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Feasibility of Extremely Heavy Lift Hot Air Balloons and Airships

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Abstract

State of the art airships and aerostats (air vehicles) use hydrogen and helium as lifting gases. Hydrogen is extremely flammable, while helium is rare and expensive. In the present work, feasibility of air vehicles using hot air, hot nitrogen, and/or hot mixture as lifting gases is demonstrated. Thermal power requirements for air vehicles using hot lifting gases are calculated. 1) It is shown that for extremely heavy aerial vehicles, whose gross takeoff mass exceeding 3,000 tons, required thermal power is proportional to $M_{\text{vehicle}}^{1/3}$ where M_{vehicle} is an air vehicle mass. 2) For lighter aerial vehicles, whose gross takeoff mass is below 100 tons, required thermal power is proportional to $M_{\text{vehicle}}^{2/3}$. Specific thermal power requirement is low for extremely heavy vehicles and high for light vehicles (For 1000 ton gross takeoff weight, specific thermal power requirements are from is 41 W/kg to 52 W/kg). 3) Using hot nitrogen and/or nitrogenhydrogen mixture decreases thermal power requirements by 10% to 24%.

Keywords: Hot air balloons; Airships; Air transportation; Thermal insulation

Introduction

In the present work, we demonstrate feasibility of using hot air and hot nitrogen with small addition of hydrogen as lifting gases for very heavy and extremely heavy airships and aerostats. In what follows we will use "airvehicle" instead of "airships and aerostats". An airvehicles is called very heavy if its gross takeoff weight is between 300 tons and 3,000 tons, and is called extremely heavy if its gross takeoff weight is over 3,000 tons. Such air vehicles may be used as luxury sky liners, and/or for transporting bulk loads over land, e.g., growth of wind power production necessitates transport of heavy wind turbines to mountain regions (as presented in [1]), a 175 m steel tower for wind turbine whose weight is 1,165 tons.

Contemporary example shows that airvehicles may be used for harvesting power from upper atmosphere. In a solar updraft tower, air heated within a solar greenhouse rises within a tower and rotates turbines [2,3]. Solar updraft tower efficiency increases with tower height. Some proposed towers, being of many kilometers high, are supported by tethered aerostats [4,5]. There are projects for harnessing solar power by high-altitude aerostats [6]. Airships can also be used to harvest high-altitude solar power [7,8]. At 50° North latitude, beam irradiation at 9 km is about 4,700kWh/year. Beam irradiation at 12 km is about 5,3.00kWh/year. At ground level, beam irradiation is about 1,150kWh/m^2 [9]. Hoos mega power tower would use the cold of an upper atmosphere and heat from ocean water to drive a heat engine [10]. Tropical atmosphere provides a perfect opportunity for harvesting the temperature dif- ference between lower and upper atmosphere. Temperature in tropical atmosphere drops from 20°C to 30°C at the surface to between -70°C and -81° C at 16 km altitude [11]. The main problem, which has prevented the construction of heat engines based on this temperature difference, is the lack of massive aerostats, which can be moored at high altitudes.

Currently, there are several projects for heavy airships. Russian engineer Orfey Kozlov and Aerosmena company is developing a hot air airship A600 with a gross takeoff weight of 1500 tons and payload of 600 ton. This airship uses engine exhaust to heat air to 200°C. A600 would cruise at 150 km/h [12].

Any airvehicle has to use a lifting gas, which is considerably lighter than air in order to provide sufficient buoyant force. Since such gases as hydrogen and ammonia have a problem of flammability, most airvehicles use helium as a lifting gas. However, for very heavy and extremely heavy airships, helium cannot be used due to its limited availability. In 2019, World helium production was 160 million m^3 and helium price was $4.30 per m^3. The major use of helium was for cryogenic applications [13].

Lifting gas for very heavy and extremely heavy airvehicles must be either hot air, or hot nitrogen, or hot N95 45 mixture, which consists of 5.5%H_2 and 94.5%N_2 by volume. This mixture is not flammable and its density is 0.92 that of air. Using nitrogen or N95H5 mixture has two advantages over air: these gases are slightly lighter than air; they require lower temperature than air in order to be sustained at a given density. At the end of Section 2, we prove that using hot nitrogen or hot N95H5 mixture reduces power requirements by 10% and 24% respectively compared to hot air. Using these gases enhances safety, as they can not sustain fire within the balloon or aerostat.

