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Study of a Two-Phase Underwater Ramjet Propulsor Employing Liquified Gas Boiling

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ABSTRACT

This work investigates the feasibility and performance of a two-phase ramjet propulsor for underwater vehicles, using the expansion work from the boiling of a liquefied gas in a nozzle to generate thrust in this innovative propulsion concept.

The two-phase marine ramjet has been studied at the Technion – Israel Institute of Technology for about two decades. Initial research focused on pumping air into the flow directly from the surrounding atmosphere. The expansion work of the air bubbles is used to create the high speed exhaust jet for thrust generation. Model predictions and experiments have shown that the marine ramjet is particularly suitable for high speed vessels, avoiding cavitation problems.

For underwater operation an independent source of gas is required. Multiphase flow was generated by injecting liquefied-gas droplets into the water, within the thrust unit. Injection led to a sudden reduction in the liquefied gas's pressure, leading to boiling inside the water medium at ambient temperature. It was hypothesized that the additional expansion work, following phase-transfer, could provide additional thrust. Tests were then conducted with a suitable liquefied-gas (R134a) in a tow-pool, where the speed of the ramjet propulsor was varied systematically in the range of 14-35 knots. Thrust at different speeds and at different liquefied-gas flow rates was measured. Direct experimental comparison of thrust by liquefied-gas boiling to compressed air bubbles was done, revealing similar results at lower velocity. At higher velocities, somewhat better peak performance was found for the liquefied-gas versus air, demonstrating feasibility and significant promise for underwater high speed propulsion.

Keywords

Marine Ramjet propulsion, boiling expansion, pressure liquefied gas

1 INTRODUCTION

A relatively large amount of work has been conducted on the compressed gas (usually air) driven Marine Ramjet (MRJ) over the last few decades, beginning in the 1950's with the US Navy and followed by others, as is well presented in the review of Muench & Garrett (1972). One study worth mentioning is that of Mottard & Shoemaker (1961) at NASA, where tow-pool experiments were conducted and thrust was measured at medium-low speeds and employing compressed air only. A similar experimental system was realized in the work of Varshay (1993), followed by static thrust measurements. Koren (2005) employed this same system for medium-low speed experiments with compressed air. In the current study, the same system is adapted for using liquefied gas and the velocity range is significantly extended. Early analytical/numerical works were conducted by Witte (1969) and Amos et al (1973), at low gas-liquid mass flow-rates, showing high efficiency, but low thrust. Lately, this work has been complimented by the analytical/numerical studies of Albagli & Gany (2003) and Mor & Gany (2004). The latter incorporated the solution into a performance simulator based on homogenous quasi-one-dimensional compressible flow assumptions, which is also considered in this study.

In the idealized theoretical analysis of the thermodynamic cycle of an MRJ conducted by Gany (2004), a reduction of ideal air cycle efficiency with increase in MRJ velocity can be seen. On the other hand, the thrust is shown to increase proportionately to the square of the velocity, similarly to the drag. Thereby presenting the main challenge of the MRJ: generating enough thrust to overcome the drag (self propulsion), at reasonable efficiency.

One method for accomplishing this is by using a different "fuel" source, with potentially higher thrust: boiling a liquefied gas. This form of propulsion has the additional advantage of allowing the MRJ submerged operation.

To date, very few investigations have focused on the possibility of a submerged Marine Ramjet. This is partially because of the technical difficulties related to employing the outside air as the propelling medium, as is usually done, and partially due to the general reduction of performance expected at greater depths, where the ambient pressure reduces maximum (ideal) available work per unit mass of gas (proportional to Thrust), according to Equation 1:

