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Estimating the Mass Mean Diameter of Droplets in a Combustible Mixture

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Abstract - 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. The use of a flow blurring injector shows promise. A flow blurring injector which vaporizes liquid hydrocarbons at low flow rates has been developed. It purports to produce gasoline droplets on the order of tens of microns. The issue considered in this paper is how to estimate this droplet size without the expensive equipment that is usually used in these situations. A model was built, based on experimentally measuring the air and fuel flow rates, which gave droplet diameters within an order of magnitude of the expected diameter.

Keywords: *Flow Blurring Injector, Gasoline Vaporization, Mass Mean Diameter*

I. INTRODUCTION

It may be possible to roughly estimate the mass mean diameter of a vapor cloud without using an expensive phase doppler particle analyzer. The limitations are that the vapor cloud must be combustible and the mass flow rates of the liquid and combustion gases must be measured.

A novel flow blurring nozzle was first proposed by Ganan-Calvo [1]. It could vaporize small quantities of liquid efficiently. Under certain conditions the flow blurring nozzle was found to be up to 10 times more efficient than plain jet air blast atomizers. A simple sketch of this nozzle is shown in Figure 1.

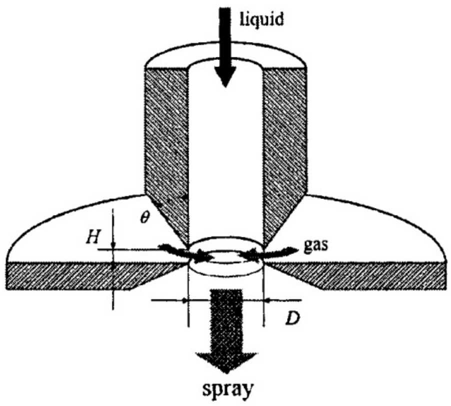

Figure 1: Fuel atomizer of Alfonso Ganan-Calvo [1]

It operates by having a bifurcation back flow pattern. This bifurcation 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 through which the liquid flows. If $\psi < 0.25$ then the flow changes from a plain jet to a bifurcation pattern. The nozzle's operation has been verified by several other researchers, Hede et al. [2] and Jiang et al. [3] Moran and Pongvuthithum [4] discuss the potential of this nozzle in meso scale applications.

The flow blurring nozzle design used by Moran and Pongvuthithum [4] is shown in Figure 2. There is a fuel supply and two sources of air, a primary air and a secondary air. The primary air is used to vaporize the fuel and constitutes between 10-20% of the overall air flow. The secondary air is provided for combustion purposes only. The secondary air is added in such a way as to aid the dispersion of the mixture by creating a pressure drop at the neck of the nozzle.

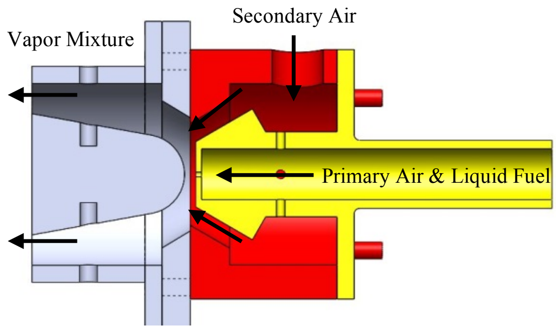

Figure 2: FB Nozzle Design for a Closed Combustion Chamber

The nozzle produces a clear blue gasoline flame as shown in Figure 3. The gasoline flow rate was 8 ml/min with primary and secondary flow rates of 0.25 and 1.33 SCFM respectively. The goal of this paper is to estimate the average droplet size of the vaporized gasoline. The premise is as follows. In order for stable combustion the flame velocity remains constant. If there are droplets in the mixture, extra air must be added to compensate for the lower mixture velocity versus when there are no droplets in the mixture. If this extra air mass flow is known an estimate can be made of the average mixture droplet diameter, as explained further below.

