Evaluation of a Dual-Fluid Cold-Gas Thruster Concept

J. D. Burges, M. J. Hall, and E. G. Lightsey

Abstract**—**A new dual-fluid concept was studied that could eventually find application for cold-gas propulsion for small space satellites or other constant flow applications. In basic form, the concept uses two different refrigerant working fluids, each having a different saturation vapor pressure. The higher vapor pressure refrigerant remains in the saturation phase and is used to pressurize the lower saturation vapor pressure fluid (the propellant) which remains in the compressed liquid phase. A demonstration thruster concept based on this principle was designed and built to study its operating characteristics. An automotive-type electronic fuel injector was used to meter and deliver the propellant. Ejected propellant mass and momentum were measured for several combinations of refrigerants and hydrocarbon fluids. The thruster has the advantage of delivering relatively large total impulse at low tank pressure within a small volume.

Keywords**—**cold-gas, nano-satellite, R134a, thruster

I. Introduction

THERE is a growing interest in the use of small-scale satellites for space-based research, communications, and defense applications. These small-scale satellites are referred to as nano-satellites, and they have a characteristic total mass on the order of 1 kg-100 kg. They require fewer resources than conventional sized satellites, but can still perform many of the important functions of larger satellites. Chemical reaction based thrusters are commonly used on large spacecraft to produce the thrust needed to change velocity and attitude. While efficient for large spacecraft, this method may not be well suited for lower cost small satellites, where simplicity, reliability, safety, and cost are driving considerations, and where precise metering of minute thrust levels is required.

Cold-gas propulsion systems have attracted interest as possible alternatives. The cold-gas propulsion technique involves releasing a pressurized gas or two-phased fluid to provide a momentum change. It offers a simple solution at a low cost. However, cold-gas thrusters tend to have much lower thrust levels than other propulsion options [1]. While cold-gas thrusters would not be optimal for larger satellites, where more complex systems are possible, they may be appropriate for nano-satellites, which have less volume available for propellant storage and complex delivery and control systems [2]. In the interest of safety, some of these systems use inert gases as propellants. Conventional cold-gas propulsion methods have several drawbacks, however. Current systems lose efficiency with use due to a loss of pressure as the propellant is depleted. Traditional cold-gas systems such as nitrogen gas require unacceptably high tank pressures to deliver the required total impulse (e.g., ~10000 kPa) for satellites that are classified as secondary payloads on rockets and man-rated flight systems, and must pose minimal safety hazard to the primary payload. These secondary satellites typically must have maximum tank pressures less than 1000 kPa. There is an as yet unmet need for a simple, low-cost, low-pressure, low-volume, high-precision, and relatively high impulse thruster that can be flown on small satellites.

Research conducted at the University of Missouri at Rolla investigated using a refrigerant as the propellant fluid [3, 4]. They showed that refrigerants offer desirable properties for nano-satellites such as a high density, especially when stored as a liquid, and have lower storage pressures than gas-phase propellants. Refrigerants such as R-134a are available at low cost and are not considered hazardous. Their concept was to use R-134a in its two-phased regime as the propellant. They performed both experiments and modeling to prove the effectiveness of the system and to evaluate its operating characteristics.

Propellants stored as compressed liquids offer total impulse capacity advantages over gaseous or multiphase saturated propellants. Because a liquid-phase propellant has a higher density than a gas-phase or saturated mixed phase propellant, more liquid propellant mass can be stored in the same volume [5]. However, multiphase propellants, in particular saturated liquid/vapor mixtures, can present difficulties in a microgravity setting since the lack of buoyancy forces may allow both the vapor and liquid phases to reach the tank exit. The result is that there is not complete control over the phase of the propellant leaving the tank, leading to variations in thrust.

II. Thruster Concept

A new concept for cold-gas propulsion which may eventually find application for nano-satellites is presented. It uses two different refrigerants (or other high vapor pressure fluids), each having a different saturation vapor pressure. The higher vapor pressure refrigerant remains in the saturation phase and is used to pressurize the lower saturation vapor pressure fluid (the propellant) which remains in the

J.D. Burges, was with Mechanical Engineering Department, The Univ. of Texas at Austin, Austin, TX 78712 USA.

