will be the basis for this combustion chamber. It will introduce the fuel in vaporized form and the combustion air. The combustion chamber will act as a power source for a small Stirling engine. Using gasoline as the power source has significant portability advantages over gaseous fossil fuel sources.

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References

[1] V. Sadasivuni and A.K. Agrawal, "A novel meso-scale combustion system for operation with liquid fuels," *Proceedings of the Combustion Institute,* vol. 32, pp. 3155-3162, 2009.

[2] D. Dunn-Rankin, M. Leal Elisangela and D.C. Walther, "Personal power systems," *Progress in Energy and Combustion Science,* vol. 31, pp. 422 - 465, 2005.

[3] J. Moran and R. Pongvuthithum, "Combustion of Gasoline for Meso Scale Combustion Applications," *Distributed Generation and Alternative Energy,* vol. 31, no. 4, pp. 71 - 79, September 2016.

[4] P.D. Hede, P. Bach and A.D. Jensen, "Two-fluid spray atomisation and pneumatic nozzles for fluidbed coating/agglomeration purposes: A review," *Chemical Engineering Science,* vol. 63, pp. 3821 - 3842, 2008.

[5] I. Whelan, D. Timoney and W. Smith, "Advanced GDI Injector Control with Extended Dynamic Range," in *SAE 2013 World Congress & Exhibition*, Detroit, 2013.

[6] D.C. Kyritsis, I. Guerrero-Arias, S. Roychoudhury and A. Gomez, "Mesoscale Power Generation by a Catalytic Combustor using Electrosprayed Liquid Hydrocarbons," *Proceedings of the Combustion Institute,* vol. 29, pp. 965-972, 2002.

[7] A. Ganan-Calvo, "Enhanced liquid atomization: From flow focussing to flow-blurring," vol. 86, no. 214101, 2005.

[8] L. Jiang and A.K. Agrawal, "Combustion of straight glycerol with/without methane using a fuel-flexible, low-emissions burner," *Fuel,* vol. 136, pp. 177 - 184, 2014.

[9] B.M. Simmons, H.V. Panchasara and A.K. Afrawal, "A comparison of air-blast and flow blurring injectors using phase doppler particle analyzer technique," in *Proceedings of ASME Turbo Expo*, Orlando, 2009.

[10] I. Kroo and P. Kunz, "Mesoscale flight and miniature rotorcraft development, in Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications," in *of Progress in Astronautics and Aeronautics*, Salt Lake City, 2001.

[11] A. Epstein and S.D. Senturia, "Macro Power from Micro Machinery," *Science,* vol. 276, no. 5316, pp. 1211-1212, 1997.

[12] N.S. Kaisare and D.G. Vlachos, "A review on microcombustion: Fundamentals, devices and applications," *Progress in Energy and Combustion Science,* vol. 38, no. 3, pp. 321-359, 2012.

[13] G. Alessandro, J.B. Jonathan, R. Subir, C. Bruno and H. James, "From jet fuel to electric power using a mesoscale, efficient Stirling cycle," *Proceedings of the Combustion Institute,* vol. 31, p. 3251-3259, 2007.

[14] V. Shirsa and A. Gupta, "A review of progress in heat recirculating meso-scale combustors," *Applied Energy,* vol. 88, no. 12, p. 4294-4309, 2011.

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