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Development of a 2-phase Flow Nozzle for Fine Droplet Generation

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Abstract

Fine sprays with droplet diameters (< 50 mm), are widely used in engineering applications, ranging from liquid pre-cooling in natural draft cooling towers to fuel injection for scramjet engines. Traditionally fine droplets are generated by passing high pressure liquid through small diameter nozzles. The downsides of this method are high energy consumption arising from pumping work and limited flow rates arising from the small nozzle exit areas.
A way to overcome these limitations is to use a 2-phase Flow Nozzle. Here, liquid is injected together with a small quantity of gas through the same nozzle. The interaction of the two fluid streams significantly enhances liquid jet break-up. This paper presents the design and commissioning of an experimental test set-up for 2-phase nozzle development and the results obtained from testing a prototype nozzle injecting hydrocarbon fuel and nitrogen. Results show that the nozzle can generate droplets below 100 mm at moderate operating pressures (5–10 bar), while maintaining flow rates comparable to those of high pressure single phase nozzles. In addition to proving the feasibility of the 2-phase nozzle concept, the experimental campaign has generated an extensive set of high speed videos, providing an insight into the liquid jet break-up process. These will be used in future computational fluid dynamic investigations.

Introduction & Background

Many industrial applications require liquid supplied in small droplets (e.g. fogging in gas turbine inlets, fuel injection for scramjet engines, atomisation) [1, 2]. Presently, the traditional way to ensure an efficient liquid break-up and achieve small droplet sizes (less than 50 µm) is to inject the liquid through small diameter nozzles at high pressures ($\Delta P > 100$ bar) [3]. However, these methods suffer from high energy consumption due to pumping work and limited flow rates arising from the small nozzle flow areas. An alternative approach for obtaining small droplets that overcomes these issues is to simultaneously inject gas and liquid through the same nozzle. Here the transfer of kinetic energy from the gas to the liquid causes the break-up and leads to an atomisation process. The underlying physics of the breakup was studied in detail by Varga et al. [4]. These types of nozzles are also known as gas-assisted or airblast/air-assisted atomisation nozzles [5].

This work presents a new test setup, development of a prototype two-phase flow nozzles, and a first set of experimental results. The results were obtained from from tests of the prototype nozzle operating with hydrocarbon fuel and nitrogen. The aim of the work is to develop a nozzle that can achieve atomisation levels similar to high pressure single phase-systems, but operating at comparatively low pressures (< 10 bar) with a low gas consumption.

The first part of this paper presents the design of the prototype nozzle. Next the test setup, measurement and data acquisition system, and nozzle test procedure are described. Finally data are presented from testing the 2-phase flow nozzle in the two configurations, once with a liquid core jet and once with a gas core jet. This data is indicative of the anticipated performance of 2-phase flow nozzles.

Nozzle Concept and Design

To facilitate testing, both with a liquid and gas core jet, the initial nozzle design was chosen to have equal flow areas for the nozzle core and the annulus. A drawing of the nozzle, together with a photograph of the completed product is shown in Fig. 1. The nozzle design incorporates two plenum chambers (Chamber 1 & 2) in the feed to the annular jet. These chambers, connected through a series of small diameter holes ensure uniformity of the gas or liquid being supplied to the outer annulus. The axial dimensions of both the circular core hole, $L2$, and the annular section, $L1$, were chosen such that fully developed and parallel flow was attained at the nozzle exit plane. A problem of the current design is the inability to maintain concentricity between the inner and outer part at the nozzle tip. Due to manufacturing tolerances, the annulus sees a circumferential variation in radial gap. This results in non symmetric flow patterns as evident from the results.

