

Non-Combustion ^4He Powered Propulsion

Nelson Enrique Bolivar and Ivaylo T. Vasilev

Abstract—One of the biggest hurdles nowadays rocket propulsion is the large use of fuel. The amount of fuel and the burning efficiency defines how long the rocket engine can work which intimately limits the range and the load capacity of the rockets and spaceships. This according to the Newton third law is unavoidable - in order to move forward you need to leave something behind. There have been several attempts in the past to create an engine which doesn't use fuel in the common sense, like the M drive, but so far all of them were unsuccessful. In this article we attempt to explore a novel principle, a recycling cycle of fuel, by optimizing parametrically a system that uses ^4He phase transition.

Index Terms—Propulsion, fuel, helium, phase change.

I. INTRODUCTION

Space propulsion is any technology or method applied to systems used to move artificial objects once they leave the Earth's atmosphere. It is sought that, depending on the mission, the objects perform maintenance, pointing, stabilization, speed changes, elevation, insertion in an orbit, corrections in its orbit, transfer from one orbit to another, to de-orbit, and that it can be pushed to reach a celestial body or somewhere in space that you want. Launch propulsion systems are called main propulsion, and space propulsion systems are called secondary propulsion systems. These systems are based on the Jet propulsion that produces a force or thrust, by the expulsion of stored matter, called propellant.

Although there are various types of propulsion, in space systems there are basically two forms of propulsion: chemical propulsion, which uses chemical reactions to produce a flow of hot gas, thus providing a strong impulse; electrical propulsion, which uses the electrical power that can be generated from sunlight with photovoltaic solar panels to propel the spacecraft by other efficient means.

II. FUNDAMENTAL EQUATIONS OF PROPULSION

The "ideal rocket equation" describes the relationship between the speed of the spacecraft and the mass of the system which is derived as follows [1]. Consider a system of variable mass in an initial rest state, which passes to a final state after it has been ignited and where its fuel has been fully burned, therefore losing mass.

$$m dv = dm v_e \quad (1)$$

This is the fundamental equation that describes the movement of a rocket in free motion i.e. not under the effects of gravity.

Note that the loss of mass of the rocket implies $m > 0$, because a positive dm in equation 1, represents a loss for the rocket. The term on the right is called thrust, it has units of force and is responsible for the rocket's acceleration [2]. Returning to equation 1, this can be written as

$$dv = v_e \frac{dm}{m} \quad (2)$$

whose solution is,

$$\Delta v = v_e \ln \left(\frac{m_i}{m_f} \right) \quad (3)$$

where Δv is the total change in rocket speed from an initial mass m_i to a necessary lower final mass m_f . This equation was first derived by the Russian Konstantin Tsiolkovski (1857-1935). Tsiolkovsky's equation tells us that the change in velocity varies with the logarithm of the ratio of the final mass to the initial mass, this implies that large changes in velocity require that most of the initial mass of the rocket be fuel.

On our journey for a finding a way to recycle the propulsion exhaust we will explore several different designs:

A. Scenario 1

The first thought experiment consisted in a system which releases metal particles as a propulsion fuel, then, using magnetic forces as an drain to consume the particles in a direction perpendicular to the motion. See Fig. 1.

The law of momentum conservation states that a closed

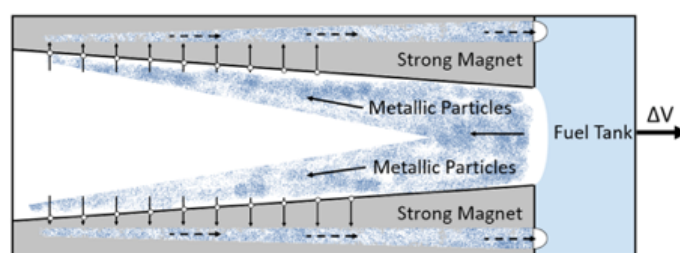


Fig. 1. Schematics for Scenario 1. The metal particles injected from the fuel tank generate thrust. The non-uniform magnetic fields collect the particle. The total momentum is conserved, so the whole systems stays motionless.

system not subjected to external forces will not change its velocity, or state of motion. The final momentum of the particles in the direction of motion is zero so the ship remains at its initial velocity [3].

