Conceptual Sizing and Feasibility Study for a Magnetic Plane Concept

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MagnePlane is a Hyperloop-derivative concept proposed as a faster, cheaper alternative to high speed rail and traditional short-haul aircraft. It consists of a passenger pod traveling through a tube under light vacuum and propelled and levitated by a combination of permanent and electro-magnets. The concept is motivated by NASA's research thrusts driven by a growth in demand, sustainability, and technology convergence for high-speed transport. Magneplane is a radical departure from other advanced aviation concepts at first glance, however it remains an aeronautics concept tackling the exact same strategic golas of low-carbon propulsion and ultra-efficient vehicles.

The feasibility of this novel concept is investigated through a technical and cost perspective, focusing on vehicle aero and thermodynamics, structures, electromagnetics, weight and mission. A high-level sizing study is performed to determine total system costs and power usage given a parametric design varying tube area, pressure, pod speed, and passenger capacity. A vehicle sizing method is developed, using open-source toolsets focusing on the strong coupling between the two largest systems: the tube and the pod. The airborne vehicle requires many of the same technologies and expertise under development for next-generation aircraft and its high public visibility and rapid development make it an ideal candidate as an aircraft technology driver and test bed.

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Nomenclature

β	Volume coefficient of expansion (K)
	Mass flow rate
ϵ	Emissivity Factor
γ	Heat Capacity Ratio
ρ	Total, Hemispherical Reflectivity
σ	Stefan-Boltzmann constant ($\frac{W}{m-K}$)
υ	Kinematic Viscosity ($\frac{m^2}{s}$)
C_p	Heat capacity at constant pressure ($\frac{J}{kg-K}$)
c_{solar}	Gross Irradiance Adjustment
G	Solar Irradiance
g	Acceleration of gravity, 9.81 ($\frac{m}{s^2}$)
Gr	Grashof Number, $\frac{g\beta\delta T L^3}{v^2}$
h	Heat transfer coefficient ($\frac{W}{m^2-K}$)
k	Thermal Conductivity ($\frac{W}{m-K}$)
L	Length (m)
MN	Mach Number
NTU	Number of Transfer Units
Nu	Nusselt Number, $\frac{hL}{k}$
P	Pressure ($\frac{N}{m^2}$)
P_{rad}	Radiated Power (W)
PR	Pressure Ratio
Pr	Prandtl Number, $\frac{\upsilon}{\alpha}$
Q	Heat flow rate (W)
Ra	Rayleigh Number, $\frac{\rho U_\infty L}{\mu}$
T	Temperature (K)
η_{ad}	Adiabatic Efficiency

I. Introduction

Aerospace engineers have promoted tube transport over the course of a century; the most prominent include Robert Goddard[1] (creator of the first liquid fueld rocket) to Dr. Robert Salter (a forefather of the satellite). As early as 1972, a study conducted by the RAND coperation concluded that high-speed 'tubecraft' was technologically feasible with political pressure being the greatest obstacle.[2] National interest was once again rekindled in 2013 with a refreshed Hyperloop concept championed by Elon Musk, CEO of Space Exploration Technologies (SpaceX) and Tesla Motors.[3] Unlike previous waves of interest, the currently popularized design has spurred widespread international development efforts amongst hundreds of leading universities, private companies with over $100M in venture capitalist backing, and smaller research efforts at NASA and the US Department of Transportation.[4] The design has continously evolved, with the latest Hyperloop derivative generating lift using magnetic levitation. In the same way an airplane is differentiated from an airship, or a hydroplane is differentiated from a boat, Magneplane is a plane in the sense that it generates lift dynamically by moving over a medium at high-speeds, rather than depending on buoyancy or static phenomena. It's transonic operation, air-breathing flow-path and aerodynamic driven design all qualify it as a plane over a train. The concept deviates from existing high-speed rail designs by eliminating the rails, enclosing the passenger pod in a tube under a partial vacuum, with propulsion handled by a set of linear electromagnetic accelerators mounted to the tube. The entire system is held either above ground on concrete columns or subterranian tunnels maintaining a relatively straight trajectory.