Experimental Set-up

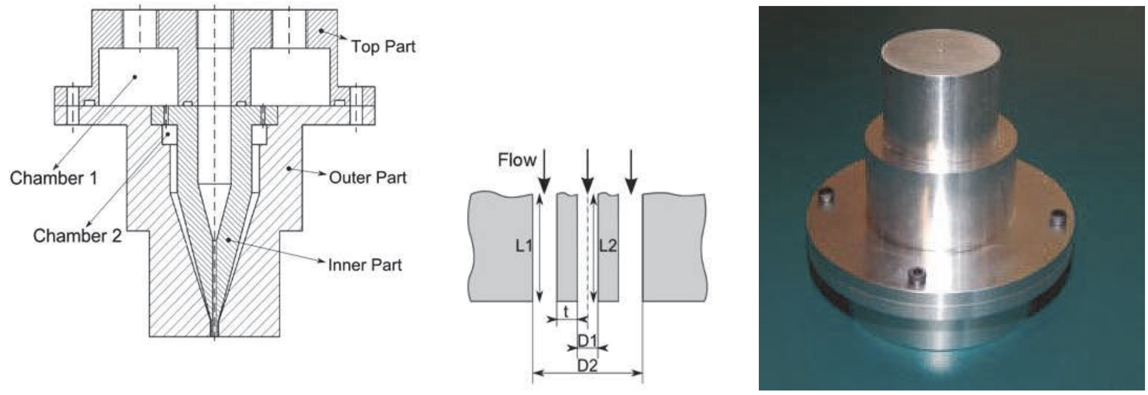
The experimental arrangement for the current study consists of three main components. The fuel and gas supply system used to control the flow through the injector, the measuring and data acquisition system used to measure supply pressures and flow rates, and the optical and high speed video system used to assess the nozzle flow.

Fuel and Gas Supply System

A schematic of the fuel and gas supply system is provided in Fig. 2. Lines filled with hydrocarbon fuel and gas are marked in grey and black respectively. The system operates on the principle of a single pressurised reservoir (*High Pressure Reservoir*), which contains gas and fuel separated through gravity. The *Regulator* connected to gas supply maintains a constant pressure in the reservoir. Having a single reservoir containing fuel and gas, ensures that the two test media are at the same pressure, and that the respective gas and fuel flow rates can be precisely controlled using the two needle valves *NV-1* and *NV-2*. The remaining components ensure safe operation and facilitate easy re-fueling between tests.

The key steps during a typical test are:

1. Set desired supply pressure with *Regulator*
2. Set restrictions for gas and fuel feed lines (needle valves *NV-1* and *NV-2*)
3. Open *High Speed Solenoid Valve* to pressurise the system; Gas and fuel flow starts
4. Wait for flow to stabilise (1 – 2 s)
5. Record data
6. Close solenoid valve; Test stops



(a) Drawing of nozzle (b) Close-up of nozzle tip (c) Nozzle prototype

Figure 1: 2-phase nozzle prototype used in current investigation. $D_1 = 1.0\,\mathrm{mm}$, $D_2 = 2.24\,\mathrm{mm}$, $t = 0.5\,\mathrm{mm}$, Core Area $= 0.785\,\mathrm{mm}^2$, Annulus Area $= 0.785\,\mathrm{mm}^2$

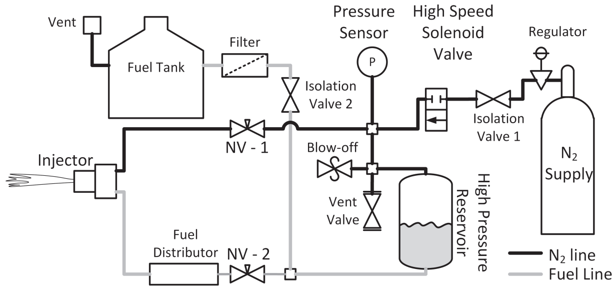


Figure 2: Fuel system schematic for 2-phase flow nozzle testing

	Pressure (bar)	Gas flow rate (%)	Liquid flow rate (%)
Random	0.017	n/a	n/a
Bias	0.186	5.0	0.5