A more detailed analysis relates the diminishing of momentum of the particles by interacting with the ship magnets, this interaction will reduce both momenta, ship and particle.

B. Scenario 2

Secondly, we aim to transform linear momentum into some other form of motion, for instance, angular momentum. If we put a cylinder in the way of the exhaust metallic particles- by hitting the cylinder some of the linear momentum is going to convert to angular momentum. As before, conservation laws - the linear and angular momentum of a closed system are always conserved independently - then what we expect happen in this case is that the overall linear momentum of the ship is going to stay the same but the system will start rotating to compensate for the new angular momentum of the rotating cylinder. Both scenarios deal with an unavoidable fact, that the momentum of the system is conserved.

III. CLOSED CYCLE

There is commonality between all rocket engines - they move through the medium of the space. But what is the space - it is not simply nothingness and void - no, the space has properties, for example:

- 1) It is very cold, about 2.7 Kelvins,
- 2) Very low pressure

So is it possible to use some of these properties to reduce the linear momentum of the engine exhaust so we can recycle it back and by doing so to still preserve some of the linear acceleration of the ship created by exhausting this fuel in the first place.

The conundrum is summarized in a simple question- is it possible to recycle your fuel keeping a finite total momentum in the system?. Consider the following set-up, The Chamber 1

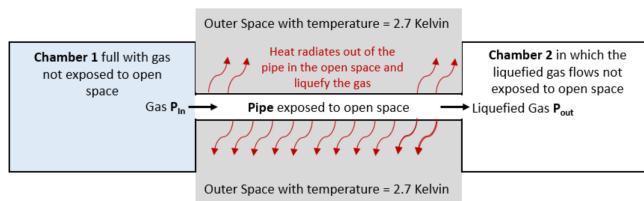


Fig. 2. Scheme of the simulation. Basic setup where the change of phase occurs into the pipe driven by constant pressure difference between chamber 1 and 2.

is full with a certain gas, Chamber 2 has lower pressure than Chamber 1 so the gas will flow from Chamber 1 to Chamber 2. A Pipe connects Chamber 1 to Chamber 2 and only the pipe is conveniently exposed to the open space to allow heat transfer. A phase transition will take place in the pipe and the liquefied gas flows from the pipe to Chamber 2. Let's divide this process into three separate stages; First, releasing gas from Chamber 1 creates a change in the linear momentum, then $\Delta P \neq 0$, the gas goes into the pipe with a momentum P_{in} . In a second stage, the gas goes through the pipe. The length of the pipe is such that all the gas liquefies. At a third stage the liquefied gas is collected in Chamber 2, where it is stored. Then, it seems clear that after both stages $\Delta P = 0$, since the momentum P_{in} is, in the absence of an external force, equal to P_{out} .

Any internal interaction that couples the gas and ship that could be used to reduce the P_{out} leads to a reduction of

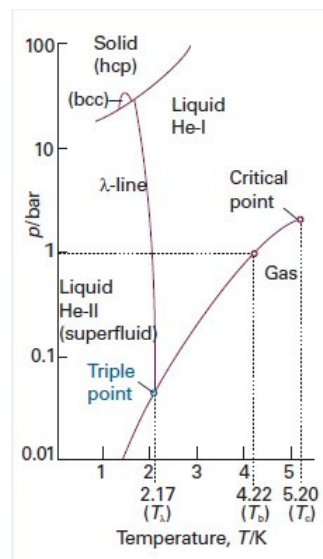


Fig. 3. The phase diagram for Helium shows other unusual behavior. ⁴He has two liquid phases with a transition between them. Helium's low temperature triple point is the point where He II, He I and He coexist. He II is a superfluid. It flows with zero viscosity.

the overall momentum of the gas-ship system, as in scenario 1. A reduction of the momentum of the gas-liquid without interacting with the ship after stage 1, will leave a momentum excess, even after completely storing the liquefied gas in chamber 2. We claim that depending on the gas used, the phase transition, and the two phase dynamics will create this effect.