The main expense for using hot lifting gas is the energy requirement for sustaining gas temperature. For small non-insulated balloons, energy expenses are exorbitant. An aerostat with a radius of 2.3 m and a total weight of 16 kg requires 66 kW heating power [15]. Hot air as lifting gas is useful only for very heavy and extremely heavy airvehicles, since by using thermal insulation they require much less specific power (power per unit mass) to sustain high lifting gas temperature.

Then we calculate thermal power requirements. Namely, we show that a typical 1,000 ton airship requires 52 MW thermal power; a typical 3,000 ton airship requires 80MW; a typical 10,000 ton airship – 125MW; a typical 30,000 ton airship – 187MW. A typical 1,000 ton high altitude aerostat requires 41MW thermal power; a typical 3,000 ton high altitude aerostat requires 70MW; a typical 10,000 ton aerostat – 122 MW; a typical 30,000 ton aerostat -196MW.

In particular, we demonstrate that for an extremely heavy airvehicle, heating power requirement is proportional to $M_{\text{airship}}^{1/3}$ and specific power requirement is proportional to $M_{\text{airship}}^{-2/3}$. For a light airvehicle, heating power requirement is proportional to $M_{\text{airship}}^{2/3}$ and specific power is proportional to $M_{\text{airship}}^{-1/3}$.

Airvehicle Thermal Power Requirements

In this section, we calculate thermal power requirements for sustaining air temperature within an airvehicle. It can be readily shown that the rates of convective heat transfer away from airvehicles can be given by

$$\begin{aligned} P_{\text{Heat}} &= A_{\text{airvehicle}}\left(T_{\text{int}}-T_{\text{ext}}\right)\left(\frac{1}{h_{\text{ext}}}+\frac{1}{h_{\text{int}}}+\frac{1}{h_{\text{wall}}}\right)^{-1} \\ &= A_{\text{airvehicle}}\left(T_{\text{int}}-T_{\text{ext}}\right)\left(R_h+\frac{1}{h_{\text{wall}}}\right)^{-1} \end{aligned} \quad (1)$$

where all the notations are defined in the “List of Notations.” The heat transfer resistance, R_h, of uninsulated airvehicle can be given by

$$R_h=\frac{1}{h_{\text{ext}}}+\frac{1}{h_{\text{int}}}. \quad (2)$$

A typical hot air balloon of to size in diameter has the following external and internal convection heat transfer coefficients [16]:

$$\begin{aligned} &h_{\text{ext}}=3.4\frac{W}{m^2K}, \quad h_{\text{int}}=16\frac{W}{m^2K}, \\ &\text{which yields} \quad R_h=0.36\frac{m^2K}{W}. \end{aligned} \quad (3)$$

Airvehicles have much higher external heat transfer coefficients than calculated above due to their rapid motion relative to air.

Now we begin calculations of thermal power requirements for an airvehicle. We assume that the formula for the surface area of an airvehicle is

$$A_{\text{airvehicle}}=5C_{\text{Shape}}V_{\text{airvehicle}}^{2/3}, \quad (4)$$

Where C_{Shape} is a factor depending on airvehicle shape. For a spherical aerostat, $C_{\text{Shape}}\approx 1$. For a saucer-shaped airvehicle with height being one third of the main diameter, $C_{\text{Shape}}\approx 1.4$. For a streamlined airvehicle with length exceeding diameter by a factor of 5, $C_{\text{shape}}\approx 1.3$. The volume of airvehicle needed to produce necessary lift is

$$V_{\text{airvehicle}}=\frac{M_{\text{airvehicle}}}{\rho_{\text{air}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right)}, \quad (5)$$

where ρ_{air} is the air density at the desired height. Substituting formula $\sqrt{5}$ into relation (4), we obtain that

$$A_{\text{airvehicle}} = 5C_{\text{Shape}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right)^{-2/3}\left(\frac{M_{\text{airvehicle}}}{\rho_{\text{air}}}\right)^{2/3}. \quad (6)$$