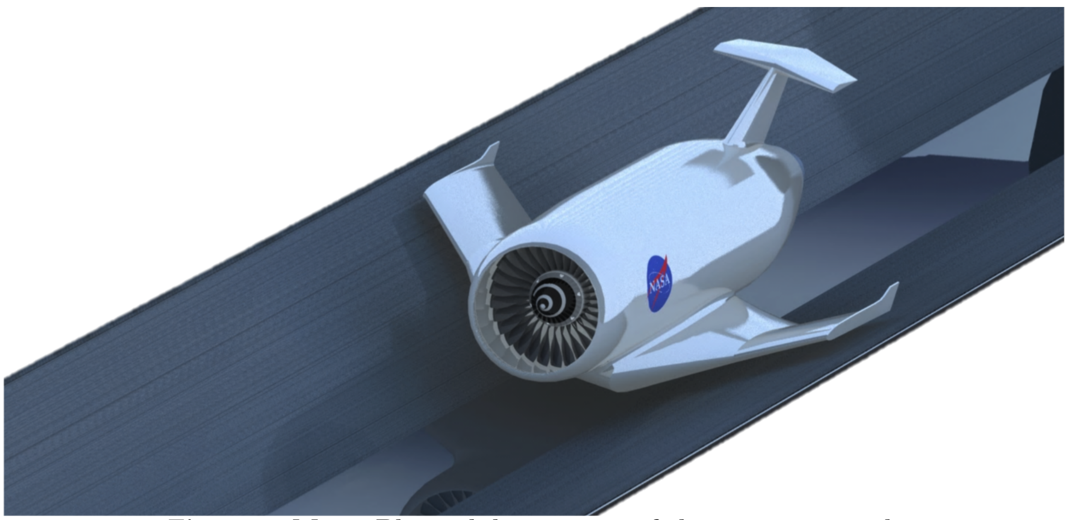

Figure 1: MagnePlane-alpha concept of the passenger pod.

II. Global Growth in Demand for High Speed Mobility

The MagnePlane vehicle flies low enough that propulsion can be offloaded to ground systems rivaling efficiencies previously limited to terrestrial vehicles. By sacrificing an airplanes traditional mission flexibility, its optimized for passenger throughput, door-to-door travel time, and energy efficiency. The concept is best-suited for distances between 250-500 nautical miles, which comprised 57% of commercial aircraft fleet operations in 2012.

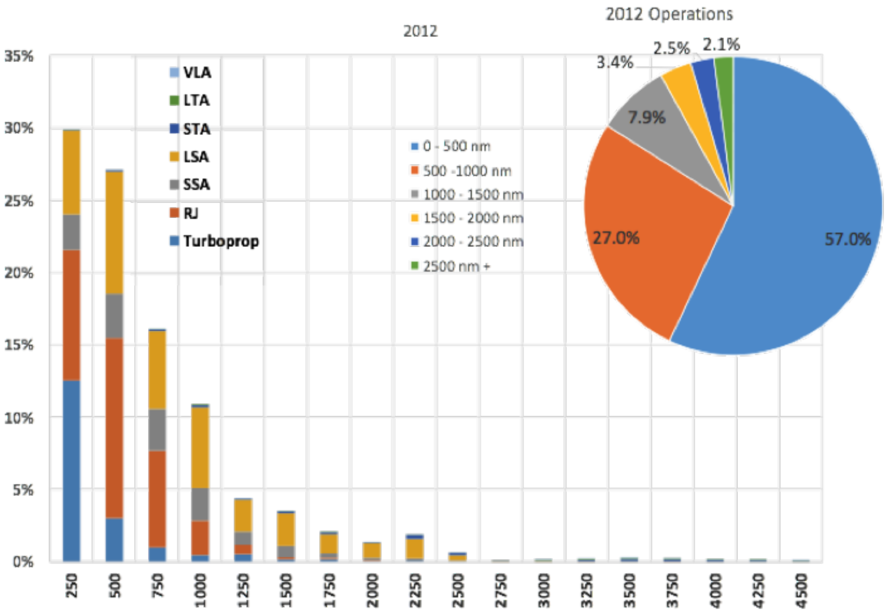

Figure 2: Credit: AATT, Mark Guynn. The bar graph plots percentage of 2012 fleet operations versus mission distance, aircraft type is distinguished by color. Alternatively the pie chart breaks down operations into six groups based on distance alone.