M. J. Hall, Professor, Mechanical Engineering Department, The Univ. of Texas at Austin, Austin, TX 78712 USA (e-mail: mjhall@mail.utexas.edu).

E. G. Lightsey, Professor, Dept. of Aerospace Engineering and Engineering Mechanics, The Univ. of Texas at Austin, Austin, TX 78712 USA (e-mail: lightsey@mail.utexas.edu).

compressed liquid phase. The fluids are separated by a piston or membrane. At fixed temperature, the propellant is maintained at a constant pressure independent of the amount of propellant remaining in the tank.

The selection of the two fluids is based upon desired properties such as liquid density, viscosity, and saturation temperature and pressure. For this proof of concept research, refrigerants and high and low vapor pressure hydrocarbons were tested as propellants. Refrigerant R-134a, propane and nitrogen were used as pressurizing fluids. Refrigerant R-134a, for example, is an inexpensive, dense liquid with a vapor pressure in the desired range, 667 kPa at room temperature [6]. For safety reasons, the research team at the University of Missouri at Rolla used a maximum safe pressure of 2118 kPa at 70^{o}C [3]. This pressure is well above the saturation pressure of refrigerant R-134a at ambient temperatures as used in this research.

As the propellant exits the system, the volume occupied by the higher saturation pressure fluid increases. As its volume increases, more of the higher saturation pressure fluid vaporizes. The higher saturation pressure fluid will remain at constant pressure as long as its temperature is constant. It is important that the high vapor pressure fluid remains in the two-phased regime until the propellant fluid is depleted. This can be achieved by choosing a fluid with suitable properties over the expected temperature range of operation of the satellite (typically 20^{o}C-80^{o}C) or implementing a simple thermal control if needed. While a heater/cooler may be necessary to keep the higher saturation pressure fluid within a desired pressure range, it would only be necessary to heat or cool the pressurizing fluid, which would have considerably smaller mass than the propellant. This would reduce energy demand relative to systems that require the temperature of the propellant to be controlled.

The constant pressure ensures that the thrust remains constant for a given ejected propellant mass. This allows for accurate and consistent thrust as a function of ejection duration. One can adjust the total momentum and mass flow rate produced from this design by changing the fluids used. One would expect that a denser propellant would produce greater thrust for the same pulse duration given the same pressurizing fluid, but other properties such as vapor pressure need to be considered. Using a higher saturation pressure pressurizing fluid would increase the pressure of the propellant, thus increasing its exit velocity, and therefore, thrust.

A production automotive port fuel injector (Fig. 1) was selected as the metering device for the propellant. Automotive fuel injectors eject a reproducible metered amount of liquid for a given input pulse duration, and are reliable, having been designed for the harsh operating conditions of the automotive environment. Further, the fact that the injector sprays the propellant as a fine mist promotes rapid and uniform vaporization, which would occur readily in the ambient vacuum of space. The pressures used were greater than typical for port fuel injectors, but the injector functioned well at pressure differentials as high as approximately 840 kPa. An example of an alternative technology is the high pressure valve actuated by a piezoelectric stack [7].

Fig. 1 Photograph of the type of fuel injector used to meter the propellant (linear dimension is 8 cm).

Several methods could be used to separate the two working fluids. The requirements of the separator are that it easily adjusts inside the container as the propellant is used and that it is impermeable. This research studied an elastic membrane and a piston concept.