Now we calculate the thermal conductivity of an insulated airvehicle wall h_{wall}. The total mass of thermal insulation is

$$M_{\text{ins}} = f_{\text{ins}} M_{\text{airvehicle}} \quad (7)$$

where f_{ins} is the fraction of airvehicle gross mass composed of thermal insulation. The thickness of thermal insulation can be given by

$$d_{\text{ins}} = \frac{M_{\text{ins}}}{\rho_{\text{ins}} A_{\text{airvehicle}}} = \frac{f_{\text{ins}} M_{\text{airvehicle}}}{\rho_{\text{ins}} A_{\text{airvehicle}}} \quad (8)$$

The wall heat transfer coefficient is the quotient of insulation thermal conductivity and its thickness:

$$h_{\text{wall}} = \frac{\kappa_{\text{ins}}}{d_{\text{ins}}} = \frac{\kappa_{\text{ins}}\rho_{\text{ins}} A_{\text{airvehicle}}}{f_{\text{ins}} M_{\text{airvehicle}}} = \frac{A_{\text{airvehicle}}}{l f_{\text{ins}} M_{\text{airvehicle}}}, \quad (9)$$

where by l we denote the specific insulation given by the inverse of the product of thermal conductivity and density:

$$l = \frac{1}{\kappa_{\text{ins}}\rho_{\text{ins}}} \quad (10)$$

Substituting (10) into (9), we obtain

$$\frac{1}{h_{\text{wall}}} = \frac{l f_{\text{ins}} M_{\text{airvehicle}}}{A_{\text{airvehicle}}}. \quad (11)$$

As we show below, specific insulation is one of the most important parameters determining performance of an airvehicle thermal insulation. In section 4, we discuss specific insulation, other properties, and cost of several available thermal insulators.

At this point, we can calculate thermal power requirements for an airvehicle. Substituting formula (11) into (11), we obtain

$$P_{\text{Heat}} = A_{\text{airvehicle}}\left(T_{\text{int}} - T_{\text{ext}}\right)\left(R_h + \frac{i f_{\text{ins}} M_{\text{airvehicle}}}{A_{\text{airvehicle}}}\right)^{-1} = \left(\frac{1}{P_{\text{H1}}} + \frac{1}{P_{\text{H2}}}\right)^{-1} \quad (12)$$

In this formula, we use the following notations: P_{H1} for the thermal power requirement for an airvehicle with no heat transfer resistance:

$$P_{\text{H1}} = A_{\text{airvehicle}}\left(T_{\text{int}} - T_{\text{ext}}\right)\left(\frac{l f_{\text{ins}} M_{\text{airvehicle}}}{A_{\text{airvehicle}}}\right)^{-1}, \quad (13)$$

and P_{H2} for the thermal power requirement for an airvehicle with no insulation:

$$P_{\text{H2}} = \frac{A_{\text{airvehicle}}\left(T_{\text{int}} - T_{\text{ext}}\right)}{R_h}. \quad (14)$$

Substituting expression (6) for $A_{\text{airvehicle}}$ into (13), we obtain the representation for P_{H1} as

$$P_{\text{H1}} = \left(T_{\text{int}} - T_{\text{ext}}\right)\frac{A^2_{\text{airvehicle}}}{i f_{\text{ins}} M_{\text{airvehicle}}} = T_{\text{int}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right) \times \frac{\left[5C_{\text{Shape}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right)^{-2/3}\left(\frac{M_{\text{airvehicle}}}{\rho_{\text{air}}}\right)^{2/3}\right]^2}{i f_{\text{ins}} M_{\text{airvehicle}}}$$
$$= 25C^2_{\text{Shape}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right)^{-1/3}\frac{T_{\text{int}} M^{1/3}_{\text{airvehicle}}}{l f_{\text{ins}}\rho^{4/3}_{\text{air}}} = 25C^2_{\text{Shape}}\left[\left(1-\frac{1}{r_T}\right)^{-1/3} r_T\right]\frac{T_{\text{ext}} M^{1/3}_{\text{airvehicle}}}{l f_{\text{ins}}\rho^{4/3}_{\text{air}}}, \quad (15)$$