Table 1: Measurement uncertainties for data acquisition system, based on full typical measurements

Control System and Data Acquisition

The test apparatus was controlled using a LabJack U6-Pro data acquisition system [6], used to control the solenoid valves, trigger the high speed camera, and to record data. The supply pressure in the high pressure reservoir was measured using a MPX5700AP piezoelectric pressure transducer. However, to characterise the nozzle, gas and liquid mass flow rate are of primary interest. To attain these, the assumption was made that the respective flow rates are only a function of components upstream of the nozzle exit. This allowed independent calibration curves of respective mass flow rate as a function of supply pressure and needle valve opening fraction (*NV-1* and *2*) to be created for both nozzle configurations. In the case of fuel flow, the calibration curve was generated by collecting the ejected liquid in a beaker and measuring the rate of change of mass using a PNX-2001 scale with an accuracy of $\pm 0.1\,\mathrm{g}$. For the gas, flow was allowed to stabilise and the *High Speed Solenoid Valve* was closed suddenly. Based on the rate of pressure decay immediately after the valve is closed and the gas volume inside the supply system, the rate of change of mass within the system and thus mass flow rate was calculated. During visualisation tests, the respective calibration curves were used to obtain gas and fuel mass flow rates based on reservoir pressure and needle valve opening fractions. The uncertainties for the various measurements, calculated in accordance with PTC 19.1 [7] are given in table 1.

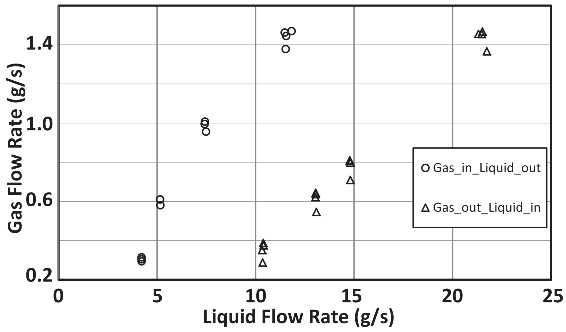


Figure 3: Combinations of gas and liquid mass flow rates tested for 2-phase flow nozzle. Config. A, Gas_in_Liquid_out; Config. B, Gas_out_Liquid_in

High Speed Video and Image Analysis

To characterise the flow exiting the nozzle the jet was visualised using a Z-type shadowgraph apparatus with 3-m-focal-length mirrors. By recording the jet with high speed video camera (Phantom v611; 15 kfps frame-rate) a clear picture of the jet break-up and the generated droplet sizes can be obtained.

These high speed videos and individual frames can be used directly for qualitative analysis of the overall performance. For quantitative performance analysis selected frames are automatically analysed using OpenCV [8] to determine droplet diameters and droplet velocities. After image pre-conditioning the blob detection function is used to identify individual droplets in each frame. Droplet size is determined by fitting circles with equivalent area to the blob objects and droplet velocity is estimated by tracking individual droplets frame-to-frame. This approach has been verified by analysing artificial images with known droplet size distributions and droplet velocities.

Results

In total over 100 tests were performed to characterise the performance of the 2-phase flow nozzle, covering two nozzle configurations (Gas_in_Liquid_out and Gas_out_Liquid_in), supply pressures ranging from 2.4 to 7.3 bar absolute, and a range of opening fractions for the gas needle valve, *NV-1*. The resulting combinations of gas and liquid mass flow rates, obtained for the two nozzle configurations are shown in Fig. 3. Here the increasing flows correspond to tests at increasing pressures. From these data it is evident that Config. A, Gas_in_Liquid_out, is more restrictive for the liquid flow. This can be explained by the lower hydraulic diameter of the annular hole ($D_H = 0.24\,\mathrm{mm}$) compared to the core hole ($D = 1\,\mathrm{mm}$), implying larger flow losses in the annulus. For all groups of data, the variation in gas mass flow rate is a result of varying the opening fraction of valve *NV-1*. To attain better gas mass flow rate control and a better insight into nozzle performance, future tests with an improved gas metering valve and pressures tappings to the nozzle plena, shown in Fig. 1(a), are planned.