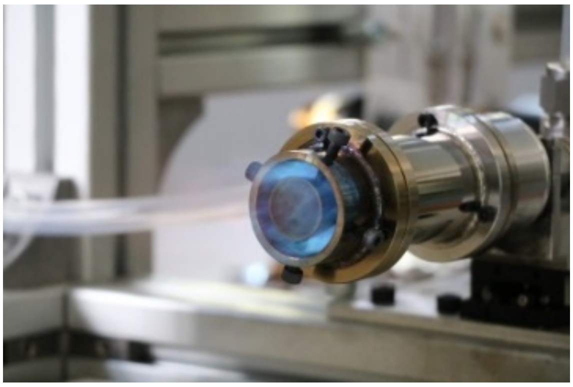

Figure 3: Flame from FB nozzle with the fuel flow rate 8 mL/min, Primary air 0.25 SCFM, Secondary air 1.33 SCFM

A cylindrical tube section was built. The nozzle was placed at one end and the mixture was combusted at the other end. It is a modular assembly with different length increments from 5 cm to 35 cm in multiples of 5 as shown in Figure 4.

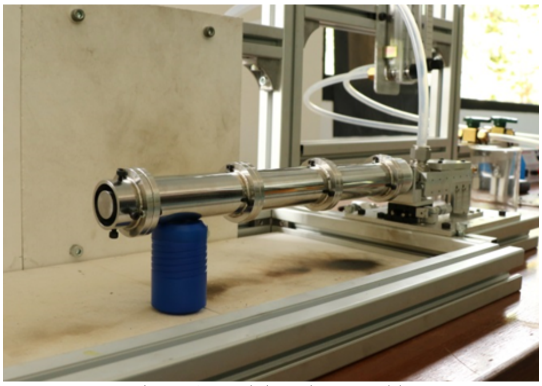

Figure 4: Modular tube assembly

The liquid particles and combustion air travel down the cylinder length and exits as shown in Figure 5. Orange streaks can be seen in the flame, in Figure 5, which indicates that there is insufficient air for complete combustion.

Figure 5: Flame from FB nozzle at a tube length of 35 cm, Fuel flow rate 6 mL/min, Primary air 0.25 SCFM, Secondary air 1 SCFM

II. METHOD

Droplet diameters have been measured previously [5]. The goal here is to estimate the mean droplet mass diameter without expensive particle analyzers. The mean mass diameter (MMD) is defined by:

$$d_{\bar{m}} = \left[\frac{\sum n_i d_i^3}{N_T}\right]^{\frac{1}{3}} \qquad \text{Equation 1}$$

Where n_i is the number of droplets of diameter d_i and N_T is the total number of droplets. Having a lower average droplet size the better for combustion. Any nozzle or vaporizer's unique geometry may influence the droplet size in an unknown manner. Previous droplets size models, from experimental data for flow blurring nozzles from others may not be applicable especially if different fluids were used.

In order to estimate the mass mean diameter the combustion cylinder with lengths of 20 cm and 35 cm were used. The 35 cm nozzle length is shown in Figure 4.

The following assumptions constitute the model. The primary air flow is assumed to be the dominant factor in controlling the MMD. Initially the fuel flow rate was fixed. The primary air was set deliberately high, resulting in a low average diameter and a clean combustion flame. A clean flame in this context means there were no visible particles or streaks and the flame color was bright blue. All air and fuel flows were recorded at this ideal setting and an average mixture velocity at the exit can be calculated.

The next step was to lower the primary air flow rate so that the MMD became larger. A larger particle size emerging from the nozzle resulted in large liquid drops seen in the flame, see Figure 6(a). These drops combusted as orange streaks. For the flame to be stable, the secondary air had to be increased by far more than the initial decrease in primary air. It was assumed that this extra air was needed to keep the flame velocity constant and stable. Since some of the fuel is now in liquid form, the result is to decrease the mixture velocity and cause flame instability. If the rate of evaporation is calculated then the minimum droplet size can also be estimated. The percentage of liquid in the mixture can also be estimated from the increase in secondary air. Finally, assuming a normal droplet distribution and combining these pieces of information yields an estimate for the mean droplet diameter.

At the first step, the conditions where a perfect flame is observable, were recorded as shown in Figure 6 (b). The average mixture exit velocity, (v_{avg}) was calculated.