where $r_T > 1$ is the notation for the ratio of the temperatures inside and outside an airvehicle. Substituting (6) into (14), we obtain the representation for P_{H2} as

$$P_{\text{H2}} = \frac{1}{R_h} T_{\text{int}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right) \times \left[5C_{\text{Shape}}\left(1-\frac{T_{\text{ext}}}{T_{\text{int}}}\right)^{-2/3}\left(\frac{M_{\text{airechicle}}}{\rho_{\text{air}}}\right)^{2/3}\right]$$
$$= 5C_{\text{Shape}}\left[\left(1-\frac{1}{r_T}\right)^{1/3} r_T\right]\frac{T_{\text{ext}} M^{2/3}_{\text{airvehicle}}}{R_h \rho^{2/3}_{\text{air}}}. \quad (16)$$

Finding the best value for r_T for every type of an airvehicle is an open engineering problem. Low r_T increases the requirement on balloon size. This in turn requires the use of lighter materials which may be expensive. High r_T means higher internal temperature, which increases the risk of fire and puts stronger requirements and burdens on insulating material. Our own suggestion is to use $1.3 \le r_T \le 1.5$.

Loading airships and especially aerostats with nitrogen or N95H5 mixture instead of air has several advantages. Namely, these gases are neither flammable nor oxidizing, which would prevent internal heat insulation or heating system from catching fire. Second, these gases have lower density than air which is important for the lift. Nitrogen has $r_\rho = 0.965$ and N95H5 has $r_\rho = 0.92$ (recall r_ρ is the ratio of the density of a given gas to air density at the same pressure and temperature.) Such gases as helium and hydrogen have very low r_ρ, which makes them useful as lifting gases. Nevertheless, they have specific problems. Helium has $r_\rho = 0.14$, but it is rare and expensive. Hydrogen has $r_\rho = 0.07$, but it is extremely flammable.

Balloons filled with nitrogen or N95H5 would still require heating of their internal gas. In order for the lifting gas to have the same density as air at T_{int}, its temperature would have to be

$$T^*_{\text{int}} = r_\rho T_{\text{int}}, \tag{17}$$

where T^*_{int} is the internal temperature of an airvehicle filled with lifting gas slightly less dense than air. Since thermal energy consumption is proportional to the difference between internal and external temperatures, thermal power required to sustain hot gas inside an airvehicle decreases by a factor κ defined as

$$\kappa = \frac{T^*_{\text{int}} - T_{\text{ext}}}{T_{\text{int}} - T_{\text{ext}}} = \frac{r_\rho T_{\text{int}} - T_{\text{ext}}}{T_{\text{int}} - T_{\text{ext}}} = \frac{r_\rho r_T T_{\text{ext}} - T_{\text{ext}}}{r_T T_{\text{ext}} - T_{\text{ext}}} = \frac{r_\rho r_T - 1}{r_T - 1}. \tag{18}$$

For $r_T = 1.50$, nitrogen has $\kappa = 0.90$, and N95H5 has $\kappa = 0.76$. For $r_T = 1.33$, nitrogen has $\kappa = 0.86$, and N95H5 has $\kappa = 0.68$. Thus, the use of N95H5 instead of air can decrease power consumption by an airvehicle by up to 32%. (Recall, that using hot air inside an air vehicle also increases the risk of thermal insulation catching fire on the inside.) Hence, hot N95H5 has significant advantages over hot air as lifting gas.

A Brief Review of Structural Materials for Aerovehicles

Aerovehicle Thermal Insulation Materials

In this section, we discuss the main characteristics of some thermal insulators used for airvehicles. An airship thermal insulator should have maximum possible specific insulation, be efficient at high temperatures, and have reasonable cost. Generally, all three aforementioned requirements cannot be fulfilled simultaneously.

Ceramic fibers are usable up to 1,000° C. Superwool ceramic blanket has density of 64 kg/m³ and thermal conductivity at 0.06 W/m° K at 200° K [17]. Superwool ceramic blanket specific insulation is $= 0.26 \frac{m^4\, {}^oK}{W\ \text{kg}}$. (As for now, ceramic wool is available at Amazon.com for $30 per [18].) In author's opinion, this insulation is not the best choice for an airship. Even though ceramic fibers have reasonable cost and high operating temperature, its specific insulation is quite low.