$$w_g = \mathbf{R}_v T_a \ln\left(\frac{P_{mix}}{P_a}\right) \qquad (1)$$

In this equation, R_v is the specific gas constant, T_a is the ambient temperature, p_{mix} the pressure in the injection chamber. Very little literature on the feasibility of an underwater Marine Ramjet propulsor can be found, all of these employ water-reactive fuels for generation of gases or steam that are then used for propulsion. The review by Muench & Garrett (1972) mentions early attempts at employing the MRJ as a torpedo propulsion method by the US Navy and Aerojet-General, employing water-reacting fuels. First, a hydro-pulsejet was examined but finally a hydroductor with a condensing exhaust, (eliminating the dependence on ambient pressure) was developed. Unfortunately, experiments weren't very successful due to intricacy of the system, and no practical applications resulted. Hacker & Lieberman (1969) analyzed the thermodynamic cycle of an underwater MRJ using a thermite fuel to produce steam then used for propulsion. Schoeffl (1988) examined the use of Triethylaluminium as a fuel, for a similar application. The conclusion of these studies has generally been that employing water reactive fuels leads to high temperature cycles, tremendous thermal losses and very low efficiency, making these methods unattractive.

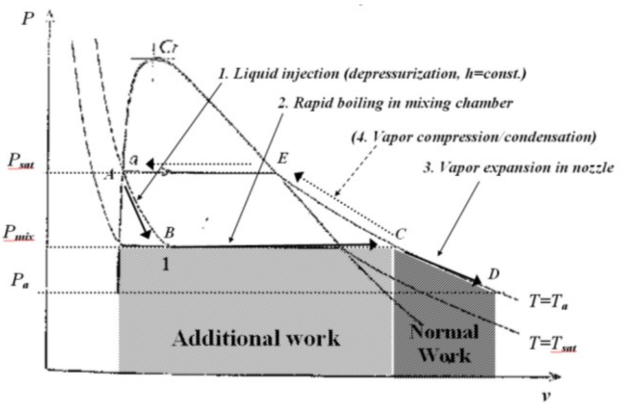

Figure 1: Thermodynamic P-V diagram of cycle (area below graph is ideal available work); compression/condensation - stage 4 of cycle, can be done outside of engine

In this study, an alternative method is presented for an underwater Marine Ramjet (MRJ) propulsor, employing the expansion of a pressure liquefied gas (PLG) due to both boiling and gas expansion while flowing through a nozzle, to perform thrust-generating work on the flowing media, according to the ideal equation:

$$w_T \approx \mathbf{R}_v T_a \left(1 + \ln\left(\frac{P_{mix}}{P_a}\right)\right) \qquad (2)$$

This equation is an approximate form, obtained under the idealized description of the cycle given in Fig. 1.

This alternative method clearly has some advantages over those of the ordinary MRJ: first, the additional potential thrust generating work depicted in Fig 1; second, as the gas is liquefied its storage is very compact as required in an underwater, self-contained unit.

However, this method is not devoid of disadvantages. The main disadvantage being that as a self-contained unit carrying its own "fuel" operation time/range is rather limited. Additionally, as a submerged unit the entire surface is subject to drag. Finally, in similar fashion to normal MRJ operation, it has an optimal work range that varies with ambient conditions.

The main question addressed in this study is whether this additionally available expansion work can be exploited to generate thrust. Normally, within a still liquid medium the expansion of an immiscible droplet undergoing boiling is generally uniform in all directions, and does not generate more displacement (work) in any one direction. However, this is not the case in the accelerating flow field that exists in the nozzle of a MRJ propulsor, leading to hypothesis that some of this work can be used to generate thrust. This hypothesis will be examined experimentally in the following investigation.

2 EXPERIMENTAL SETUP

The tow-pool setup employed in this experimental investigation is briefly described and schematically shown in Fig. 2. This system was designed and built by Varshay (1993), with some modification by Koren (2005) for operation with compressed air at medium velocities (up to 50g/s of air & 25 Knots).

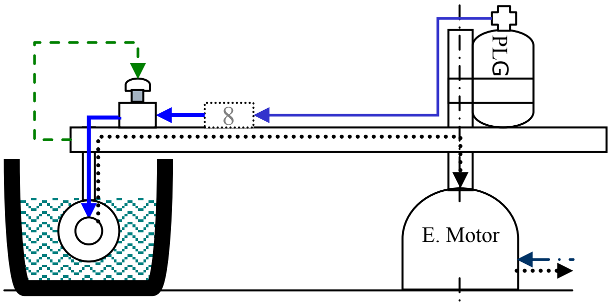

Figure 2: Schematic profile view of MRJ tow-pool with boiling-PLG propulsion: ── PLG flow, – – – Pneumatic command, ····· Pressure readings, –·–·– Electric motor command