A selection of images from the high speed videos, showing the different flow patterns achieved by the two nozzle configurations at low and high supply pressures is shown in Fig. 4 and 5. In addition, as reference for comparison, Fig. 6, shows the jet generated by a conventional single pulsed phase fuel injector. The flow conditions corresponding to the images, and calculated parameters, relevant to jet breakup are summarised in table 2. The non-uniformity observed in Fig. 5(a) is attributed to manufacturing tolerances of the nozzles, which lead to a circumferential variation in annulus radial gap.

Based on the images alone, it is evident that both 2-phase flow nozzle configurations generate a significant cloud of finely atomised spray (mist) that is not present for the fuel injector. For Config. A, it can be seen that the bulk of the annular liquid jet, apart from the sheet departing at a high angle, is broken up into the fine mist. 50 mm from the nozzle exit only a small number of individual droplets remain. The diameter of these droplets is less than 0.75 mm for the low pressure case, reducing to less than 0.50 mm for the higher pressure case. In contrast for Config. B, it can be seen that the jet starts to break up from the outside. However at a distance of 50 mm from the nozzle exit, the remnants of the core jet are still clearly evident. These remnants show evidence of developing Raleigh-Taylor waves as the liquid accelerates, as identified by Varga et al. [4]. Away from these jet remnants, the droplets appear smaller than what was observed for Config. A, however it is not clear what portion of the liquid is being carried in the form of ligaments and fine mist. Qualitative comparison of the two configurations, base on Fig. 5 would suggest more fine mist is created by Config. A, as here the dark region indicating mist is larger and as the liquid jet has disintegrated better.

Discussion

To gain an insight into the break-up process, aerodynamic Webber number was calculated:

$$We = \begin{cases} \frac{\rho_{gas} V_{jet}^2 D_{jet}}{\sigma} & \text{single phase nozzles} \\ \frac{\rho_{gas} (V_{jet} - V_{gas})^2 \frac{1}{2} D_{jet}}{\sigma} & \text{2-phase flow} \end{cases} , \qquad (1)$$

based on a representative jet diameter, D_{jet} of 1 mm for both nozzle configurations is shown in table 2. The high Webber numbers observed put the current experimental conditions in a region where aerodynamics forces acting on the liquid far outweigh surface tension, thereby causing the mist generation at the respective liquid surface. A further effect that enhances jet break-up for Config. A is the fact that above the critical pressure ratio (1.893 for N_2), the nozzle exit is choked and thus the gas jet is under expanded when exiting the nozzle. The subsequent expansion of the gas, immediately after exiting the nozzle, is expected to further destabilise the annular liquid jet, thereby enhancing break-up and atomisation.

Comparing the 2-phase flow nozzles to the fuel injector, it can be seen that the Webber number is increased by more than one order of magnitude as a result of the high gas velocities, confirming that the break-up enhancement and the generation of the fine mist is largely driven by the presence of the high speed gas jet. It is encouraging to see the strength of this effect, even gas mass flow rates factions of 10 % and 5 % compared to the liquid mass flow rate for Config. A and B respectively. Improved nozzle tip designs, such as bringing the liquid and gas phases closer together than the current separation of 0.5 mm, are likely to further enhance the break-up process, but further investigation of the geometry is required.

Conclusion and Future Work

A test facility for testing 2-phase flow nozzles was presented. Data from a prototype 2-phase flow nozzle, tested in two configurations, once with a liquid core jet and once with a gas core jet, showed the potential of such nozzles to generate fine mist ($D < 0.1\,\mathrm{mm}$) at low supply pressures (3.0 to 7.3 bar). While for both cases some larger droplets remained, the generation of a large quantity of fine mist is a significant improvement over comparative single phase nozzles. In the tested cases the gas mass flow rate was between 5 and 10 % of the fuel mass flow rate, showing that the improvements can be achieved through the addition of small quantities of gas.

