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Hydrogen tube vehicle for supersonic transport: 5. Aerodynamic tunneling☆

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ABSTRACT

Aerodynamic tunneling is the process of transporting a vehicle from terrestrial point A to B via a closed tube containing an atmosphere more aerodynamically favorable than air. Equations are derived for "gas efficacy," Γ, a measure of how well a gas increases Mach-1 speed or decreases drag of a vehicle. Theoretical results, Γ_p and its Mach-normalized form Γ_1, based on reducing the vehicle to a flat plate, allows efficacy to be calculated ab initio as a function of only four gas parameters: ratio of specific heats, pressure, density, and viscosity. Hydrogen has the highest normalized gas efficacy ($\Gamma_1 = 48.5$ s/kg). Ammonia, hydrocarbon gases, and helium have above-average efficacies. Xenon has the lowest (10.1 s/kg). Binary mixtures of hydrogen and methane (or natural gas) are proposed for lowering the upper flammability limit at a relatively small penalty in efficacy.

Introduction

Aerodynamic tunneling has the potential of enabling high-efficiency, quiet, supersonic transport. The concept entails transporting a vehicle from terrestrial point A to B via a closed tube containing an atmosphere more aerodynamically favorable than air [1]. Tube pressure is essentially the same as outside air pressure, taken as 101.3 kPa. In a tube, the physical identity of the atmosphere can be chosen at will (a) to increase the speed of sound so that Mach 1 corresponds to a higher absolute speed (m/s) or (b) to decrease gas density or viscosity so that drag is reduced. The origin of the term "aerodynamic tunneling" is its analogy to "quantum tunneling": Quantum tunneling lowers the potential-barrier for passage of an electron, and by analogy, aerodynamic tunneling lowers the sonic and drag barriers to transit of a vehicle. While the Mach number inside the tube is below unity, a vehicle can arrive at point B ahead of its sound in air outside the tube and is therefore supersonic. A conservative speed limit of such a vehicle, using propeller propulsion, has been estimated [2–4] as Mach 0.74 in hydrogen (1 km/s), which corresponds to Mach 2.8 for a land vehicle outside the tube and to Mach 3.3 for the same body hypothetically at 11,000 m, a typical cruise altitude of transport airplanes.

I previously developed a semi-quantitative ranking of gases for the purpose of evaluating gases for aerodynamic tunneling, but the method, based on a figure of merit, lacked a theoretical foundation [1]. The only physical example of aerodynamic tunneling is a supersonic rocket sled that

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impacted a helium-inflated polyethylene tunnel, which allowed it to accelerate to hypersonic speed because of reduced drag and aero-thermal effects [5]. A substantial literature exists on the aerodynamics of bodies operating in air-filled tubes (see Refs. [6–13] and references therein), but because air was the medium, these studies do not address aerodynamic tunneling.

We have commenced a project to experimentally demonstrate and investigate aerodynamic tunneling. There are no known data for non-air tube vehicles, and thus our proposed experiments will break new ground. Engineering design of the scaled prototype vehicle is summarized in Fig. 1. Equilibrium (cruise) speed of the prototype will be Mach 0.27 in several gases, including hydrogen. Mach 0.27 in hydrogen (354 m/s) is slightly greater than Mach 1 in air, a speed that is unsustainable for aircraft.

The purpose of this paper is to lay the theoretical foundations of a quantitative method of analyzing gases for their efficacy in aerodynamic tunneling. Parameter Γ, termed "gas efficacy," is a measure of how well gases achieve the objectives of high speed and low drag. By comparing Γ-values, prospective gases can be evaluated for aerodynamic tunneling. Although hydrogen has been proposed as a tube gas, others have favorable properties, and we will see that hydrocarbon gases and helium are also promising tube gases. The analysis includes gas efficacy for mixtures of gases, which can offer benefits of reduced flammability or cost. Parameter Γ itself does not address characteristics other than speed and drag, e.g., it does not address breathability of the gas as fuel or oxidant, safety, cost, or thermal conductivity.