A cross section of the Marine Ramjet engine is shown in Fig. 3. The engine is suspended at the end of a long supporting arm that also functions as the compressed-air supply piping. The arm is rotated at desired speeds by a computer-controlled electrical motor. The angular velocity of the arm and power consumption of the motor are measured; from which the calibrated drag can be established. The air supply is measured by a choked-flow orifice measurement method. There are also pressure measurements (with pressure transducers) at different locations along the MRJ engine, as depicted in Fig. 3, which are periodically calibrated. From these the pressure distribution before and during operation can be established. The entire data are transferred via optical encoder through the center axis of the rotating arm to a computer, and recorded by a custom Labview program. A signal is recorded from each channel every 0.8sec, and results are time averaged to reduce noise induced error.

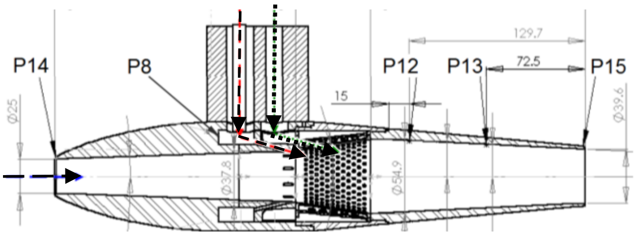

Figure 3: Cross section of MRJ motor (39.6mm outlet nozzle) modified for boiling PLG (– – – PLG flow, ▪▪▪▪▪▪ Air flow, ——— Water flow; P = pressure readings)

In Fig. 3, the overall dimensions of the test MRJ engine are: maximum outer diameter (for calculation of the drag coefficient) is 80mm, the overall length is 390mm (mixing chamber is 55mm long and nozzle is 158mm long). In the figure, the "P" labels indicate the location of pressure measurement; the flow of PLG is indicated by a short-dash line, the compressed air flow by a dotted line and the water flow by a long-dash line. P14 is a measurement at the inlet indicating the effective capture cross section. P12, P13 and P15 are measurements along the nozzle giving an idea of the pressure and velocity distribution in it. P8 is a pressure measurement close to the outlet of the PLG, for verification that PLG is in liquid form (above saturation pressure) before injection into the water flow in the mixing chamber.

2.1 System modification

As the MRJ has significant advantage at higher speed and the associated shorter residence time is closer to the total boiling time of the droplets, the first modification to the system was to increase operation speed. This was done by optimizing the transmission from the electric motor (see Fig. 2) to obtain speeds up to 36 Knots, an increase of 50% in maximum MRJ tow-pool velocity.

For the introduction of liquefied gas (or compressed air) to the MRJ test engine, additional modifications where introduced. The liquefied gas is contained in a high-pressure tank that is attached to the revolving arm and flows from there to the MRJ engine. This tank is periodically re-pressurized with nitrogen (inert gas) to maintain constant flow rate and avoid low pressure leading to low flow-rate two-phase injection. The engine employs two inlets, one for compressed air and one for liquefied gas, and a manual three-way valve for selection between them. Furthermore, the duration of the liquefied gas injection is dictated by a remotely controlled pneumatic valve. The liquefied gas is injected into the main water flow in the engine, through an injection ring that allows the adjustment of flow rate (in the air equivalent mass flow rates from 3g/s up to 30g/s) and the injection radial distribution, by use of ten 0.8mm jets/plugs.

The PLG flow rate was measured by an Omega FTB2001 axial turbine low flow meter, specifically calibrated for the low viscosity liquefied gas used (a 14% overestimation was found). Eventually, due to problems with the electronics, the flow meter was removed from the system and an average, indirect method was used: weighing the gas tank before and after every experiment and division by the injection duration, retrieved from the pressure readings, leading to some uncertainty in the flow rate measurements, as explained in the following subsection.