As stressed in NASA's Strategic Implementation Plan, operations must keep pace with both an overall growing transportation market and simultaneous growth in market share dedicated to high-speed transport. By 2050, 41% of world traffic market share will be high-speed transport.[5]

Hyperloop offers a compelling opportunity to offset this congestion. In terms of travel speed and door-to-door travel time, it's designed to occupy a highly desired gap between existing ground and air travel modes.

Furthermore, Hyperloop is positioned in the segment of the aeronautics market most sensitive to technology improvements. Optimizing operations in the 200-500 mile range is estimated to have the greatest effect on demand for person trips per year in 2025 as shown in Figure 4.

This critical range also coincides with the most price sensitive region of air travel. Beyond speed and energy efficiency, Hyperloop offers a unique high throughput capability relative to conventional aircraft. This departure from typical aircraft constraints is intended to provide a compelling price point at a time where automobile vehicle miles are projected to increase by 7 billion when airline fares increase by 10% in 2015 as shown in Figure 5.

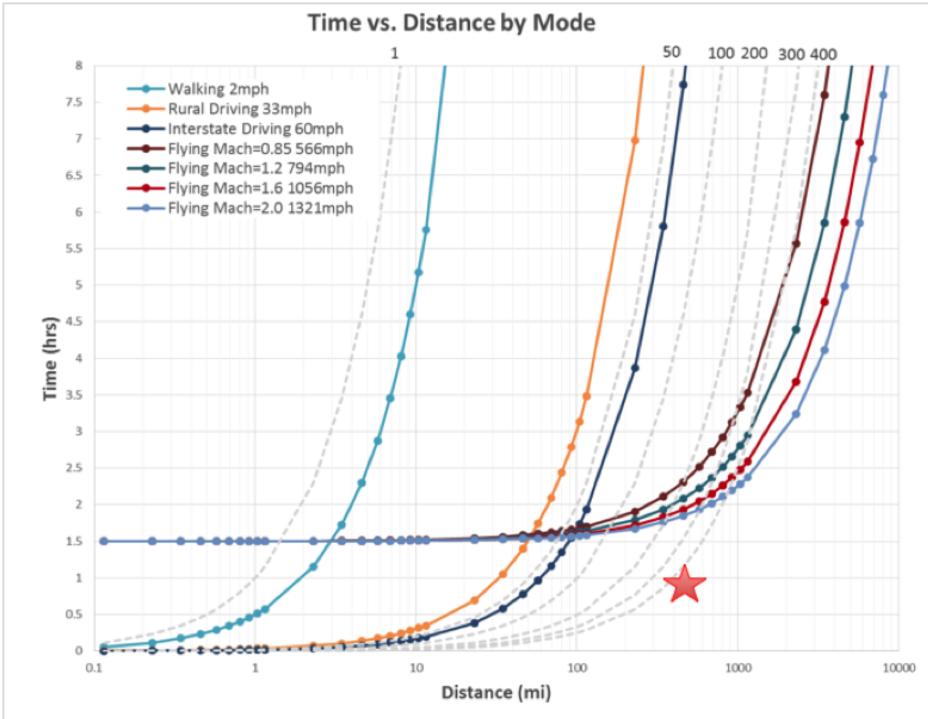

Figure 3: Relationship between travel time and distance, across multiple travel modes. Hyperloop offers innovation in passenger boarding, and delays associated with runway taxi, holding patterns, and other issues exacerbated by airport congestion. Source: NASA CAS Big Questions Workshop, G. Welch, J. Seidel