For FESTO hot air balloons, Aerofabrix insulation is used. This insulation has a density of 75 kg/m³ and thermal conductivity of 0.0265 W/m° K. Aerofabrix service temperature is at least 150° C [19]. Specific insulation of Aerofabrix is $\iota = 0.50 \frac{m^4\, {}^oK}{Wkg}$. Aerofabrix insulation has reasonable specific insulation and high operating temperature.

Polyisocyanurate insulation is a rigid board. Its service temperature is up to 100° C. Its density is 40 kg/m³ and thermal conductivity of 0.037 W/m° K at 93° K [20]. Specific insulation of Polyisocyanurate is $= 0.68 \frac{m^4\, {}^oK}{W\ \text{kg}}$. If flexible polyisocyanurate insulation can be produced, it should be a good choice for airship insulation. Polyisocyanurate insulation has high operating temperature and high specific insulation. The problem with polyisocyanurate insulation is that it is rigid, rather than flexible.

Low Density Polyethylene Foam (LDPE) insulation has good flexibility. Its density is 18kg/m³. Its thermal conductivity is 0.045 W/m°K at 10°C [21]. LDPE has specific insulation $\iota = 1.2 \frac{\text{m}^4\, {}^o\ \text{K}}{W\ \text{kg}}$. LDPE has 100° C service temperature [21]. PaperMart sells this LDPE at $19/kg [22]. Thus, LDPE has high specific insulation, reasonable operating temperature, and low cost.

Plastic bubble thermal insulation consists of film inflated by an instant bubble machine. Inflated bubble wrap has very low density of 7.5 kg/m³. However, pure bubble insulation transmits a lot of heat in the form of infrared thermal radiation. To be effective, plastic bubble thermal insulation must contain one or more layers of reflective aluminum foil. Diamond radiant barrier foil is an aluminum radiation barrier with areal density of 58 *g/m²*. It is likely that the best option would be a combined insulation consisting of alternating layers of Diamond radiant barrier foil and bubble wrap insulation. Combined bubble insulation has density of 11.1 kg/m³. This insulation has thermal conductivity of 0.055

W/m° K [23] and specific insulation $= 1.6 \frac{m^{4\,o} K}{W \text{ kg}}$. Bubble film plastic, sold at Uline, melts at° C [24]. Its service temperature should be at most 30°C. Instant bubble film is sold at Uline.com for $19 per kg [24] and Diamond radiant barrier foil is sold on Amazon at $17 per kg [18]. Insulation consisting of layers of bubble wrap and Diamond radiant barrier has good specific insulation and low cost, but it has very low operating temperature. This insulation is not appropriate for low altitude airvehicles, since they require higher operating temperatures. It can be used effectively for high altitude airvehicles.

Atmosphere ™ duct wrap is fiberglass insulation covered with aluminum foil. Its density is 12 kg/m^3. It can be used up to 120° C. Its thermal conductivity rises from 0.040 W/m° K to 0.063 W/m° K when temperature changes between 10° C and 93° C [25]. To calculate ι, we use the average thermal conductivity value of 0.050 W/m° K, which yields specific insulation of $\acute{y} = 1.7 \frac{m^{4\,o} K}{Wkg}$. This insulation costs $19 per kg. Johns Manville duct insulation has similar parameters and about the same price [18]. Fiberglass insulation has excellent specific insulation, reasonable operating temperature, and low cost. Nevertheless, it may degrade as a result of airship surface vibrations.

Melamine foam insulation, being highly flexible, has excellent properties. Its density is 9 kg/m^3; thermal conductivity is under 0.035 W/m° K; specific insulation is $\iota = 3.2 \frac{m^4 \text{ K}}{W \text{ kg}}$; and service temperature is 190° C. Melamine foam insulation costs at least $350 per kg [26]. Melamine foam insulation has excellent specific insulation, excellent operating temperature. Its cost is exorbi- tant.

Finding the best insulation for hot air airships remains an open challenging problem. In our opinion, the best insulation would consist either of foam or aluminized bubble insulation. Below, some considerations and theory supporting our view point are presented.