Each experiment was conducted as follows: water temperature was measured at two opposite locations in the pool and the gas tank (liquefied-gas runs) was weighed. The MRJ engine was then accelerated until it leveled off at the desired velocity, after a short duration at constant velocity the pneumatic valve was remotely opened and air/liquefied gas was injected for 10-15 seconds. The valve was closed, and after another short duration the MRJ engine was slowed to stand still. All data were recorded, plotted and saved in preparation for the next run. The liquefied-gas experiments were immediately followed (or preceded) by an experiment in which compressed air was used, for comparison under similar conditions (water level in the pool, water temperature, velocity and flow-rate). A typical plot of the data is given in the following section.

2.2 Uncertainty of results

Injection time-length was typically above 13sec and a reading was taken every 0.8sec, leading to a 6% uncertainty in average mass flow-rate. Flow rate was not controlled with high precision as it was strongly influenced by local injection conditions, but all experiments were conducted within 15% mass flow rate of the average. Given that the variations in flow rate between experiments are larger than the uncertainty level, final results were interpolated to the average value (assuming local linearity in the dependence of thrust on flow rate). Pressure readings calibration led to an estimated bias-error up to 5kPa. Drag measurements were accompanied by a high level of noise and therefore averaging over a minimum of 10 data point was used. This led to an error estimation of below 1N. Generally, lower errors are associated with higher velocities (the noise-to-signal ratio decreased with an increase in average drag).

3 RESULTS

Following the modifications described, the first stage of the experiments was aimed at validating the measurements against previous results obtained for operation of the MRJ engine with compressed air. This included the thrust, drag and pressure distribution measurements in the MRJ engine.

3.1 Drag evaluation

The power output of the electrical motor was measured, from which the resisting force at the end of the arm could be found. After calibration (as done by Koren 2005) the resisting force could be converted to total drag. Upon injection of the "fuel" (either compressed air or liquefied gas), a drop in the drag was measured. The value of this drop is the thrust found, see example in Fig. 4. As explained in the previous section, the data collected included pressure readings, drag readings, choked air-flow rate (in compressed air experiments) and PLG-tank weight measurements (in PLG experiments).

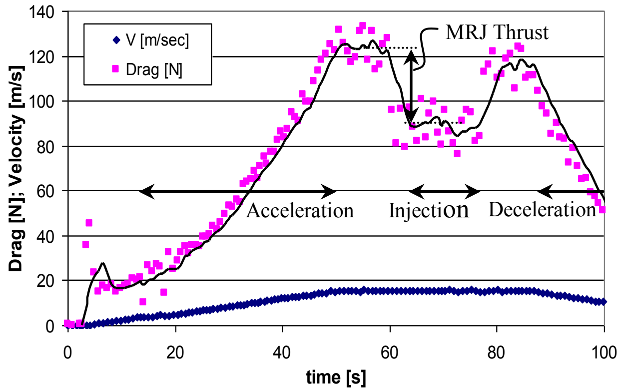

Figure 4: Typical drag and velocity readings during an experimental run showing thrust, at 15m/s

Pressure readings where taken from several locations along the MRJ engine: the inlet (indicating the capture diameter), the mixing chamber (max working pressure), and in three locations along the nozzle. Typical results are shown in Fig. 5.

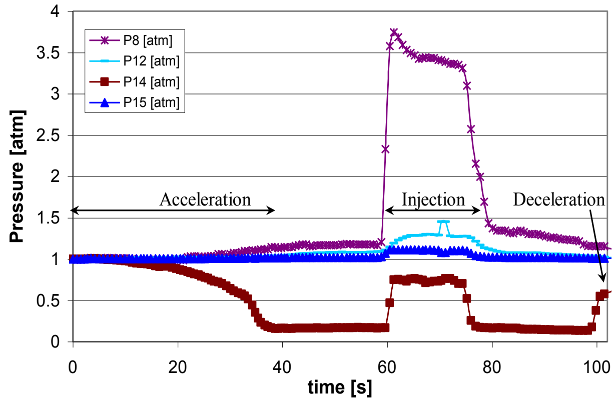

Figure 5: Typical pressure readings from the MRJ engine, at 15m/s (see locations of measurements in Fig. 2)

In all experiments the focus was on obtaining high efficiency, so a relatively low gas-liquid mass ratio was maintained (GLMR=0.3%, the ratio of thrust generating gas to the driven liquid - water); therefore no positive thrust was observed in this specific experimental system. This is partially because the existing setup adds significant "parasitical" drag, and is not designed to demonstrate positive thrust. Positive thrust has been demonstrated in a previous version of the system, at somewhat higher gas flow-rates. By conducting a series of tow-pool runs without water in the tow-pool, the parasitical (system) drag was evaluated. This drag was then deducted from the total drag measured to give a "net drag", caused only by the water. This is shown in Fig. 6.