The mass flow rate is given by:

$$\dot{m}_{total} = \rho_{avg} V_{avg} A_{exit} \qquad \text{Equation 2}$$

And:

$$\dot{m}_{total} = \dot{m}_{air} + \dot{m}_{fuel} \qquad \text{Equation 3}$$

Rearranging to give:

$$V_{avg} = \frac{\dot{m}_{air} + \dot{m}_{fuel}}{\rho_{avg} A_{exit}} \qquad \text{Equation 4}$$

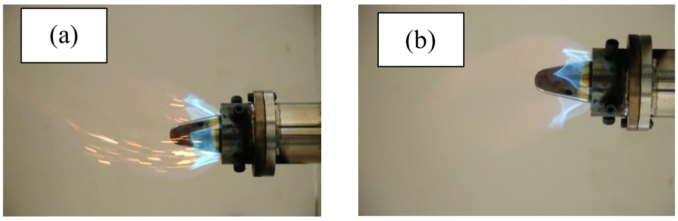

Figure 6: (a) The test results show that the droplet combustion conditions, (b) the conditions when the droplets evaporate completely

The known parameters in Equation 4 are $\dot{m}_{air}, \dot{m}_{fuel}$ and A_{exit}. There are two unknowns, V_{avg} and ρ_{avg}.

Assuming that all of the fuel is fully vaporized, a reasonable assumption given the flame contains no streaks. The average mixture density is given by Equation 5:

$$\rho_{avg} = \rho_{air}(y_{air}) + \rho_{fuel,vapor}(y_{fuel}) \qquad \text{Equation 5}$$

$$\rho_{air} = \frac{P_{total}}{RT}$$

$$P_{tot} = P_{gauge} + P_{atm}$$

$$R_{air} = \frac{8314}{Mw}$$

$$y_{air} = \frac{n_{air}}{n_{air} + n_{fuel}}$$

$$n_{air} = \frac{\dot{m}}{Mw}$$

$$n_{fuel} = \frac{\dot{m}}{Mw}$$

$$\rho_{fuel,vap} = \frac{P_{fuel,vap}}{RT}$$

$$P_{fuel,vap} = y_{fuel} \times P_{tot}$$

$$R_{fuel} = \frac{8314}{Mw}$$

$$y_{fuel} = \frac{n_{fuel}}{n_{air} + n_{fuel}}$$

The average mixture density, ρ_{avg}, is estimated from Equation 5 and with that the average velocity is obtained using Equation 4.

The next step is to lower the primary air flow so that the flame now contains liquid droplets as shown in Figure 6 (a). In order to stabilize the flame the secondary air is increased. The assumption now made is that the average velocity remains constant between both flames. In the second case, since there is liquid in the exhaust the average density is given by:

$$\bar{\rho}_{mix} = \rho_{air}(y_{air}) + \rho_{fuel,vapor}(y_{fuel,vapor}) + \rho_{fuel,liquid}(y_{fuel,liquid}) \qquad \text{Equation 6}$$

And from mass conservation:

$$y_{air} + y_{fuel,vapor} + y_{fuel,liquid} = 1 \qquad \text{Equation 7}$$

Since the average velocity is assumed the same as the first case this average density is also given by:

$$\bar{\rho}_{mix} = \frac{\dot{m}_{air} + \dot{m}_{fuel}}{V_{avg}A_{exit}} \qquad \text{Equation 8}$$

Looking at the variables in these equations, assuming the $\rho_{fuel.vapor}$ is the same as before, $\bar{\rho}_{mix}, \rho_{air}, y_{air}, \rho_{fuel,liquid}$ are all known. There are only two unknowns, $y_{fuel,vapor}, y_{fuel,liquid}$ which can be solved from Equation 6 and Equation 7.

The fraction of the fuel that is in vapor form can be found from:

$$\%\text{vapor} = \frac{y_{fuel,vapor}}{y_{fuel,vapor} + y_{fuel,liquid}} \qquad \text{Equation 9}$$

The next step is to estimate how long it takes a droplet to evaporate in the pipe. Taking a droplet of size, D_o its time to evaporate is given by:

$$\tau = \frac{\rho_l D_o^2}{8\bar{\rho}_{mix} D_{12}(m_{1,s} - m_{1,e})} \qquad \text{Equation 10}$$

Where:

