

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THRUST AUGMENTATION ON A MICRO VALVELESS PULSEJET

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Abstract: This paper investigates the scalability of pulsejet thrust augmenters, the associated drag and new geometric configurations that reduce drag. While augmenters have been shown to increase static thrust on large pulsejets, this research presents small-scale augmentation data. Thrust augmentation for a 50 cm pulsejet was experimentally tested to compare the optimum augments position along the exhaust path to theoretical results. A second experiment using an 8 cm pulsejet with augments was compared to the 50 cm performance using the same experimental methods. Both augmenters more than doubled static thrust at their peak. Using a CFX model, the additional augments drag produced a net loss in a moderate flow field. An optimal micropulsejet augments was designed in CFX to reduce drag and produce a net gain in thrust in a prescribed convective flow field.

Keywords: Pulsejet; Micro-propulsion; Thrust augmentation

INTRODUCTION

Pulsejets were designed in the early 1900s and were first used on a large scale as the propulsion system for the German V-1 cruise missile in World War II. Pulsejets suffer from poor thermodynamic efficiency compared modern air-breathing propulsion systems and have thusly been limited to use as hobby RC engines. Pulsejets however have become one of the few viable options currently available for small-scale propulsion devices for micro aerial vehicles (MAVs) because of the scaling difficulties associated with miniaturizing complex turbomachinery. The pulsejet is a valved or valveless unsteady propulsion device with a cycle that can be modeled as follows [1]: air enters into the combustion chamber and mixes with fuel and hot exhaust products from the previous cycle. The mixture exceeds the autoignition temperature and a combustion event occurs. Due to volume generation resulting from the heat release, a compression wave is generated, increasing the pressure inside the combustion chamber, and driving the products toward the exhaust. Because the pulsejet is intrinsically a subsonic device, the gases flowing out of the exhaust tube overexpand and an expansion wave then travels back into the combustion chamber. This expansion wave reduces the chamber pressure to sub-atmospheric pressures. The resulting low-pressure pulls open reed valves to draw in a fresh air charge through the inlet and the next cycle begins. In a valveless pulsejet, the process is similar, except the combustion products flow out both the inlet and the exhaust and the low pressure pulls a fresh charge directly through the inlet without opening valves. These devices are acoustically resonant, and the

operating frequency is uniquely determined by the geometry of the pulsejet, and can be modeled as a wave tube, where the frequency scales inversely with exhaust duct length. Micropulsejets are appealing for MAVs due their ease in manufacturing, but the thrust generated by these devices leaves a bit to be desired.

Unsteady augmenters are simple devices with no moving parts that can be placed in line with the exhaust of unsteady flow devices to create an increase in mass flux. For unsteady propulsion devices, this can result in increased thrust. The parameter of importance for a thrust augments is thus the thrust augmentation ratio, which can be calculated using Equation 1.

$$\phi = \frac{T_{aug}}{T_{unaug}} \quad (1)$$

The numerator is the total thrust of an augmented system, while the denominator is the thrust of the driver. While most research on pulsejets and augmented pulsejets was performed in the 1960s [2], interest in unsteady augmenters has increased due to their potential applications with pulse detonation engines (PDEs). Because pulsejets very closely mimic the PDE cycle, research has been performed on large and hobby-scale pulsejets to gain an understanding on the thrust augmentation for different augments designs as well as mass entrainment characteristics of these augmenters in order to improve operation of PDEs [3]. This research however may have a direct

impact on the use of micropulsejets for MAVs. If the thrust augmentation ratio produced by large-scale pulsejets can be achieved on the small scale, augmentation may be able to improve the viability of micropulsejets for MAV applications.

EXPERIMENTAL SETUP

The 50 cm long, 3.18 cm exhaust diameter hobby pulsejet testing was carried out in conjunction with a study of valve fatigue and thus required runs in excess of 10 minutes. Testing was initially performed with commercially available Dyna-jet Redhead hobby pulsejets. Because tests were run static for long durations, these commercially available hobby pulsejets had a tendency to fail at the welded seams. A pulsejet with similar combustion chamber and exhaust characteristics and compatible with the Redhead valve system was machined from stainless steel with 6.35 mm thick walls in order to withstand the duration of each experimental run. As such, the pulsejet was not near flight weight, but provided similar thrust characteristics as the hobby-weight models and eliminated the concern for catastrophic failure of the pulsejet body. The hobby scale augments was machined out of aluminum stock and was similarly thicker and more robust than a flight weight model. The augments that was tested followed specifications provided by Dr. Paxson of reference [3], as shown in Figure 1.