Planned future work include improvements to the test set-up and further investigations into nozzle performance. These incorporate tests spanning a wider range of gas mass flow rates and changes to the nozzle geometry to improve the liquid gas interaction to further enhance break-up and atomisation.

Acknowledgments

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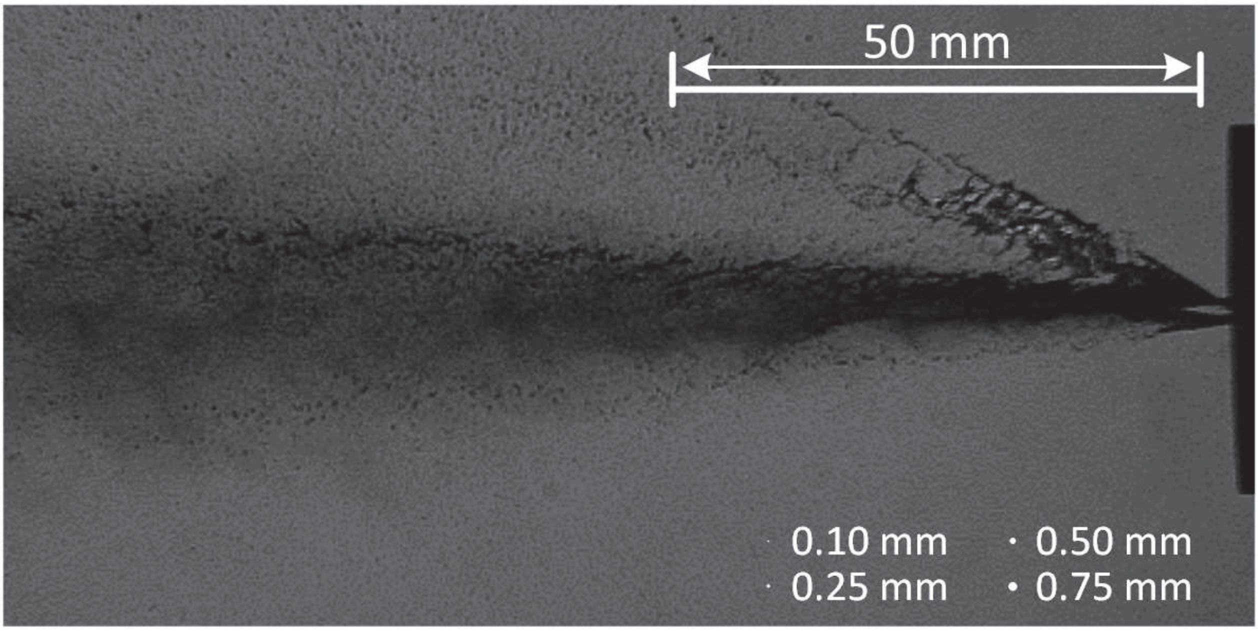
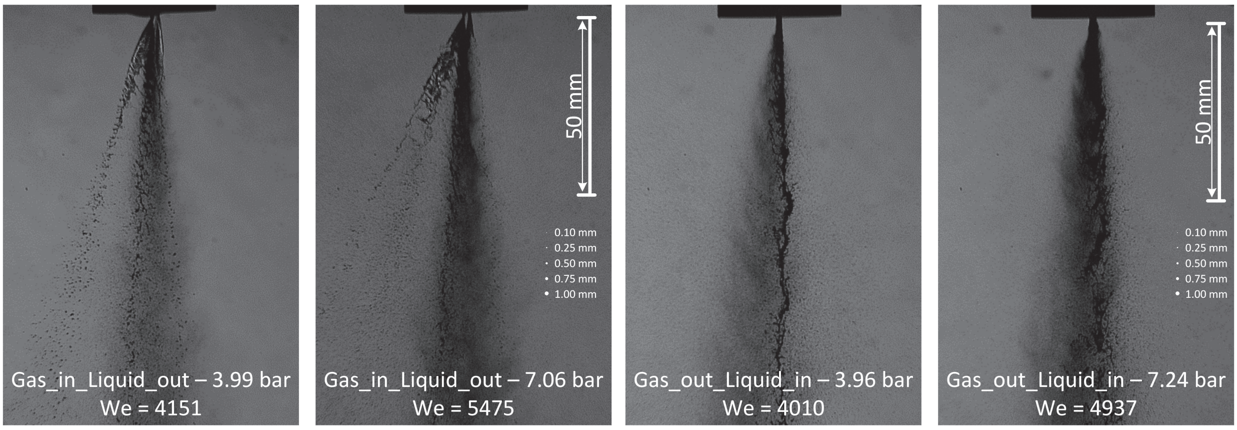