- τ is the lifetime of the droplet
- ρ_l is the density of the liquid drop
- D_o is the starting diameter of the droplet
- D_{12} is the diffusivity coefficient, $7\text{x}10^{-7} m^2/s$ from Al Zubaidy et al. [6]
- $\bar{\rho}_{mix}$ is the mixture density outside the droplet
- $m_{1,s}$ is the mass fraction of gasoline vapor at the droplet surface, assumed to be saturated
- $m_{1,e}$ is the mass fraction of gasoline vapor away from the droplet surface, assumed to be zero

It is assumed the particles exiting the nozzle travel down the length of pipe at an average velocity, V_{avg}. Knowing the pipe length, L_{pipe} it is possible to estimate the length of time each droplet spends in the pipe, $t_{drop} = \frac{L_{pipe}}{V_{avg}}$. This assumes the droplet moves at the average velocity and ignores any droplet accelerations. If a droplet vaporizes before reaching the end of the pipe it is reasonable to say that $\tau_{drop} < t_{drop}$. If the droplet is large and does not fully vaporize before reaching the pipe end then $\tau_{drop} > t_{drop}$. If $\tau_{drop} = t_{drop}$ then the droplet size is just so that it vaporizes right at the exit point. Let the diameter where this happens be known as D_{evap}.

Knowing D_{evap} and the % vapor, a model for estimating the particle size begins to come together as shown in Figure 7. Let $\mu_{droplet}$ be the average droplet diameter from the nozzle. This is the parameter of interest in this analysis. Unfortunately it is not possible to calculate $\mu_{droplet}$ from the model without another data point. Another D_{evap} and the % vapor are needed. In order to get this the fuel flow rate is increased slightly, by 1 ml/min and the process repeated.

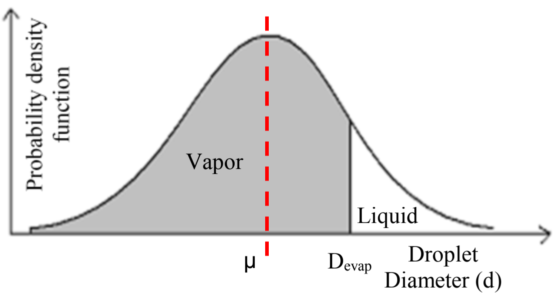

Figure 7: The Normal Distribution

Now, data is available from two sets of tests and this can estimate the MMD of oil droplets ($\mu_{droplet}$) and the standard deviation ($\sigma_{droplet}$). A slight adjustment needs to be made to the normal distribution since the % vapor gives the vapor volume divided by the total volume. Volume is proportional to the cubed of diameter, so we can adjust the normal distribution for volume as shown in Equation 11. c is the % vapor amd has only 2 unknowns, $\mu_{droplet}, \sigma_{droplet}$. From the second experiment we get a different c but assuming the same $\mu_{droplet}, \sigma_{droplet}$. Therefore will 2 equations and 2 unknowns it can be solved numerically.

$$c = \int_0^{\frac{\pi}{6}d_{evap}^3} \frac{1}{3\sigma\sqrt{2\pi}} e^{-\frac{\left(\left(vol\frac{6}{\pi}\right)^{\frac{1}{3}} - \mu\right)^2}{2\sigma^2}} (vol)^{-2/3} \left(\frac{6}{\pi}\right)^{\frac{-1}{3}} d \qquad \text{Equation 11}$$

III. RESULTS

Using all of the assumptions that have been described throughout this paper the average droplet size can be solved numerically for different Air/Fuel ratios as shown in Table *1*.

TABLE 1: AVERAGE DROPLET DIAMETER MODEL RESULTS, PIPE LENGTH 35 CM

A/F Ratio	Average Fuel flow rate (ml/min)	MMD (μm)
2.31	4.5	12.50
1.89	5.5	26.68
1.60	6.5	10.90
1.39	7.5	11.50
1.23	8.5	11.12
1.10	9.5	11.70
0.99	10.5	11.11

Figure 8 shows the average diameter for various air/fuel ratios from our model and compared with the original model from Calvo [1]. This original model was developed for water droplets only and so its applicability to gasoline is unknown. However, it shows both models are on the same order of magnitude which isn't bad considering all the assumptions. In figure 8 the air/fuel ratio is the ratio of primary air to the fuel flow since it is only the primary air that controls diameter size. Most of the droplets fall into the range of 10.9 – 12.5µm. At the air fuel ratio of 2 there appears to be an outlier of a droplet size of 27µm which is larger than the other estimates. Why this is so is still unclear.