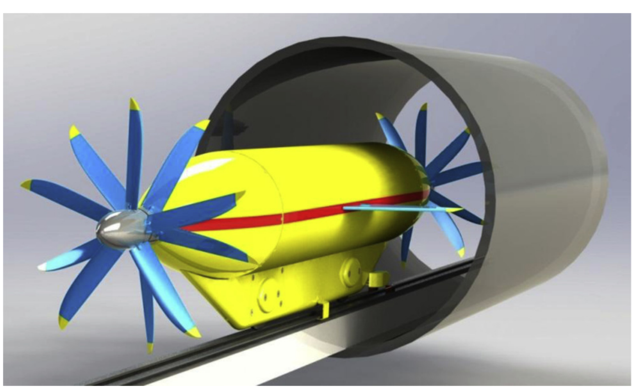

Fig. 1 – Engineering CAD model of the prototype supersonic tube vehicle: Vehicle dimensions: length, 1.40 m; maximum fuselage diameter, 0.168 m; and propeller diameter, 0.307 m. The tube is PVC water pipe, with inside diameter of 0.476 m and outside diameter 0.508 m, which encloses the experimental atmosphere. Vehicle equilibrium speed is Mach 0.27 in each gas: For H_2, this corresponds to Mach 1 in air outside the tube. Contrarotating propellers and absence of crosswinds in the tube enables use of a single rail to support and guide the vehicle, and a one-rail vehicle has lower infrastructure cost and lower drag [5] than a two-rail vehicle. Ailerons provide balance at high speed; a landing gear extends at low speed. Electrification of the rail structure provides power for the four contrarotating rotors.

Results and discussion

Based on the criteria of speed and drag, define gas efficacy Γ as

$$\Gamma = \frac{c}{D} \tag{1}$$

where c is the speed of sound (m/s) in the gas and D is drag (N) of a vehicle operating in the gas. For an ideal gas, the speed of sound is given by Laplace's formula [14]

$$c = \sqrt{\frac{\gamma p}{\rho}} \tag{2}$$

where γ is the ratio of specific heats (dimensionless), p is tube pressure (Pa), and ρ is tube gas density (kg/m^3). Drag is given by

$$D = \frac{1}{2} C S \rho V^2 \tag{3}$$

where C is the drag coefficient of the vehicle, S is a measure of vehicle area (such as surface, frontal, or planform area), and V is vehicle speed. Substitution of Eqs. (2) and (3) into Eq. (1), followed by simplification, gives

$$\Gamma = \frac{2\sqrt{\gamma p}}{C S \rho^{3/2} V^2} \tag{4}$$

as the gas efficacy, for a given vehicle, of a gas having parameters γ, p, and ρ. The units of Γ are s/kg. By operating a given vehicle as a "probe" (or measuring instrument), with fixed parameters C, S, and V, we can measure Γ as a function only of the gas parameters. Hence, gases can be quantitatively compared for efficacy.

If the vehicle is reduced to a flat plate, we can do this theoretically: Because the drag coefficient for a plate is known analytically, Γ can be calculated ab initio from only gas parameters, which thereby obviates the need to empirically measure the drag coefficient, area, and speed in Eq. (4). The drag coefficient for an ideal flat plate, experiencing only laminar flow, is known [15,16] as

$$C_p = \frac{1.328}{\sqrt{Re}} \tag{5}$$

where Re is the dimensionless Reynolds number, $Re = \rho V L/\mu$, L is the plate's length (m), and μ is gas viscosity (Pa s). Eq. (5) is valid for incompressible, laminar flow. Incompressibility, the essential criterion [see reference [16, p. 989]], requires the plate's speed V to be below approximately Mach 0.3 [15]. Let the probe be a rectangle of length $L = 1$ (parallel to the flow), and let its speed be $V = Mc$, where M is the Mach number. With substitution of these values for V and L, Eq. (5) becomes

$$C_p = 1.328\sqrt{\frac{\mu}{\rho M c}} \tag{6}$$

Let the plate have width perpendicular to flow of $b = 0.5$ (m) and be infinitesimally thin. Its surface area, counting both faces, is therefore $S = 2 \times b \times L = 1$ m^2.

Substituting the above results $C = C_p$, $S = 1$, and $V = Mc$ into Eq. (4) gives, after simplification,

$$\Gamma_p = \Gamma_1 \cdot \Gamma_2 = \frac{1.506}{(\gamma p)^{1/4} \rho^{1/4} \mu^{1/2}} \cdot \frac{1}{M^{3/2}} \tag{7}$$

where Γ_p is the gas efficacy based on the flat-plate probe, factor Γ_1 is a function of four gas parameters (γ, p, ρ, and μ),