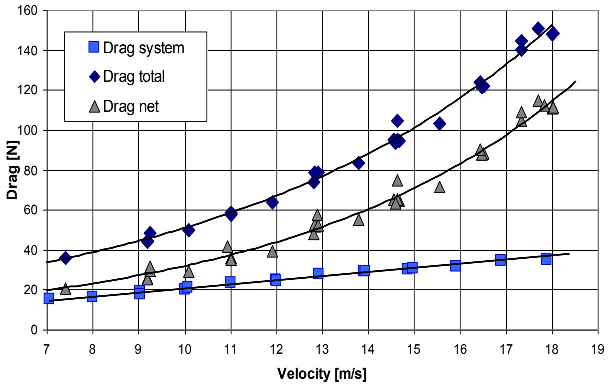

Figure 6: Measured drag of the MRJ; the net drag (triangles) is due to the water only

From the net drag the drag coefficient can be calculated as a function of velocity (Reynolds number), this is shown in Fig. 7. The drag coefficient, Cd, is around 0.2 for the majority of the range of Reynolds numbers examined (using the cross-sectional area based on the largest outer diameter, see Fig. 3, not the wetted area).

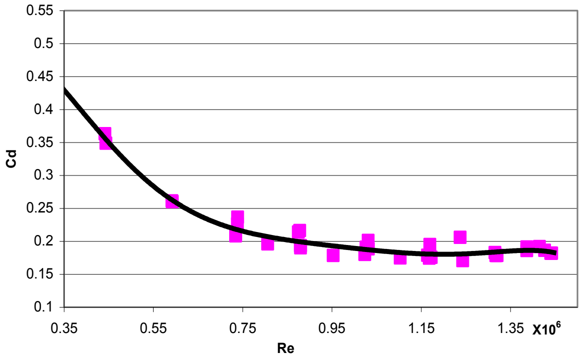

Figure 7: The Drag coefficient measured on the MRJ engine in the tow-pool

For direct comparison, all gas flow rates presented in this work are air-equivalent mass flow rates (i.e., all gases have their mass flow rate divided by the ratio of their molecular weight to that of air), so that similar gas volume flow-rates are injected. The reason for this is that the thrust is generated by expansion and is dependent on the gas-phase volume fraction. With the larger outlet nozzle (39.6mm) examined, no pressure readings were available from the MRJ engine, due to technical limitations.

3.2 System validation (compressed air)

As mentioned in the introduction, the most relevant work done on MRJ propulsion is the work of Koren (2005). In that work, experiments were run in the same tow pool, at lower velocities, using only compressed air for thrust generation. Unfortunately, in his work the velocity was limited to 11-13 m/s, so direct comparison within the majority of the range is not possible. Re-examining those results and comparing them to this study, reveals that there is good agreement at lower velocities. This is shown in Fig. 8.

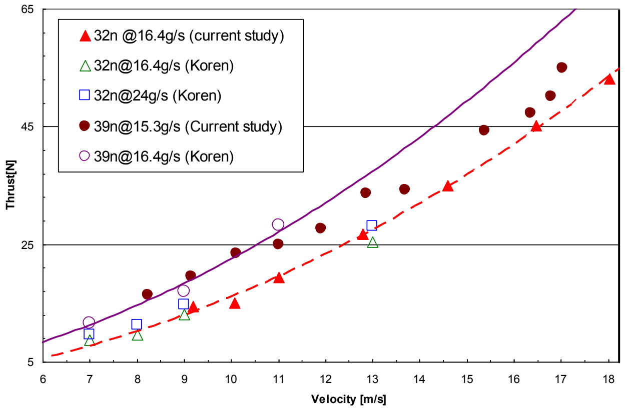

Figure 8: Thrust for 32mm and 39.6mm outlet nozzle, at different air mass flows: measurements (symbols) and power-law trend prediction (lines); filled symbols are from current work, hollow ones are from Koren (2005).