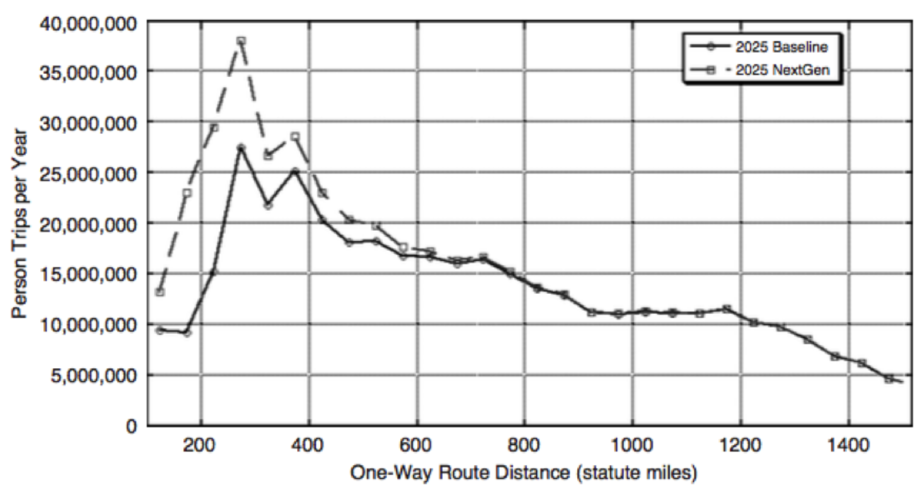

Figure 4: Potential increase in commercial airline demand because of NextGen. Source: Forecasting Model for Air Taxi, Commercial Airline, and Automobile Demand in the United States, H. Baik, et al.

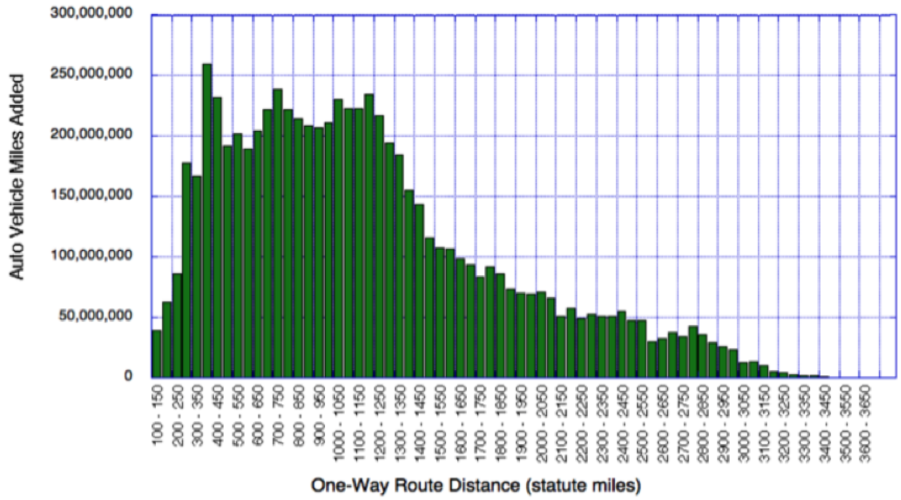

Figure 5: Distribution of displaced aircraft miles due to a 10% increase in ticket cost

III. Hyperloop Model Overview

The model expands on previous works[4] ,[6,7] and is built using OpenMDAO, a python-based modeling and optimizaiton framework. This work focuses on thermodynamic, aerodnymanic, structural, weight, sensor and power considerations, with additional calculations for cost and mission design. The full system model integrates multiple discpline tools including Fun3D, Pointwise, AFLR3, SUPIN, NPSS, Solidworks, PyCycle, Pointer, and Engineering Sketch Pad. OpenMDAO is used for it's built in drivers, solvers, optimizers, database recorders, external-code wrappers as well as it's mathematical derivative management. Each discpline is further discussed in the following sections.

A. tube

TUBE TEXT

1. PropulsionMechanics

2. TubeTemp

a. TubeWallTemp

b. TempBalance

3. TubeAndPylon

4. Vacuum

5. SteadyStateVacuum

FlowStart Compressor

B. cost

TubeCost Text

C. pod

D. mission

images/TopAssembly.png

Figure 6: Workflow and dependencies between the top-level Hyperloop assemblies.

