Cold Gas Propulsion System for Hyperloop Pod Chassis

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Abstract. Hyperloop is a futuristic fifth mode of transportation proposed by SpaceX. A Pod shaped vehicle travels through a partially evacuated tube at speeds close to the speed of sound. This paper aims at designing a cold gas thruster system for propelling the Hyperloop pod. The system has a compressed air reservoir, this air is expanded through pressure regulators and further expanded and accelerated using a convergent-divergent nozzle. This paper discusses the architecture of the system, regulator pressure setting, suitable nozzle design and CFD analysis in a far-field environment.

Nomenclature:

| Symbol | Description |
|--------|-------------|
| t      | Time in sec |
| P_f    | Final tank pressure in Pa |
| P_i    | Initial tank pressure in Pa |
| P_a    | Tube pressure in Pa |
| C      | Free air flow rate in m³/s |
| V      | Volume in m³ |
| m_max  | Maximum mass flow rate in kg/s |
| A      | Area in m² |
| P_0    | Inlet pressure in Pa |
| V_rel  | Relative velocity of the gas in m/s |
| k      | Specific heat ratio |
| R      | Gas constant |
| T_0    | Inlet temperature |
| A*     | Throat area in m² |
| M_a    | Mach No. |
| ρ_0    | Inlet density in kg/ m³ |
| μ      | Expansion angle in rad. |
| T,P,ρ  | Temperature, pressure and density at general point respectively |
| F      | Force in N |
| W      | Work in joules |

1. Introduction
Hyperloop, a concept that can revolutionize the world of transportation cutting the time barrier by many folds in ground transportation technology. Hyperloop concept is envisioned by visionary entrepreneur Elon Musk in the year 2012 presented in his white paper 'Hyperloop Alpha' [1]. In the same year, he opens sourced the idea of Hyperloop for entrepreneurs, students, and other teams. Hyperloop transport
technology is based on the concept of pod traveling in a partial vacuum tube while achieving sonic speed. Elon Musk, in his white paper, proposed a design of pod which works on linear induction motor propelling pod speed up to 1200 km/h. Hyperloop pod utilizes near vacuum tube for transport reducing air resistance, the air bearing is used to reduce the rolling resistance in nutshell increasing the efficiency of the overall system.

Figure 1. CoEP Hyperloop Pod (2017).

Hyperloop systems main attraction is its supersonic speed which in the Hyperloop Alpha proposed as a linear induction motor. (There are some innovative means are available to propel the Hyperloop pod such as cold gas thrusters, electric induction etc.) “Hyperloop One” successfully tested its XP-1 passenger pod, reaching speeds of up to 192 mph (309 km/h) [2].

For Hyperloop pod competition [3] we developed a pod as seen in Fig. 1, that can travel up to the maximum speed of 360 km/h (the year 2017). The architecture of the pod is shown in Fig. 2. The pod is initially propelled with the help of Brush-less DC (BLDC) motors (1) up to the speed of 44 m/s, after that a Halbach array of magnets (2) are lowered. They, then provide the upward force required to levitate the pod. As the levitation starts, the pod is propelled further with the help of a cold gas thruster system (3). After achieving the predetermined braking conditions, the pod is braked with the help of Eddy current brakes (4). Throughout the journey, the attitude of the pod is maintained by a stability mechanism (5) as well as adjusting the position of levitation magnets. All the mechanisms are mounted on the chassis (6).

The levitation reduces the frictional losses incurred during the motion and a smooth and long cruising range. However, in this stage, the motors cannot provide the drive due to the lack of traction. The gas thruster system is thus required to provide the required propulsion. As the combustion is not allowed inside the tube, cold gas thrusters are used. They can provide the thrust whenever required.
2. Literature review
Since the year 2015 SpaceX organizes Hyperloop pod concept for various university student and non-student teams in order to invent new solutions for different subsystems of Hyperloop. They design and build the pod and a select few teams get a chance to have a test run in California situated 1:2 scaled test track. In this paper, we discuss the high-speed cold gas propulsion system for a sub-scale prototype of Hyperloop pod which can achieve the maximum speed of 350 km/h in the year 2017. This concept was first used by Arizona state university (ASU) team in 2016 [4]. ASU team’s compressed air thruster operates for 2.1 s over 295 m of track and can accelerate the pod at a rate of 7.91 m/s². The compressed air thruster allows the pod to reach a maximum velocity of 150 m/s. In our design concept which we proposed for hyperloop pod competition in the year 2017, our High Propulsion system is required to produce the thrust force of 3600 N to overcome the drag and propel the pod by 5.75 m/s² and reach the maximum velocity of 350 km/h.