Two important things are evident from Fig. 8: one, with the smaller outlet nozzle (32mm) an increase in "fuel" flow rate does not result in much increase in thrust; and two, switching to the larger outlet nozzle increases thrust significantly. This is understood to be because the smaller outlet nozzle causes a pressure increase (in the mixing chamber, under gas injection) to be projected forward to the inlet of the MRJ; as a result, the inflow of water is reduced (less working fluid) inhibiting the thrust increase. For the 39.6mm nozzle there is good agreement between results at lower velocities, at higher velocities thrust is lower than that predicted by a power-law extrapolation from Koren's results (solid line). This form of extrapolation works well in predicting thrust for the smaller outlet nozzle (32mm).

3.3 Operation with liquefied gas (R134a)

For the liquefied gas driven MRJ the gas chosen was R134a. R134a is a synthesized refrigerant (Tetraflouroethane, $H2FC-CF3$). It is a gas at atmospheric pressure, but liquefies at a moderate pressure of ~6atm and room temperature.

Table 1: Saturation Properties of R134a at atmospheric pressure and a temperature of -26.07°C

	h_{fg} (J/g)	ρ (kg/m^3)	Cv (J/g*K)	Cp (J/g*K)	μ (μPa*s)	k (W/m*K)	σ (N/m)
Liquid	216.2	1376.7	0.848	1.28	378.7	0.1039	0.01543
Vapor		5.258	0.688	0.794	9.779	0.00931	

At least 23 successful runs were conducted with R134 as the propulsion fluid, within the range of interest for direct comparison to air. Its properties were taken from the NIST Chemical Webbook Database (2008), shown in Table 1.

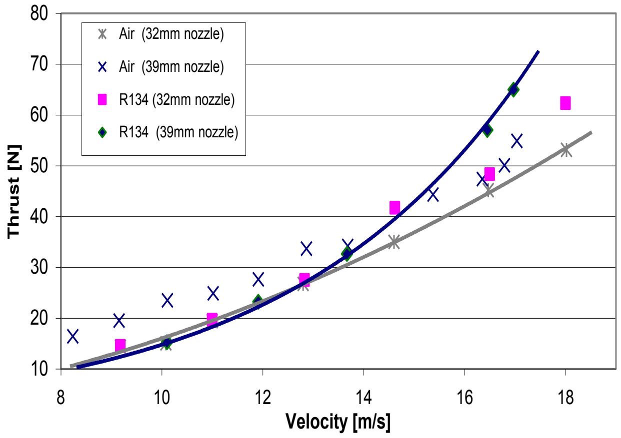

Figure 9: R134a Thrust vs. velocity at constant air equivalent mass flow rate, 17g/s

Nozzle with 32mm outlet:

This set of experiments was conducted at an average water temperature of 24ºC. The R134's performance is very similar to that of air. Above 14m/s the R134a seems to have a thrust advantage of 10-15%.

Nozzle with 39.6mm outlet:

This set of experiments was conducted at an average water temperature of 26ºC (causing slightly faster boiling than the previous series), and without pressure readings from the MRJ engine. With the larger nozzle at lower velocities, thrust was similar in value to the small nozzle, with a clear advantage to the compressed air. Around 15m/s both the R134 and compressed air have similar thrust, while at higher velocities the boiling R134 seems to have an ever increasing advantage, reaching 20% at 17m/s.

4 CONCLUSIONS

This study is one of only a few attempts to apply the Marine Ramjet principle for underwater operation, and the only one known to use the method of phase transfer.