IV. Compressor Power and Battery Sizing

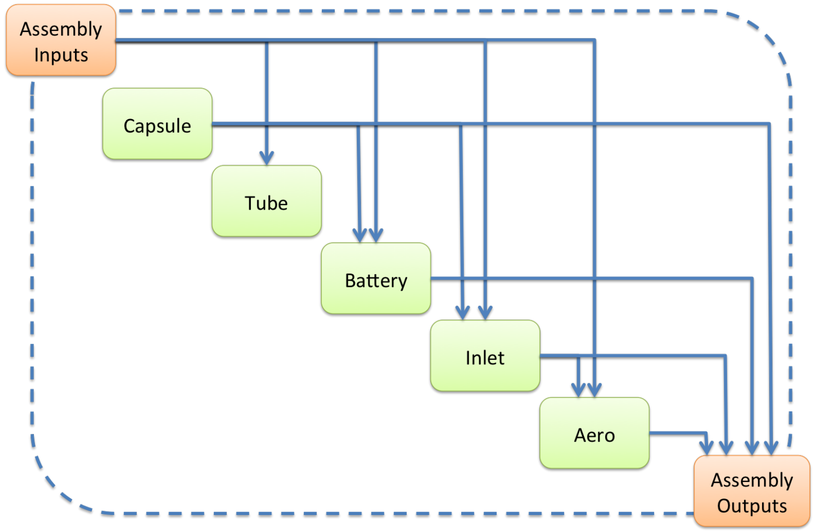

Figure 7: Expanded pod geometry assembly

V. Magnetic Levitation and Linear Induction Motors

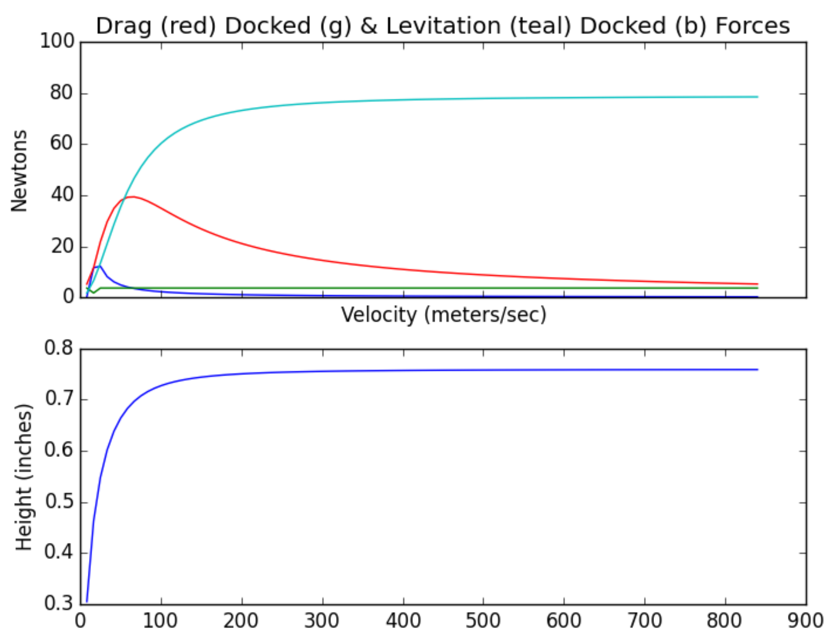

Figure 8: Halbach Maglev Lift and Drag versus Vehicle Speed