III. PROTOTYPE DESCRIPTION

A proof-of-concept prototype was developed to experimentally investigate the thruster concept. The thruster prototype tank consisted of a steel containment cylinder between top and bottom aluminum end-plates that contained the fluids. Four threaded rods around the perimeter secured the end-plates to the cylinder. The cylinder had a height of 12.7 cm, an outer diameter of 10.6 cm and inner diameter of 9.2 cm. A rubber O-ring in a circular groove sealed the perimeter at each end of the steel cylinder. The prototype tank was over-designed for safety and convenience; a flight version would be considerably lighter weight, using thinner construction and lighter materials. Stainless steel tubing, 0.635 cm (0.25 in) in diameter, with one three-way valve and two two-way valves allowed for necessary fluid flow for the two fluids for filling and use. Pressure gauges measured the pressure of the stored fluids and the propellant at the outlet of the tank. Fig. 2 depicts the basic setup for the test rig.

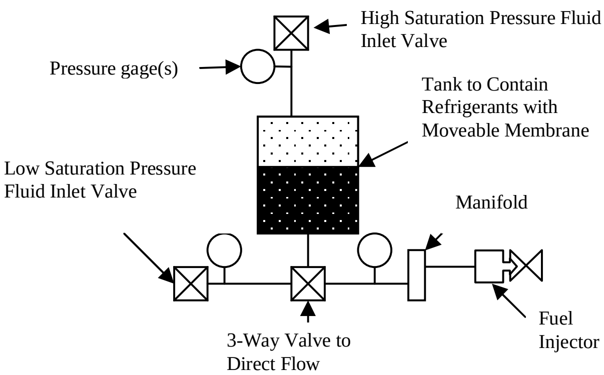

Fig. 2 Basic Test Rig Set Up

The first configuration studied used a rubber bladder inside the tank to separate the propellant and pressurizing fluid. The pressurizing refrigerant surrounded the bladder maintaining a constant pressure inside the tank. This configuration functioned well, but purging the rubber bladder of air was difficult. As a result, a moveable piston configuration was adopted to separate the two fluids; this configuration was used for most of the testing. Fig. 3 is a schematic of the piston based design. The piston used was made of aluminum and had a diameter of 8.9 cm. A silicone O-ring around the perimeter of the piston sealed the two fluid reservoirs from each other and allowed for sliding of the piston inside the cylinder while still providing adequate sealing. Since the two fluids were at the same pressure, one O-ring was sufficient to keep the fluids separated. A photograph of the bladder attached to the cylinder base is shown in Fig. 4. Fig. 5 is a photo of the piston and cylinder used for that configuration.

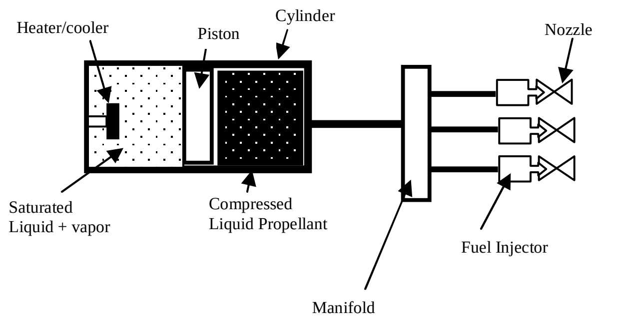

Fig. 3 Piston Design Schematic

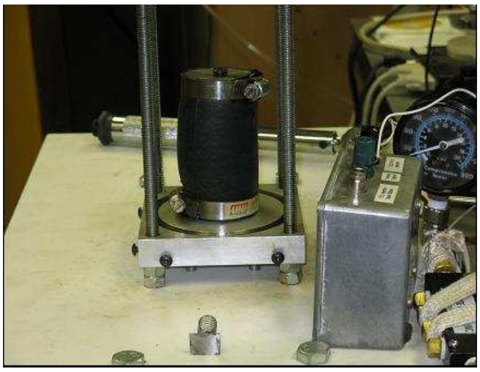

Fig. 4 Rubber bladder used to contain the propellant

Fig. 5 The containment cylinder (left) and the piston (right) which fit inside the containment cylinder and used to separate the propellant from the pressurizing fluid

The piston-type design shown in Fig. 3 shows several features that might be used in a commercial version of the thruster that were not incorporated into the experimental prototype. These include a heater/cooler in the pressurizing fluid tank to maintain a desired temperature of the pressurizing fluid, multiple fuel injectors for different thrust directions, and nozzles on the fuel injectors to direct the expanding and vaporizing propellant flow.