3. System Architecture
The Pod is initially propelled from rest to a speed of 44 m/s, after which the levitation magnets are engaged as discussed in the previous section. At this stage, the cold gas propulsion is triggered. This is due to the fact that the efficiency of the thruster system will increase with the increasing speed, as shown in Fig.3.
In the cold gas propulsion system, the gas (air) is stored at 200 Bar in a composite tank with Aluminium inner cylinder and Carbon Fibre wrapped tanks at 300K (tube temperature). The on-off state of the entire system is controlled manually using a quarter turn valve for safety purpose. The flow thereafter is divided into three streams using a one by three manifold. Three solenoids operated valves are used downstream. The flow is divided for safety as well as limiting condition of mass flow rate and fool proofing. After that, the Air is passed through a pressure regulating valves and is expanded to 14 bar. The Air coming from all three valves are connected to an accumulator which will act as the buffer to give a continuous airflow of 5 kg/sec, which is then accelerated to Mach 3.8 through a DeLaval nozzle. However, due to the drastic pressure drop, there is a substantial temperature decrease. The low temperatures create a risk of Ductile to Brittle transition [5] in valves, hoses and hose fittings. Thus a suitable material selection is crucial for smooth and safe operation. The special cryogenic valves and fittings are used for this purpose. Cryogenic transfer hoses offer a leak free and safe flow of air. The De-Laval nozzle is made of Aluminium 5083 87 Cold Formed.

4. Design
The selection of gas plays a crucial role in deciding the reservoir volume. The various parameters like compressibility factor, cost, availability, the dangers involved in handling the gas. The Pressure setting in the regulating valve is a crucial parameter in nozzle design as it will determine the nozzle inlet

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**Figure 3.** Performance of various propulsion systems: Propulsion Efficiency Vs. Flight Velocity.

**Figure 4.** Construction of the cold gas propulsion system.
pressure for the choking condition. The selection of gas, as well as the calculations of the regulator setting, are discussed in this section.

4.1. Selection of Working Fluid

Some text. The working fluid selection greatly influences, not only the system performance but also the system size and weight. The volume of occupied by the gas at initial pressure and temperature will determine the reservoir tank size and thus its weight. Thus compressibility is an important selection parameter for the gas. Apart from that Saturation temperature, adiabatic constant, etc. are also important and are summarized in Table. I for Air, Nitrogen and Carbon Dioxide. These gasses were specifically shortlisted because of their availability and validation owing to the frequent use in many applications.

| Table 1. Physical properties of various gases under consideration [6] |
|-----------------|-----------|-------|
| k               | 1.4       | 1.4   |
| R               | 286.9     | 296.8 |
| T_{sat}         | 112.3642  | 109.2096 |
| Compressibility factor | 1.0326 | 1.0577 | 0.3899 |

4.2. Pressure Regulator setting

The regulator pressure is set at the pressure equal to the tank pressure at the end of the 8.7th second. This will ensure a constant pressure downstream the pressure regulator. The nozzle is then designed for the maximum flow rate of 5kg/sec and the inlet pressure equal to the regulator setting.

The pressure setting was calculated using the gas reservoir sizing.

\[ t = \frac{V(P_i - P_f)}{(C P_a)} \]  

(1)

By substituting appropriate values in Eqn. 1, for t, P_i, P_a, V and C and solving for P_f, the pressure in the tank at the end of 9th sec was calculated and was found out to be about 14 bar. This was the pressure set for a pressure regulator.

4.3. Nozzle Contour Design

Nozzle design is the thrust producing device in the system. It receives pressurized air from the accumulator at 14 bar and stagnation condition. The air is then expanded and by the virtue of Bernoulli’s principle, accelerated to the supersonic velocity (Ma = 3.8). As the supersonic speeds are involved, a convergent-divergent nozzle is required. Assuming the compressible flow, the Maximum mass flow rate (chocking condition) gives us the Throat area from equation (2). Exit area is calculated using equation

Figure 5. Block Diagram: Cold gas propulsion system.
The expansion angle at the throat is calculated using equation (7), while the other state variables are calculated using equations (4)-(6). The results are summarized in Table 2 for Air, Nitrogen and Carbon dioxide respectively. As, a rule of thumb, the upstream radius of curvature is kept to be 1.5rt while the upstream radius of curvature is kept to be 0.382rt. Where rt is the throat area radius.

\[
m'_{\text{max}} = AP_0 \sqrt{\frac{k}{RT_0}} \left( \frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}} \tag{2}
\]

\[
\frac{A}{A^*} = \frac{1}{Ma} \left( \frac{2}{k+1} \left( 1 + \frac{k-1}{2} Ma^2 \right) \right)^{\frac{k+1}{2(k-1)}} \tag{3}
\]

\[
\frac{\rho_0}{\rho} = \left( 1 + \frac{k-1}{2} Ma^2 \right)^{\frac{1}{(k-1)}} \tag{4}
\]

\[
\frac{T_0}{T} = \left( 1 + \frac{k-1}{2} Ma^2 \right) \tag{5}
\]

\[
\frac{P_0}{P} = \left( 1 + \frac{k-1}{2} Ma^2 \right)^{\frac{k}{(k-1)}} \tag{6}
\]

\[
\mu = \sin^{-1} \left( \frac{1}{Ma_1} \right) \tag{7}
\]

\[
v(Ma) = K \tan^{-1}(K * Ma) - \tan^{-1}(\sqrt{M}) \tag{8}
\]

Where,

\[
w, K = \frac{k+1}{\sqrt{k-1}}
\]

\[
M = (Ma^2 - 1)
\]