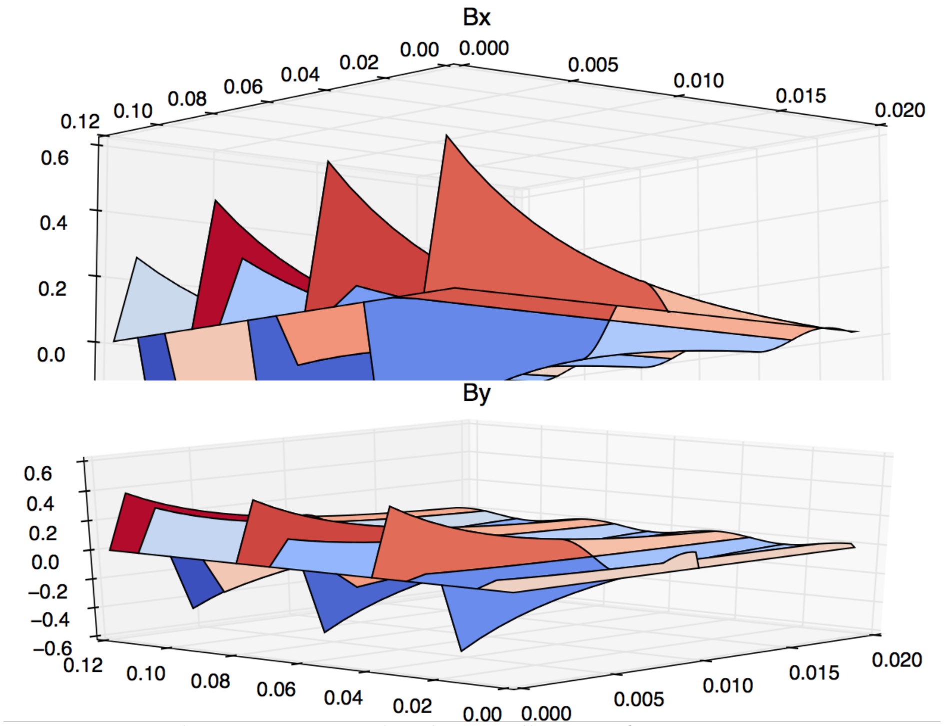

Figure 9: Magnetic Flux vs distance from magnet

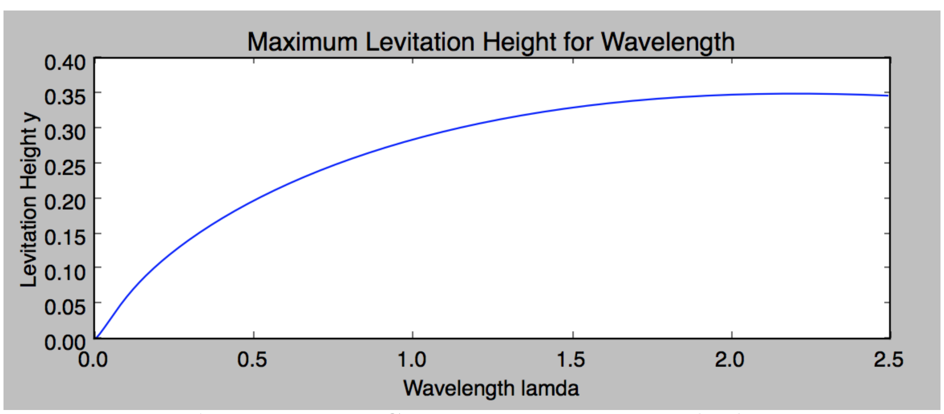

Figure 10: Raw Cost per passenger vs Tube h1

VI. Tube Structure and Cost

A trade-off exists for the distance between support pylons and tube thickness.