IV. Results

Experiments were performed to validate the thruster concept and to characterize its performance. It was tested using different pressurizing and propellant fluids, operating pressures, and injector pulse-widths (open durations). Of interest was the momentum produced by the ejected propellant. Measuring the mass quantity ejected and its corresponding mass-average velocity allowed the momentum to be determined.

A. Ejected Mass

The ejected propellant mass was measured as a function of injector pulse-width. For the linear region of a fuel injector for which the ejected mass is proportional to the injector open duration, the mass flow rate follows Eqn. 1 [8].

$$\mathrm{m_f} = \mathrm{C_f}\,\mathrm{A_j}\,\sqrt{2\rho_f(P_i - P_o)} \tag{1}$$

Since the system expels a small amount of fluid per pulse, the mass from several ejections (usually about 10) were collected and averaged. Vaporizing propellant fluid was collected in an inverted graduated cylinder immersed in water. A polyethylene tube connected to the fuel injector nozzle was inserted into the open bottom of the inverted graduated cylinder. The propellant displaced water from the cylinder allowing the volume to be measured. Liquid propellants were captured directly into a graduated cylinder for mass measurements.

Eight different fluid combinations were tested; these are shown in Table 1. For two cases, compressed nitrogen was used as the pressurizing fluid to get the highest pressures; R-134 was used for lower pressures, propane was used for intermediate values of pressure. Because N_2 is an ideal gas rather than a saturated fluid, it required open line external pressurization to maintain a constant operating pressure. The pressures shown in the table and in succeeding figures are absolute pressures in kPa.

TABLE I
Eight different test configurations

Test Case	Propellant Fluid	Pressure (kPa)	Configuration	Pressurizing Fluid
A	Propane	924	Piston	Nitrogen
B	R-134a	924	Piston	Nitrogen
C	R-134a	855	Piston	Propane
D	Heptane	855	Piston	Propane
E	Octane	855	Piston	Propane
F	Pentane	855	Piston	Propane
G	Pentane	669	Bladder	R-134a
H	Pentane	669	Piston	R-134a

Propellant fluids tested included high vapor pressure, fluids R-134a and propane, but also fluids that are liquids at laboratory ambient conditions: pentane, n-heptane, and iso-octane. Fig. 6 shows the normalized mass ejected for a 10 ms pulse width. The normalized mass is defined as the mass in grams ejected divided by the pulse duration in ms. Fig. 7 shows a similar bar graph, but of the normalized volume flow (ml of liquid per ms) at the 10 ms pulse width. The normalization process is convenient for comparing results from different pulse-widths. A pulse-width of ten milliseconds was chosen for analysis because it provided sufficient amounts of fluid for accurate mass and velocity measurements, and the flow was at steady state for a relatively long time beyond the injector needle opening duration of approximately 1.5 ms.