Tow-pool experiments were conducted where the drag, thrust and pressures in the MRJ engine, were measured, up to a velocity of 35 knots (18m/s). From comparison to the work of Koren (2005) it was found that the system performs consistently and predictably. Analysis of the results obtained in the current study for operation with compressed air at higher velocities shows that switching to the larger outlet nozzle (39.6mm) not only increases thrust, but allows for additional significant thrust increase by increase of the gas mass flow rate. Indeed, it seems that positive thrust (overcoming the net drag) can be obtained around 33g/s (air equivalent mass flow) with the larger nozzle. However, as air displays a linear thrust increase trend while drag increases exponentially, this positive thrust is predicted to exist only up to 13m/s. This gas mass flow rate is equivalent to a GLMR of 0.45%, a value not very far from the maximum efficiency value of 0.3% and still well below the flow rate of 0.8% at which positive thrust was obtained in the work of Mottard & Shoemaker (1961) at similar velocities. Within this study, the highest value of thrust that was reached was 74N (83% of the net drag), with the larger nozzle for R134a boiling, at 16.3m/s and 22g/s air equivalent mass ratio. This suggests that overcoming the net-drag is possible at 16-17m/s at mass flow rates of ~30g/s, with the boiling gas rather than air.

Compressed air was found to have an advantage over the boiling of the liquefied-gas at lower velocities. However, above 15m/s the boiling R134 has an increasing advantage over compressed air up to about 20% higher, at the maximum velocity reached with the large nozzle (17m/s). In the larger nozzle, the thrust of compressed air follows a trendline with a power of 1.2, drag generally increases with velocity by a power of 2, whereas the R134a boiling increases according to a 2.6 power. This exponentially increasing trend is very promising. There is expected to be a thrust-peak, for R134 boiling at even higher velocities, as thrust will drop off once the boiling liquid cannot complete boiling within the nozzle leading to loss of potential work.

Unfortunately, the experimental system is not set up for higher velocities or demonstration of positive-thrust, so these remain as speculations, at present.

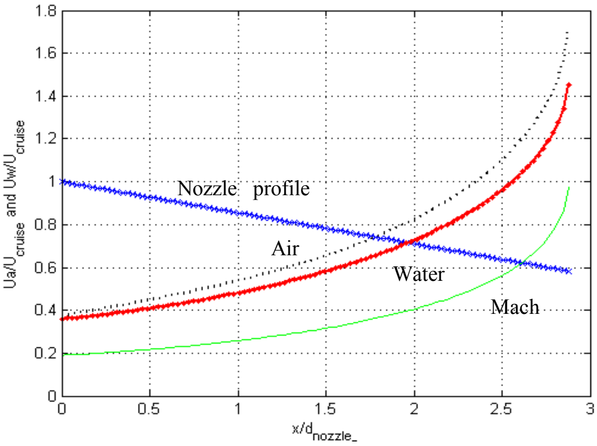

Figure 10: Air and water velocity profile along nozzle of the tow-pool MRJ engine, predicted by Simulator (Mor & Gany 2004) at 15m/s and 16g/s of air.

A possible explanation for the additional thrust found for the case of a boiling liquefied gas, is as follows: although boiling related expansion normally occurs in all directions and cannot seemingly contribute to thrust in any direction, when it occurs in a strongly accelerating flow a significant part of the expansion can be directed in a specific direction (downstream in this case), thereby displacing water and adding thrust. This means that peak thrust could be obtained in the given nozzle when boiling is brought close to the exit. Near the exit of the nozzle, acceleration obtains a maximum, as seen from a multiphase nozzle flow simulator run (Fig. 10). From analysis of the results, it seems that this peak-point was not reached with the R134a, and higher thrust is expected at higher velocities, up to a maximum value beyond which the droplets do not completely boil in the nozzle. A significant challenge raised by this peak thrust is that it is very sensitive to many parameters (nozzle geometry, boiling substance, ambient temperature/pressure and droplet size) and would require very accurate and careful design to utilize it.

An additional advantage to the use of a liquefied-gas is that use of a fuel in liquefied form is very compact. An advantage that is appreciable in time-limited and/or submerged applications, such as a MRJ torpedo or other high speed ROV (remotely operated underwater vehicle).

The configuration of the MRJ nozzle was originally designed for compressed air flow. As a next step it is suggested to redesign this section in an optimized way, for a boiling "fuel". By generating higher acceleration further upstream in the nozzle higher boiling-related thrust could result (such is the case in the constant pressure gradient nozzle studied by Albagli & Gany (2003)).

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