To achieve $P_{in} > P_{out}$, we first must choose a gas that under such a situation does not interact with the ship, so that after stage 1 the gas and the ship are decoupled.

IV. PHASE TRANSITION AND HELIUM

Helium, ⁴He, at normal temperature and pressure is a gas, a state that maintains up to approximately 4.22 K. Below that temperature, ⁴He is liquid. Two phases can be distinguished within that liquid: Helium I, between ~ 4.22 and ~ 2.18 K or lambda point and Helium II, below ~ 2.18 K, [4], [5], [6], [7].

At the lambda point, Helium I becomes Helium II, in a phase transition without boiling. This is due to the very high thermal conductivity of this substance: any heating, before causing a temperature gradient, makes the liquid turn almost instantly into a gas, see Fig. IV. Another one of the important properties of Helium II is the lack of viscosity it shows when passing through narrow capillaries, and almost zero viscosity in other scenarios [8]. The most accepted explanation for this phenomenon contemplates a complex mixture of phase II and phase I atoms, and it is the latter that makes the whole thing viscous. The absence of viscosity guarantees that interaction with the pipe does not affect the momentum. Also, superfluidity for ⁴He implies the coexistence of two phases in the pipe with very complex dynamics. As a first approach ruled by Navier-Stokes equations, with the addendum of a two phase dynamics. Let us explore this dynamics numerically using the setup described above.

V. SIMULATIONS AND RESULTS

ANSYS FLUENT software pack with full version [9] was used for modeling the pipe gas-liquid dynamic of ⁴He, including the gas, and phases He I and He II. The aim was to set the initial and final conditions and run a multi-parametric optimization, in such a way that several plausible scenarios could be attained. The density-based solver in ANSYS FLUENT solves the governing equations 4 of continuity, momentum, and energy and species transport simultaneously as a set of equations [10], [11].

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) &= 0 \\ \frac{\partial(\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) &= -\nabla p + \nabla \cdot (\tau_m + \tau_{SGS}) \\ \frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\rho \vec{u} H) &= \vec{u} \cdot (\tau_m + \tau_{SGS}) + (\vec{q}_m + \vec{q}_{SGS}) \end{aligned} \tag{4}$$

where ρ is the density, \vec{u} velocity, E total energy per unit mass, and p pressure of the fluid. The τ 's are the viscous components and \vec{q} 's the heat flux. The term H contains source terms. ANSYS also contemplates Fluid-Fluid momentum exchange and phase change modeling. A general multiphase system consists of interacting phases dispersed randomly in space and time and using averaging techniques and closure assumptions to model the unknown quantities. Eulerian solving method is used to run a parametric simulation based on the setup in Fig. 4 was programmed. 4.

For the pipe the maximum length was set to 30 m and radius

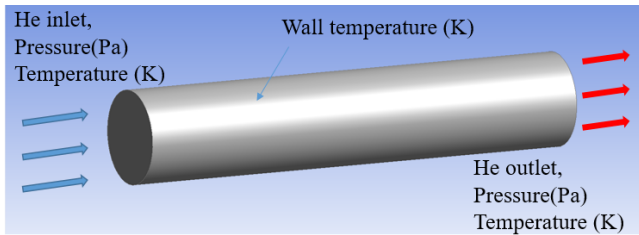


Fig. 4. System Setup for optimization

of 5 m.

Given the parameters to be optimized, a small mesh was setup (Fig. 5) and a large number of iterations were used to ensure

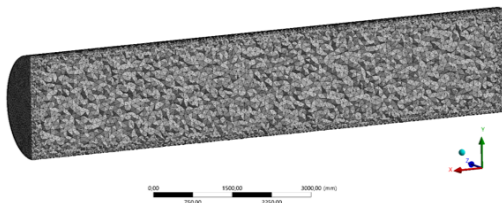


Fig. 5. Spatial mesh

proper convergence of the results, see Fig. 6

The table 7 shows the results for several parametric optimizations given the constraints imposed by Helium physical characteristics, and using primarily inlet temperature, length