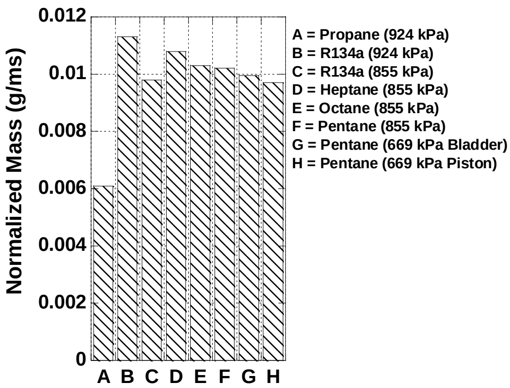

Fig. 6 Normalized mass expelled at 10ms pulse width

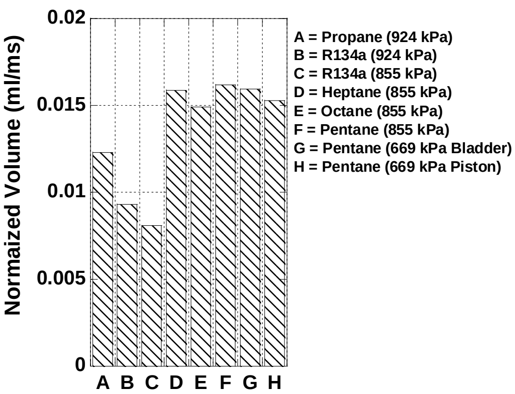

Fig. 7 Normalized volumes expelled at 10ms pulse width

For comparison, the eight test cases are broken down into three sets, one for each operating pressure. The mass deliveries for pentane at 669 kPa using the two different methods of the bladder and piston are very similar (the two right-hand columns of Figs. 6 and 7). This was expected, although it was thought that the elasticity of the rubber bladder might add to the pressure and thus, the mass output for the bladder method, and the friction imposed by the o-ring of the sliding piston might reduce the mass delivery for the piston method; these factors were not found to be significant, however.

All of the other results were obtained using the piston configuration. The high vapor pressure propellants propane and R-134a were compared for the high pressure condition of 924 kPa. Based on Equation (1), the R-134a was expected to expel 1.56 times the mass of propane for a given pulse duration as determined by the square root of their density ratio. The density of liquid propane is 493 kg/m^3, R-143a 1206 kg/m^3. The measured mass value for R-134a was 1.82 times that of propane, 16.5% greater than the theoretical value.

Pentane, n-heptane, and iso-octane were compared at the 855 kPa operating pressure. Pentane, n-heptane, and iso-octane all have similar densities of 626, 684, and 688 kg/m^3 [9], respectively. The R-134a's liquid density is approximately twice that of the hydrocarbons tested. As such, the R-134a was expected to expel approximately 1.4 times the mass as the hydrocarbons tested. Fig. 6 shows that the hydrocarbons actually had a slightly greater mass output than the R-134a.

A parameter not accounted for in Eqn. (1) must have influenced these results. The viscosity of the propellants was considered, but the viscosity of R-134a is similar to that of pentane and actually less than n-heptane and iso-octane.

The next theory explored was the possibility that R-134a was vaporizing in the injector orifice, affecting the flow. The vapor pressure of R-134a is greater than the 1 atm exit pressure, unlike that of the pentane, iso-octane and n-heptane. This would also explain why the expelled mass of R-134a was slightly higher than expected relative to propane. Propane has an even higher vapor pressure than R-134a (953.9 kPa vs. 665.3 at 25^{o}C), although propane also has a higher enthalpy of vaporization (344 kJ/kg vs. 181 kJ/kg for R-134a at 20^{o}C). Thus, it is believed that the unexpected mass delivery differences were due to partial vaporization of the R-134a and propane within the injector nozzle which impeded the flow. This effect would probably be somewhat greater in the vacuum of space. Injectors with different exit nozzle designs may show different flow characteristics, but no other injectors were tested.

B. Velocity Determination

A measure of the mean velocity of the delivered mass was required to calculate the propellant momentum per pulse. The test setup was horizontal to the local gravity direction, cancelling the gravity effects at both ends of the flow. Bernoulli's equation provides a theoretical value for the velocity for an ideal inviscid fluid [10].

$$\mathrm{V} = \sqrt{2\Delta P/\rho} \tag{2}$$

Actual flows, however, deviate from these ideal conditions. Typically, fuel injectors have flow coefficients of approximately 0.7 to 0.8 [11]. Thus, the measured velocity was expected to be about three-fourths of the value calculated with Bernoulli's equation.The mass-averaged velocities were derived from measurements of momentum exchange between the ejected fluid and a ballistic pendulum. Ballistic pendulums have been used previously to measure the specific impulse of cold-gas thrusters [12]. The ballistic pendulum consisted of a copper cup soldered to a small copper tube. The copper cup had a mass of 6.45 grams, an outer diameter of 1.78 cm, an inner diameter of 1.57 cm, and depth of 1.50 cm. The copper tube arm had a length of 11.5 cm. The total mass of the pendulum was 11.15 grams and a total length of 17.5 cm from the center of the cup to the pivot point. Using the measured horizontal movement of the pendulum, the velocity of the spray was calculated using the known masses of spray and the pendulum [13].