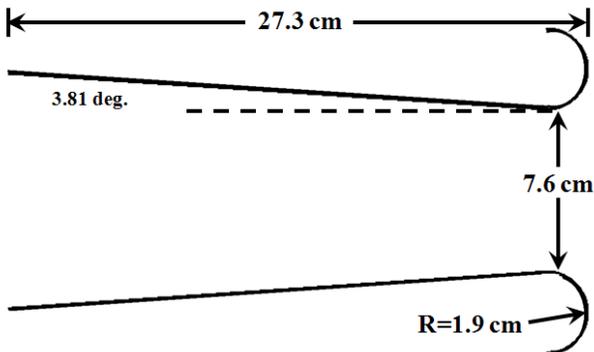


Figure 1. Augments dimensions for 50 cm pulsejet thrust measurements

A calibrated spring-loaded thrust plate was placed in line with the exit of the augment, which was affixed to an optical breadboard. The augment was placed at a distance from the thrust plate such that all of the momentum flux from the augment impinged on the plate. This distance was previously confirmed using PIV techniques. The thrust plate was calibrated by noting the displacement of the plate for incremental increases in force. The 50 cm pulsejet

was set on rails, allowing for the pulsejet body to translate in order to vary the distance between the pulsejet exhaust tip and the entrance to the augment. Important parameters in the measurement of thrust augmentation are shown in Figure 2.

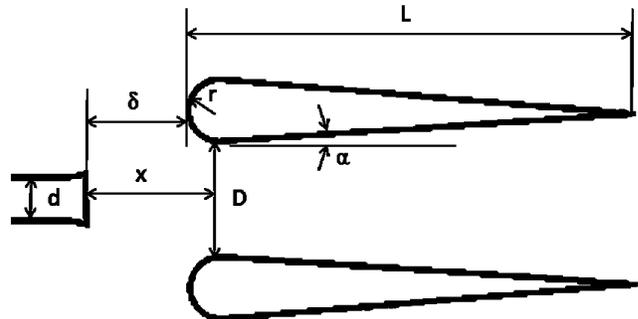


Figure 2. Important pulsejet and augment parameters

The augment for the 50 cm pulsejet had the following non-dimensional characteristics: $D/d = 2.4$, $L/d = 8.6$, $r/d = 0.6$. The 50 cm pulsejet was run on liquid ethanol metered to a mass flow rate of 2.3 g/s and ignited with a spark plug. Once the pulsejet began running, the spark plug was turned off to allow the pulsejet to run unaided. The pulsejet was allowed to run until red-hot before thrust measurements were taken in order for the maximum steady-state thrust to be achieved. A base thrust measurement was taken without the augment in line with the pulsejet exhausting the same distance from the plate as the augment exit was placed. The thrust augmentation data was taken on two occasions; once at an ambient temperature of 288 K, and once at an ambient temperature of 293 K.

The 8 cm pulsejet augmentation experiment was designed as best as possible to mimic that of the 50 cm testing. The augment for this micropulsejet was designed such that all non-dimensional characteristics were the same as that of the 50 cm scale. The exhaust diameter, d , for the 8 cm pulsejet was 0.45 cm. Because friction in slider bearings was too great to use a spring-loaded thrust plate for thrust measurements on this scale, a different thrust measuring method was employed. A thrust plate with an H-shaped side profile was hung from a trapeze device and the small angle deflections were used to determine thrust. The 8 cm pulsejet, also machined out of stainless steel, was run in a valveless configuration on hydrogen that was directly injected into the combustion chamber at a fuel flow rate of 8 SLPM. Forced inlet air was used to run the pulsejet because it makes startup and sustained

runs easier. The forced air was set so that deflection of the thrust plate was negligible when the pulsejet was not in operation. The pulsejet was run without valves using a forward facing valve configuration because of the difficulty in scaling operable valves. Because of this, the reported values of thrust refer to the thrust from the exhaust of the pulsejet and not the net thrust, which would be decreased due to the negative thrust produced by exhaust products escaping through the inlet. In this way, the augmentation ratio refers only to the increase in exhaust thrust, which is the only thrust generated from the valved model, such as the 50 cm pulsejet. The thrust augmentation data was taken on one occasion at an ambient temperature of 295 K.

EXPERIMENTAL RESULTS

Research suggests that the presences of the augmenter can change the operation of the propulsion device, so the unaugmented thrust was taken without the thrust augmenter in line with the device [3]. The base thrust of the 50 cm pulsejet was found to be 16.1 N on both occasions, with peak augmented thrusts of 33.1 and 34.0 N at $\delta/d = 2.6$ and 2.2, respectively, resulting in augmentation ratios of about 2.1 for both. The base thrust of the 8 cm pulsejet was 10.1 mN and the peak augmented thrust was 23.9 mN at $\delta/d = 2.0$, resulting in a peak augmentation ratio of 2.4. The thrust augmentation ratio of each pulsejet is shown in Figure 3 with respect to the exhaust diameter-normalized distance between the pulsejet and augmenter.