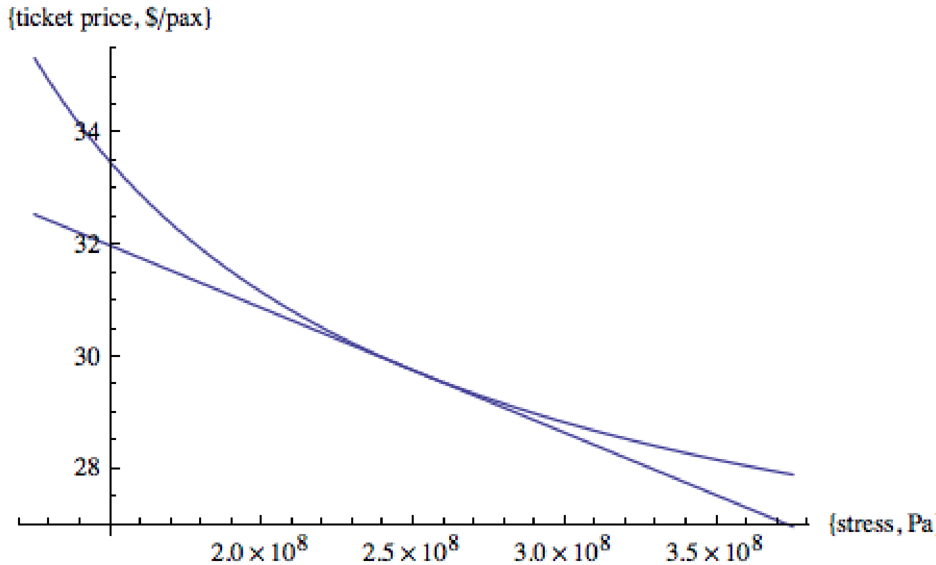

Figure 11: Raw Cost per passenger vs Tube Stress

VII. Mission

The mission is driven by the turn radius of the vehicle at high speeds. To optimize the trajectory, tighter turns needed to be traded against pod speed.

VIII. Aerodynamic and Compression Cycle Considerations

Depending on the ratio in cross-sectional area between the pod and tube, it may make sense to eliminate the on-board compression system. This would reduce the vehicle weight, but increase drag. The net power is tightly coupled with the rest of the system.

IX. Conclusions

References

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A. Sample Source Code and External Contributions

A. Github

B. Usage Example

Since assemblies often require iteration and convergence, a solver is then added. Each added parameter gives the solver variables to vary, until all declared constraints are satisfied.

B. Engineering Equations

8,9,10

$$Q_{conv} = \underbrace{\frac{k \cdot Nu}{D_{o,tube}}}_{h} \underbrace{\pi L_{tube} D_{o,tube}}_{\text{Area}} \underbrace{(T_{tube} - T_{amb})}_{\Delta T} \tag{1}$$

$$Q_{rad} = \underbrace{\epsilon \sigma (T_{tube}^4 - T_{amb}^4)}_{\text{Radiated Power per unit Area}} \underbrace{\pi L_{tube} D_{o,tube}}_{\text{Surface Area}} \tag{2}$$

$$\frac{A_{bypass}}{A_{tube}} = \frac{M_{pod}}{M_{bypass}} \left(\frac{1 + \frac{\gamma - 1}{2} M_{bypass}^2}{1 + \frac{\gamma - 1}{2} M_{pod}^2} \right)^{\frac{\gamma + 1}{2(1-\gamma)}} \tag{3}$$

$$Nu = \left(0.6 + \frac{0.387 Ra^{\frac{1}{6}}}{[1 + (\frac{0.559}{Pr})^{\frac{9}{16}}]^{\frac{8}{27}}} \right)^2 \tag{4}$$

$$Q_{conv} = \underbrace{\frac{k \cdot Nu}{D_{o,tube}}}_{h} \underbrace{\pi L_{tube} D_{o,tube}}_{\text{Area}} \underbrace{(T_{tube} - T_{amb})}_{\Delta T} \tag{5}$$

$$T_{t,exit} = T_{t,inlet} \left[1 + \frac{1}{\eta_c} \left[\pi_c^{\frac{\gamma - 1}{\gamma}} - 1 \right] \right] \tag{6}$$

$$Q_{released} = effectiveness \cdot \underbrace{(T_{hot,in} - T_{cold,in}) \, [\dot{m} C_p]_{fluid}}_{Q_{max}} \tag{7}$$

$$\underbrace{\dot{m}_{air} C_{p,air} (T_{out,air} - T_{in,air})}_{Q_{released}} = \underbrace{\dot{m}_{water} C_{p,water} (T_{out,water} - T_{in,water})}_{Q_{absorbed}} \tag{8}$$

$$T_{t,inlet} = T_{tube} [1 + \frac{\gamma - 1}{2} M^2] \tag{9}$$

$$Q_{solar} = \underbrace{(1 - \rho_r) c_{solar} G}_{\text{Solar Heat per unit Area}} \underbrace{L_{tube} D_{o,tube}}_{\text{Effective Area}} \tag{10}$$

[To be continued...]