The effect of friction was neglected in the analysis, thus the measurement yields a conservative estimate of the velocity. A check that was performed to increase confidence in the accuracy of the ballistic pendulum was to vary the mass of the pendulum. The mass of the pendulum should not affect the velocity results. Different masses did in fact produce the same velocity value for a given operating condition within the statistical uncertainty of the measurements (about +/- 10%).

Fig. 8 shows the velocity values determined from this method for the different operating conditions. In theory, since velocity is a function of pressure and the fluid's properties, specifically density, the velocity should be constant, independent of pulse width once the spray is at steady state. No matter how long the injector needle is open, the pressure differential remains the same. This, of course, neglects injector opening and closing times. These data show that the velocities for each operating condition fluctuate within a similar range of velocities independent of pulse-width. Thus, averaging over multiple pulse-widths was used to improve the statistical accuracy of the mean velocity measurements.

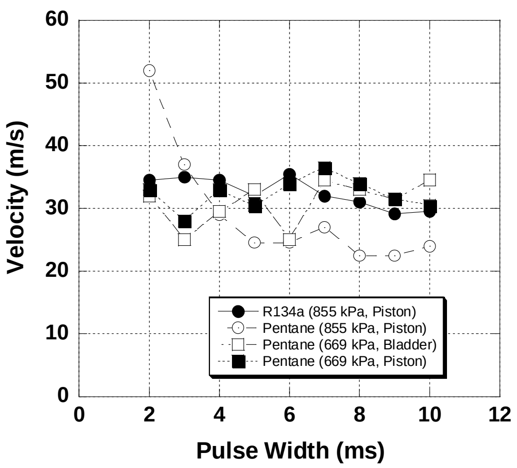

Fig. 8 Mass-average velocity versus injector pulse width

Velocities were typically in the range of 22 – 38 m/s and were insensitive to the injector pulse width. In general, velocities would be expected to increase with increasing pressure, but as can be seen in Fig. 8 for pentane at the highest pressure of 855 kPa, this was not always the case. At the highest pressure of 855 kPa the operational pressure limit of the injector was being approached such that the pressure was becoming too high for the injector solenoid to fully raise the injector needle. In automotive engines, the injectors more typically operate in the range of absolute pressures of 250-400 kPa. For the piston method, the standard deviation of nine values about the mean velocity of 32.2 m/s was 2.3 m/s. For the bladder method the standard deviation of the nine values about the mean velocity of 31.0 m/s was 3.56 m/s. The mean velocity values yield a specific impulse for the thruster of about 3 s. This can most likely be improved with the use of a properly designed nozzle. The measured mass-average velocities were less than the velocity of 46.2 m/s estimated from Eqn. (2). These deviations from theory yield a fuel injector flow coefficient of about 0.7, which is consistent with the range of values from 0.7 to 0.8 cited in the literature [7].

C. Momentum Results

The momentum of the spray is the product of the ejected mass and the mass-average velocity, and is calculated from the results already discussed. Since the mass expelled is proportional to pulse-width and the velocity is nearly constant regardless of pulse-width, the momentum of the expelled propellant increase linearly with pulse-width.

The mass data of Fig. 6 and the velocity data of Fig. 8 provide the corresponding momentum values shown in Fig. 9 as a function of pulse-width. As with the previous figure, the values calculated are for the conditions of R-134a and pentane at 855 kPa, in the piston configuration and pentane at 669 kPa, in both the piston and bladder configurations. Fig. 10 compares the momentum values at the 10 ms pulse-width.