Figure 4: High speed video frame showing spray patterns from 2-phase flow nozzles. (Config. A, 7.06 bar)



(a) Config. A, Gas_in_Liquid_out

(b) Config. B, Gas_out_Liquid_in

Figure 5: Comparison of differnt 2-phase nozzle configurations. See table 2 for operating conditions and calculated parameters.

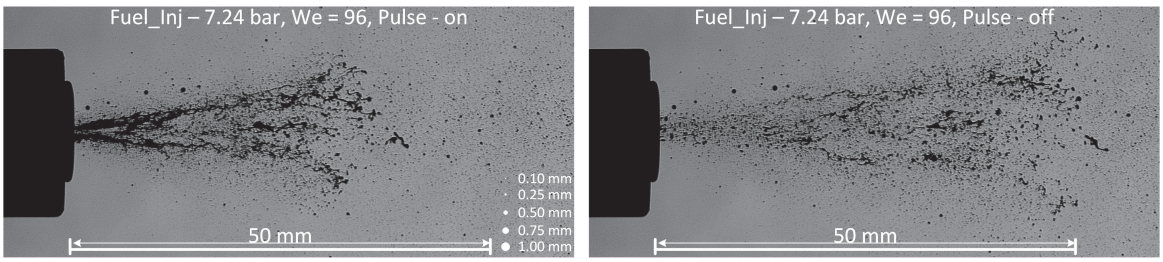


Figure 6: Jet break-up and atomisation by single phase fuel injector. Delay between frames, 0.59 ms. Jet pulse, 1.0 ms on, 3.0 ms off.

Test Config.	Supply Pressure (bar absolute)	Gas flow rate ($g\,s^{-1}$)	Liquid flow rate ($g\,s^{-1}$)	Gas exit velocity ($m\,s^{-1}$)	Liquid exit velocity ($m\,s^{-1}$)	Webber Number	Typical droplet diameter[3] (mm)
A, 3.0	3.99	0.61	5.16	273	7.9	4151	mist, < 0.1 mm [4]
A, 6.0	7.07	1.27[1]	11.48	322	17.6	5475	mist, < 0.1 mm [4]
B, 3.0	3.96	0.62	13.04	280	20.0	4010	mist, < 0.1 mm [5]
B, 6.0	7.24	1.30[1]	21.51	322	32.9	4937	mist,< 0.1 mm [5]
FuelInj	7.42	n/a	5.37	n/a	31.0[2]	96	$0.1 - 0.75$

[1] gas mass flow rate limited by choking at nozzle exit, [2] velocity estimate based on high speed images, [3] based on high speed video,50 mm from nozzle exit, [4] isolated droplets remain < 0.50 mm, [5] remnants of core jet exist at 50 mm

Table 2: Test Conditions and calculated parameters for the investigated 2-phase flow nozzle and Fuel Injector