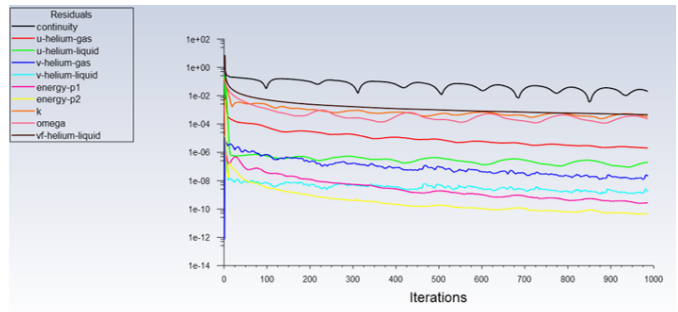


Fig. 6. Residuals Vs. Iterations showing proper convergence of the parameters considered.

and radius of the pipe as parameters. The table shows 20 points that represent a set of optimize parameters that fulfills the desire conditions of the momenta. The inlet temperature and pressure are also reported. The momenta are M_1 which refers to the momentum entering the pipe, and M_2 as the momentum of the liquefied gas leaving the pipe. Other parameters are the length and radius of the pipe.

The last column of 7 shows the ratio between M_1 and M_2 , defined as $R = \frac{M_1}{M_2}$. A ratio larger than one means that the momentum M_2 leaving the pipe is lower than M_1 and R give us the decreasing proportion between them.

N	Inlet pressure(Pa)	Inlet temperature (K)	Length (m)	Radius (m)	M1 (N)	M2 (N)	Ratio
1	2,53	6,80	22,50	2,55	1169,14	1080,92	1,08
2	4,90	9,78	15,45	4,93	5070,00	4793,54	1,06
3	4,73	3,62	15,14	4,79	2789,40	2737,14	1,02
4	4,90	3,81	15,84	0,15	0,66	0,63	1,05
5	0,27	9,82	29,26	0,11	0,09	0,045	2,08
6	4,43	9,95	29,92	4,98	17702,20	12941,30	1,37
7	4,99	3,70	29,57	4,53	5554,25	5398,14	1,03
8	0,18	9,66	15,13	4,70	4124,11	3804,93	1,08
9	4,95	9,88	29,17	0,46	69,75	53,15	1,31
10	4,72	9,75	15,36	0,31	11,16	9,93	1,12
11	0,24	9,19	15,26	0,13	0,40	0,30	1,34
12	0,36	3,75	28,69	0,17	0,28	0,24	1,16
13	0,58	3,90	29,31	4,96	6018,03	5818,04	1,03
14	4,89	3,87	29,43	0,22	1,78	1,63	1,09
15	0,25	3,79	15,18	1,01	84,11	81,59	1,03
16	0,17	9,73	29,08	4,98	16325,90	12193,70	1,34
17	0,88	4,39	15,31	4,86	2526,62	2438,51	1,04
18	4,67	6,89	22,33	4,91	4551,70	4248,85	1,07
19	4,94	6,95	15,27	2,64	1189,80	1125,80	1,06
20	2,44	9,91	21,85	4,63	5792,72	5169,65	1,12

Fig. 7. Number of points of 3D simulations that arose values of $R > 1$. The points $N = 5$, $N = 11$ and $N = 16$ are the most stable.

There are three points with the most interesting results, points $N = 5, 11, 16$. At point $N = 5$ the results are the one with more efficiency, $R = 2.08$, equivalent to a 108% decrease of the exhaust momentum. This particular point has a pipe length of ~ 29 m and a radius ~ 0.1 m, although the output and input momentum are very low. The fraction of gas-liquid distribution in the pipe increases as we go near the center of the pipe, as seen in fig. 8 while the velocity magnitude decreases, reaching a stationary point after the middle of the pipe, close to 25 m, see Fig. 9. This is an indication of the phase change influence on the final momentum.