The above procedure was repeated again for a pipe of length 20cm. The MMD results are shown in **Error! Reference source not found.** with the model compared to the original in Figure 9.

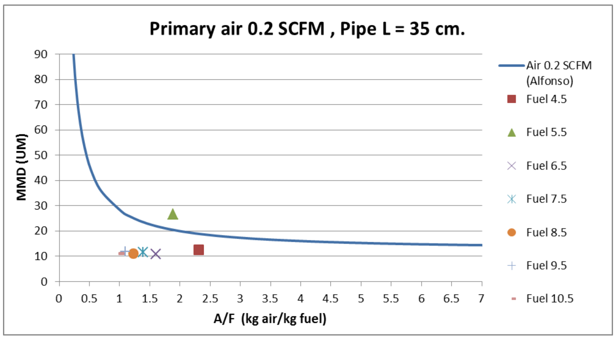

Figure 8: Model of average droplet diameter (MMD) for a 35 cm pipe length, compared with the original model from Calvo [1]

TABLE 3: AVERAGE DROPLET DIAMETER MODEL RESULTS, PIPE LENGTH 20 CM

A/F Ratio	Average Fuel flow rate (ml/min)	MMD (μm)
2.31	4.5	7.17
1.89	5.5	28.83
1.60	6.5	7.34
1.39	7.5	7.60
1.23	8.5	17.16
1.10	9.5	6.94

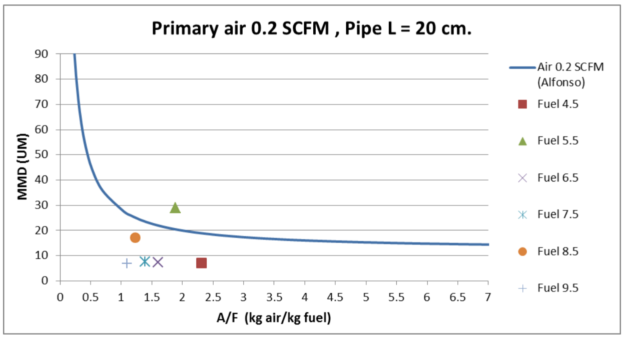

Figure 9: Model of average droplet diameter (MMD) for a 20 cm pipe length, compared with the original model from *Calvo* [1]

IV. DISCUSSION

Figure 9 shows the MMD estimate and compares it to that of Calvo [1]. The results are within the same order of magnitude but beyond that it is hard to say. It was not possible to run the test at low fuel rates which would have given a more clearly view because of flame stability issues. The model from Calvo was built from tests performed with water and ethanol only. This may also explain the difference as gasoline was used in these experiments. It cannot be claimed that the data follows the trend of the theoretical curve. The range of Air/Fuel ratios is not wide enough to compare trends. It would be interesting to see what this model gave for A/F ratios of 0.5 and below. Without such data it is just possible to say that it gives the correct order of magnitude for the mass mean diameter for all flow rates.

V. CONCLUSIONS

This paper presents a rough model to estimate the average droplet size in a combustible vapor cloud. There were many assumptions that went into the calculations:

- The droplets were assumed to be normally distributed
- The droplet velocity was assumed to be constant as it traveled down the tube
- The combustion velocity at the exit was assumed to remain constant regardless of the average size of the droplets

These assumptions may not be completely valid. The experimental conditions for this method to work are that:

- The mixture must be combustible
- The air and fuel flow rates must be measured
- Two fuel flow rates are measures and the model gives an average mean diameter between both flow rates

Despite these limitations, the results show a order of magnitude agreement with the model for the droplet distribution obtained from PDPA measurements. The experimental Air to Fuel ratio was limited to between 1 – 2.5 which is quite a narrow range. It would be more optimal to have the capability of extending this range but it was not possible at this time. At the extremes of this range, there was either too much or too little air for stable combustion. In the future it is hoped to be capable of extending this range and using that to increase the model accuracy.

VI. ACKNOWLEDGEMENTS

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