Another crucial parameter of the nozzle design is the Nozzle length. It not only influences the flow profile, but also the weight of the system. A smaller length or sharp changes in profile may lead to the formation of shock waves. Extremely longer nozzles make the design bulky and excessive skin friction losses. The geometrical parameters are depicted in Fig. 6.
5. Modeling and Simulation

The nozzle was modeled as a 2D axis-symmetric case. The inlet condition of 14 Bar and stagnant condition. The meshing was done in ICEM CFD and the model was simulated in ANSYS Fluent solver. The standard wall function k-epsilon turbulence model was used. The outlet vent pressure was maintained at 0.1 Bar which is equal to the ambient pressure of the tube. The results of the stationary nozzle are summarized in Fig. 7 and 8. The results vary about 1.5% from the analytically calculated values.

5.1. Nozzle Simulation: Stationary condition.

During the initial phases, the nozzle was simulated in a stationary condition with the boundary conditions stated previously. The contour was verified to be shock free. The pressure and velocity contours are respectively shown in below Fig. 7 and 8.

Table 2. Nozzle characteristic properties for various gases

|          | Air    | Nitrogen | CO2     |
|----------|--------|----------|---------|
| T0       | 300    | 300      | 300     |
| T*       | 250    | 250      | 262.1232|
| P*       | 749394.1 | 749394.1 | 776973.2|
| A*       | 0.00151 | 0.001536 | 0.001261|
| r*       | 0.021931 | 0.022117 | 0.020042|
| r*(mm)   | 21.93061 | 22.1174  | 20.04187|
| v*       | 316.8833 | 322.3042 | 252.6361|
| A1       | 0.011251 | 0.011444 | 0.013406|
| r1       | 0.059859 | 0.060369 | 0.065342|
| r1 (mm)  | 59.85936 | 60.36919 | 65.34163|
| A/A*     | 7.450111 | 7.450111 | 10.62927|
| P1       | 16149.81 | 16149.81 | 12816.26|
| V_out    | 659.3625 | 670.6423 | 574.0622|
5.2. Nozzle Simulation: Far-field analysis.
However, as the pod picks up the speed, the relative velocity between surrounding and nozzle leads to a changing outlet pressure condition which is actually a function of pod speed. For this, to investigate the shock whether any shocks occur during that boundary condition, we did far-field analysis, wherein the wind moves over the nozzle equal to the pod speed. The results of the simulation are depicted in the pressure and velocity contours in the below figure 9 and 10.
It can be seen that the exit velocity is increased by 1.2%. The Thrust provided was equal to 3465 N.

\[ F = m' V_{rel} + P_a A \]  

(9)

The analytically calculated thrust was about 3180 N. Thus there is a difference of 1.2% in analytical and simulated results.

6. Safety and state diagram

Cold gas propulsion is the second stage of acceleration, wherein the pod will be levitating and the wheel contact from the tracks will be relieved. In this condition, the state of the pod is continuously monitored by the IMU (inertial measuring unit), pressure sensors at tank, accumulator, and nozzle and the anemometer at the nozzle inlet. If any abnormality is detected the Air supply is cut off through the solenoid valves, and the pod is braked. If the maximum speed is reached before the predetermined distance from the tube end, the pod is cruised thereafter. Complete state diagram and the decision tree are summarized in flow chart Fig. 11.

The cylinder is a pressure vessel is susceptible to explode. To consider the impact of the explosion, TNT equivalence of the system is calculated. TNT equivalence is a standardized technique of comparing an explosive entity with that of TNT. The TNT value is calculated using the equation.
\[ W = P_0 V_0 \left( \ln \left[ \frac{P_0}{P_a} \right] - 1 \right) + P_a V_a \]

From this, the following values can be derived:

\[ W = 17.644 \times 10^6 \text{Joules} \]

1 joule = 2.39E-13 kiloton of TNT

As a result,

\[ W = 4.2169 \text{ kg of TNT} \]

7. Conclusion

In this paper, the architecture and working of cold gas propulsion (High-speed propulsion) were discussed. Various working fluids and geometrical and physical parameters that affect the performance and integrity of the system were carefully evaluated and simulated. The analytically and numerically calculated results for the exhaust velocities and pressures differ by 1.2%, which is quite acceptable. The far-field analysis was done to reduce the dependency on the assumption that the nozzle/system will be stationary. The control algorithm, state diagram upon various possibilities are also discussed in this paper. However, as it can be noticed, the TNT value of the system is quite high. This makes it dangerous to work around. For this various safety measures are needed to be taken. A close monitoring of the state of the system and an equally quick response to the stimuli is necessary. A thorough investigation is thus needed in this area.

The efficiency of the system can be improved by increasing the temperatures of the gasses. This will, however, increase the power consumption and a strain on the battery. Thus a trade-off between the produced thrust and consumed energy is required.

The cold gas propulsion system is an efficient system to propel the pod without internal combustion. The viability of the concept can be further improved by using an onboard compression system, as an axial compressor at the front of the pod, instead of a reservoir. This will not only reduce the TNT value of the system but also help in overcoming the drag and designing the pod closer to Kantrowitz limit.

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