The point $N = 11$ on the other hand, has a length ~ 15 m and a similar radius than point $N = 5$. A shorter pipe changes the actual configuration, the Inlet and outlet temperatures are

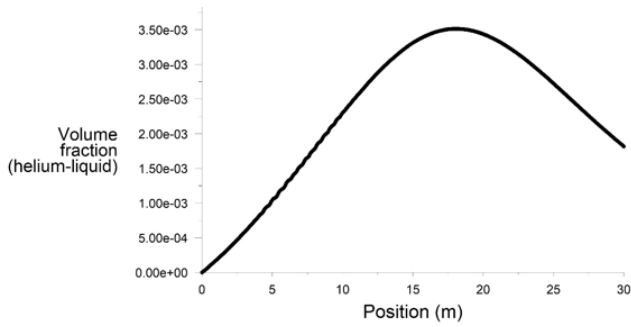


Fig. 8. Volume fraction

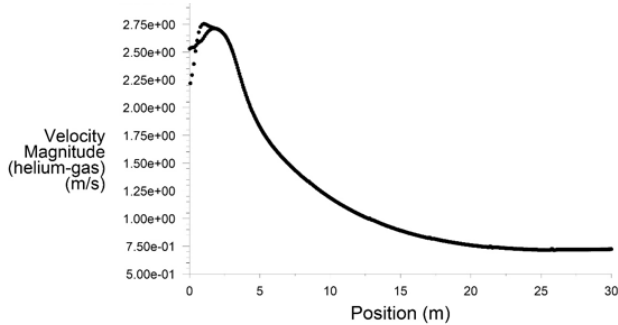


Fig. 9. Velocity

also similar, but the result $R = 1.34$ or equivalent 34% is smaller. Figures 10 and V shows how the volume fraction peak in this case is closer to the pipe's beginning, the velocity maximum is rather far than $N = 5$, indicating that most of the liquefaction takes place in the middle of the pipe as in $N = 5$, but that under the same pressure conditions the velocity is larger also around the middle reducing slightly as reaching the end of the pipe. The output momenta are one order of

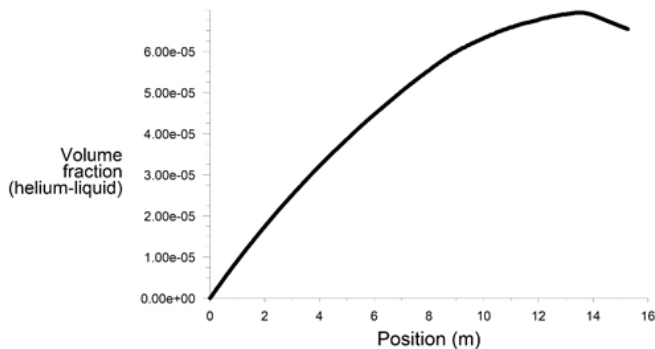


Fig. 10. Volume fraction for the point $N = 11$.

magnitude larger than $N = 5$, also an indication that the requirements for larger R are very subtle, a product of the phase change, and sensitive to the amount space needed to achieve the transition.

The point $N = 16$ has almost the same length ~ 29 m but a significantly larger radius ~ 5 m. Figure 12 shows the fraction of volume never reaching a maximum, the liquid phase

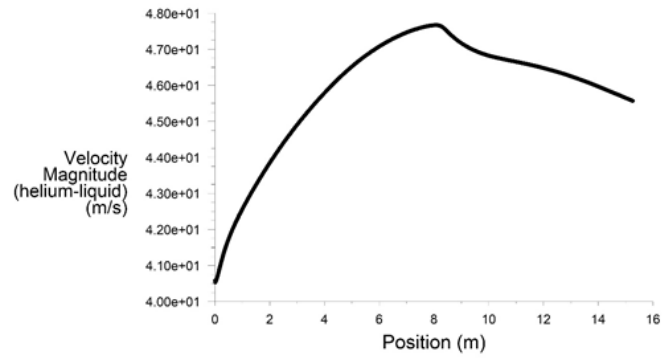


Fig. 11. Velocity Magnitude for the point $N = 11$.