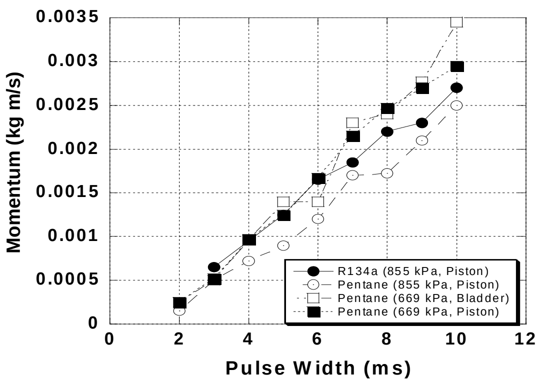

Fig. 9 Momentum values versus pulse-width

Fig. 9 shows that the momentum values for the different operating conditions are nearly the same at the smaller pulse-widths. As pulse-width is increased, however, the differences among the momentum values increase. Fig. 9 also shows the linear increase in momentum transfer as a function of the time that the propellant is flowing. Fig. 10 shows the momentum values for the 10 ms pulse width. The difference between the largest momentum value (pentane in the bladder configuration at 669 kPa) and the smallest momentum value (pentane in the piston configuration at 855 kPa), amount to a -27% difference between the higher-pressure condition and the lower pressure condition.

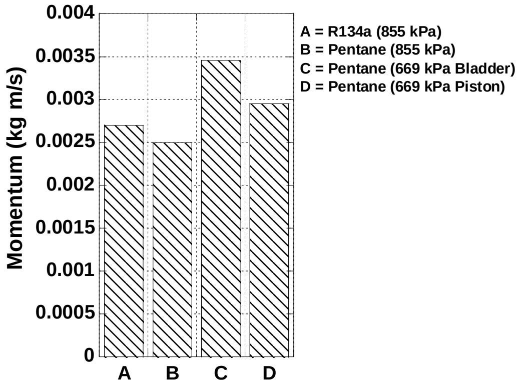

Fig. 10 Momentum values at the 10 ms pulse-width

The momentum actually decreased for the pentane when the pressure was increased from 669 kPa to 855 kPa. This occurred because the system pressure approached the operating limits of the fuel injector, as mentioned above. The most important conclusion derived from these data is that it is possible to accurately control the momentum of the ejected propellant fluid by adjusting the pulse width. In this manner, the operator can produce the desired momentum change needed for an adjustment by selecting the appropriate pulse-width. Furthermore, the injector operation is reproducible, yielding reproducible amounts of thrust for a given pulse-width. This should allow precise metering of thrust.

V. CONCLUSION

A new cold-gas propulsion method with possible application as a thruster for small satellites was successfully designed, built, developed, and tested. The system used an automotive port fuel injector to regulate and deliver a vaporizing liquid propellant. During the testing, spray characteristics such as fluid mass and mass average velocity were measured. Several fluids were investigated as propellants. R134a, in particular, appears promising due to its convenient saturation vapor pressure, its ability to vaporize readily during ejection and its inert nature. The critical result from this development is that the new thruster concept worked as expected. The higher saturation pressure fluid, when used in its two-phase form, kept the lower saturation pressure fluid in its sub-cooled liquid phase and at a constant pressure. By storing the propellant as a liquid at constant pressure it should be relatively simple to achieve precise desired thrust amounts in a production version of the thruster.

The expelled mass from the injector was found to be proportional to the electronically controlled injection pulse-width; and was a function of the fluid density, injector pressure differential, and the fluid vaporization characteristics. In general, the observed velocities were in the range expected based on Bernoulli's equation and typical values for injector flow coefficients. Due to the storage of the propellant as a liquid, the tank pressure required to deliver a given total impulse is lower than that of other cold-gas such as nitrogen gas. This may be a significant consideration for nano-satellites that frequently fly as secondary payloads and therefore cannot pose a safety hazard to the primary payload.

NOMENCLATURE

A_j	exit flow area of the fuel injector orifice (m^2)
C_f	fuel injector flow coefficient
m_f	mass flow rate (kg/s)
P_i, P_o	pressure inside and outside of the injector (N/m^2)
ΔP	pressure differential experienced by fluid (N/m^2)
V	fluid velocity (m/s)
ρ_f	density of the fluid (kg/m^3)

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