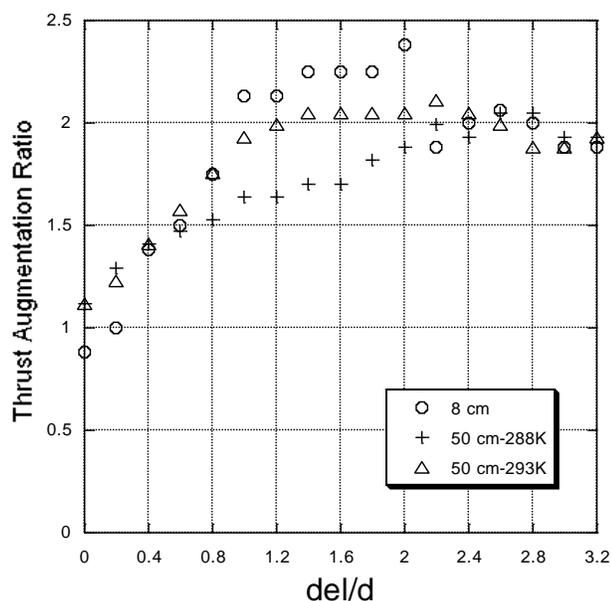


Figure 3. Augmentation ratio for pulsejets at varying δ/d distances

The thrust augmentation ratio appears to be a close fit over the normalized range for the second run of the 50 cm pulsejet and the 8 cm pulsejet with most discrepancies within about 10% of each other, while the first run of the 50 cm pulsejet shows less augmentation over most of the range. A couple of notable regions exist. Along the normalized distance of 1.0 to 2.6, the augmentation ratios vary with discrepancies of up to 50% from the first 50 cm test to the 8 cm measurements. This is interesting as it corresponds with the distances at which each reaches a peak augmentation ratio. Outside of this range, all three pulsejets appear to agree fairly well, with discrepancies appearing only when the pulsejet approaches very closely to the augmenter lip and vary by about 20%.

The experimental set up for both runs of the 50 cm pulsejet were consistent and followed the same procedure, and only the temperature varied. The ambient temperature of the 8 cm pulsejet was also greater than that of either 50 cm pulsejet test. The obvious discrepancies in augmentation behavior between the two 50 cm pulsejet runs suggest the possibility that the temperature of the ambient air may greatly affect the thrust generated by the augmenter. Though enough data has not been taken to claim a direct correlation between ambient temperature and thrust augmentation ratio, it may be interesting to take data in a controlled environment so that the augmentation ratio could be measured with varying temperature in order to establish a correlation.

COMPUTATIONAL RESULTS

Computational modeling has been performed with a commercially available solver, CFX 11, in order to investigate the performance of augmenters with pulsejets and to develop a better understanding of which augmenter dimensions most affect thrust improvements [4]. It was shown that the vortex generated by the pulsejet provides two methods of generating additional thrust. The low-pressure vortex attaches to the front lip of the augmenter and creates suction in front of the augmenter to generate thrust. The vortex also entrains additional mass, which results in an increase in momentum flux. This same validated computational model was used here to investigate the drag characteristics and impact on thrust increase when a 4.5 cm pulsejet and augmenter system was put in a convective stream. At a flow speed of 50 m/s, the drag attributed to the augmenter more than canceled out any thrust increases. As such, the augmenter was then a net loss. It was also shown

in [4] that the augments could be moved forward along the vortex path and scaled down such that the vortex attached to the same point on the scaled augments lip. This suggests the possibility that an augments with a smaller overall diameter could be moved closer to the pulsejet to decrease drag while still providing some level of thrust augmentation. As such, an augments with a D/d ratio of 2.23 was used with an x/d ratio of 1.8, corresponding ratios from [4], in a convective stream of 25 m/s. In addition, the outer lip of the augments was eliminated such that the augments is cut off to form an outer surface that only maintains the lip radius to the point closest to the pulsejet exhaust and becomes a flat surface from nose to tail. Reduction in drag thus will occur for several reasons: the reduction by half in convective flow velocity, which was dictated by changing mission parameters, the decreased diameter of the augments, and finally the limiting of the augments outer surface. Figure 4 shows the pulsejet and augments used for the simulation.



Figure 4. Simulated 4.5 cm pulsejet and drag-reduced augments

The unaugmented 4.5 cm pulsejet produced a net thrust of 8.7 mN and the net augmented thrust was 14.9 mN. This corresponds to a thrust augmentation ratio of 1.7. The drag reduction was admittedly coarse, but these results are nevertheless encouraging as they show that it is possible to tailor an augments that will increase thrust at reasonable flight speeds of MAVs. Further drag reduction may be possible with a more methodical approach.

CONCLUSION

Micropulsejets may be a viable option for small scale propulsion applications due to their simplicity, but their poor efficiency results in low thrust. This research showed that micro-scale augments can more than double the static thrust of micropulsejets and have similar thrust augmentation profiles to that of larger scale augments. This research also suggested the possibility that thrust augmentation ratio for pulsejets may scale in some way with the ambient temperature, but did not provide conclusive evidence for such an assumption to be made. In addition, it was shown computationally that an augments can increase thrust in a moderate convective stream representative of MAV flight vehicles.

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