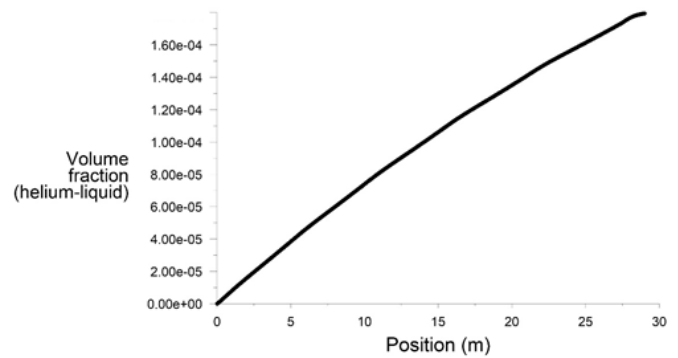


Fig. 12. Volume fraction for the point $N = 16$.

dominates at the end of the pipe. The velocity in figure 13 indicates a drop in the velocity, marked as the volume fraction increases. The final momenta on the other hand increases significantly, indicating a semi-stable point, where the system is not reaching equilibrium values. The sensitivities of the

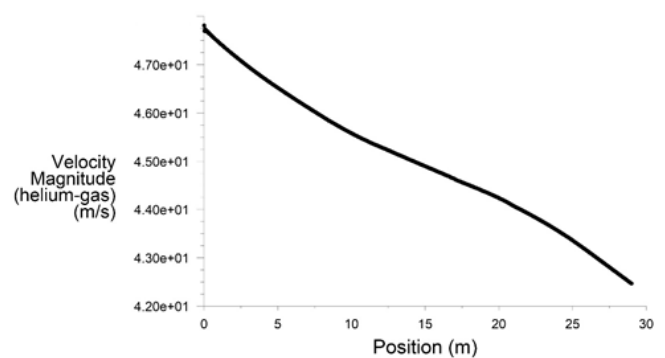


Fig. 13. Velocity magnitude for the point $N = 16$.

system in the parameters is shown in Fig. V- large radius significantly reduces the ratio, the length a secondary crucial parameter. The largest sensitivity comes from the temperature

as expected, also the radius dramatically changes the ratio R . It is clear that point $N = 5$ appears as the best candidate in

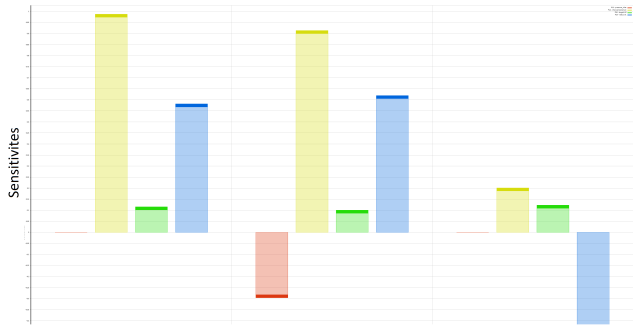


Fig. 14. Sensitivities to the changing parameters. Blue bar is the radius, green bar length of the pipe, yellow bar inlet temperature and red bar is pressure inlet. From left to right set of bars, M_1 , M_2 and R .

terms of maximal ratio, also reaches a minimal momentum for outlet and inlet parameters, which translates into less energy necessary to maintain the chambers unbalance in pressure and temperature. As shown in figure 15, there is a large contrast in the velocity between the initial and final points up to two orders of magnitude for this point.

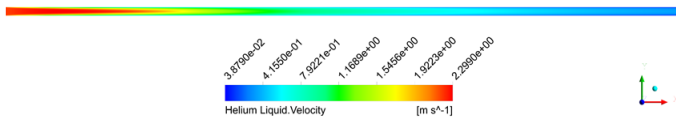


Fig. 15. Velocity distribution in half the pipe for the point $N = 5$.

We can also look at the temperature distribution in Fig. 16. It shows the optimal temperature unbalance. The fraction distri-

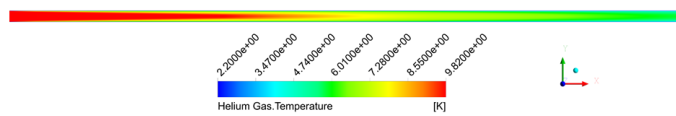


Fig. 16. Temperature distribution in half the pipe for the point $N = 5$.

bution reveals how the role of the liquid Helium reshapes the distribution of velocities, the lower the temperature, the larger the volume of liquid fraction and that minimizes the velocity. We can also look at the static pressure, that clearly signs the

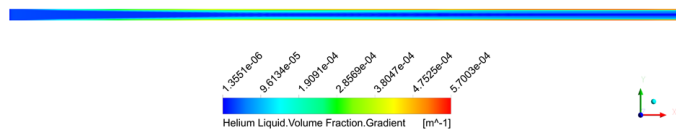


Fig. 17. Volume fraction distribution in half the pipe for the point $N = 5$.

diminishing in the mixture pressure, effect we interpret mostly due to the superfluid behavior of the 4He at the end of the pipe, see Fig. 18.

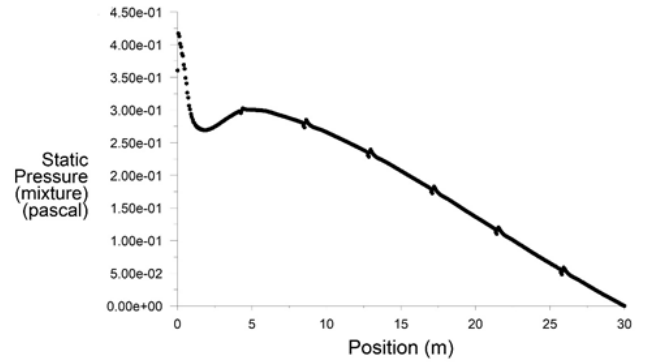


Fig. 18. Static pressure in the pipe for the point $N = 5$.

VI. CONCLUSION

The setup proposed shows that by taking advantage of the low temperatures in outer space we can significantly reduce the exhaust gas momentum during the phase transition of helium. This implies that we can store and recycle the liquid helium without losing all the momentum, making the whole setup a closed cycle. We can utilize this mass in several different ways such as transporting the liquefied helium from Chamber 2 to Chamber 1, heat up and exhaust it in the pipe to Chamber 2. In this way the system can work solely with electricity as a power source to heat and move the helium inside of the system to create acceleration for the ship, making it a non-combustion 4He based electrical powered closed cycle propulsion.

The liquidizing of some flowing materials, like Helium results into multi-phase dynamics that works as an optimization system for macroscopic changes. The proposed setup leads to very interesting results, depending on geometry, temperature and the pressure difference between the chambers. For long pipes ~ 29 m and small radius ~ 0.01 m the system has maximal optimization to reduce P_{out} . The lack of viscosity plays a fundamental role, as it can be seen when the radius is increased. If the radius is increased by two orders of magnitude and under the temperature range that we are considering, much less gas is liquefied in the pipe, then the coexistence of He I and He II phases causes a larger overall viscosity in the system. The viscosity produces interaction with the walls of the pipe, reducing the optimized situation for momentum reduction. A similar situation in terms of the viscosity takes place when the pipe is shortened. Phase transition gives a landscape of possibilities for macroscopic applications to propulsion systems.

VII. NEXT STEPS

There are several ways we can optimize the system, to include other gases, Hydrogen and oxygen and possibly a mix of them. Optimizing the geometric parameters, that is, length of the pipe, radius, temperature etc, will have different effects on the ratio of momenta with different gases. There are several types of phase transition to consider - it can be full or partial between gas and liquid for Helium and Hydrogen. For Oxygen it can be full or partial between gas and liquid

and partial between liquid and solid. Perhaps the interplay between both phases along the pipe could be relevant. Another scenario worth to explore is changing how the gas is injected into the pipe; in the present work we consider a continuous flow of gas, in contrast we could consider a pulse of gas that under the right pressure difference conditions could give other set of parameters for the $R > 1$ condition. By tweaking these parameters and materials we can find the most optimal scenarios in which the difference between $P_{in} > P_{out}$ is the largest.

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