Theoretical calculations of thermal conductivity of foam and bubble insulations have been developed recently [27]. This conductivity can be given by the following sum [27]:

$$\kappa_{\text{ins}} = \kappa_{\text{gas}} + \kappa_{\text{solid}} + \kappa_{\text{rad}}, \tag{19}$$

where κ_{gas} is thermal conductivity due to gas filling the foam, κ_{solid} is thermal conductivity due to solid bridges and membranes within the foam, and κ_{rad} is thermal conductivity caused by thermal radiation passing through the foam. The value of κ_{gas} is almost identical to thermal conductivity of the filling gas, the value of κ_{solid} is generally considerably lower than other terms [27].

As is shown in Glicksman LR, et al. [28], radiative component of thermal conductivity can be approximated by

$$\kappa_{\text{rad}} = 0.070 \frac{W}{m^o K} \left(\frac{T}{293^o K} \right)^3 \left(\frac{d}{1mm} \right) \times \left(\frac{\rho_{\text{polymer}}}{10^3 \text{ kg/m}^3} \right) \left(\frac{\rho_{\text{foam}}}{1 \text{ kg/m}^3} \right)^{-1/2} \tag{20}$$

where ρ_{foam} and ρ_{polymer} are the foam and polymer densities respectively and d is the foam cell diameter. A typical light foam or bubble wrap has polymer density close to 10^3 kg/m^3, and foam or bubble density of 10^3 kg/m^3. At 293° K, its thermal conductivity is

$$\kappa_{\text{rad}} = 0.023 \frac{W}{m^o K} \left(\frac{d}{1 \text{ mm}} \right) \tag{21}$$

Using this formula one can evaluate, that in foam, with cell diameter being below 0.5 mm, the radiative compo- nent of thermal conductivity is below 0.012 W/m° K. In bubble insulation, with bubble diameters about 5 mm, radiative component of thermal conductivity is above 0.012 W/m° K unless layers of bubble insulation are alternated with foil layers.

Fabric and Cording

In order to describe available cords and fabrics, we introduce several measures and definitions. The amount of cord can measured in units of energy:

$$(\text{cord strength}) \cdot (\text{length}) = N \cdot m = J. \tag{22}$$

Specific strength of cords is the quotient of the cord tensile strength and its density. The units of specific strength are

$$\frac{\text{specific strength}}{\text{density}} = \frac{N/m^2}{\text{kg/m}^3} = \frac{\text{N} \cdot \text{m}}{\text{kg}} = \frac{J}{\text{kg}}. \tag{23}$$

Another way to measure specific strength of a material is via its breaking length. The breaking length of a material, is defined as the length of a suspended cord/column made of that material, which would break under its own weight. Specific strength and breaking length of any material satisfy a linear relation:

$$\left(\text{specific strength}\right) = g\left(\text{breaking length}\right). \tag{24}$$

An important economic parameter for any cord is specific cost given by

$$C_{\text{Cable}} = \frac{\left(\text{cost}\right)}{\left(\text{strength}\right)\cdot\left(\text{length}\right)} = \frac{\$}{J}. \tag{25}$$

All these measures cannot be directly applied to any fabric. However, all aforementioned measures can be used for the threads from which the fabric is composed. One way to reinforce an airvehicle is to cover its surface with three square mesh nets. The first net composed of thin cords should be of hole size. The second net composed of intermediate cords has 1dm hole size. The third net composed of thick cords has 1 m hole size. All three nets are sewn to the airvehicle shell and to each other. This triple covering prevents airvehicle shell from sharing.

The airship needs two types of fabric. First, it needs air-tight fabric in order to prevent hot air from escaping. Unlike airships using hydrogen or helium as lifting gases, hot air airship does not need absolutely air-tight or impervious fabric - which is very expensive. Amazon sells Emma Kites ripstop airtight nylon fabric with areal density of 48 g/m^2. It costs $4.30 per m^2 or $90 per kg [29]. It is likely that a large airship would need several layers of this fabric. Some layers would be on the inside of thermal insulation, and some layers would be outside.

A large airship also needs heavy and robust fabric in order to sustain internal pressure, which may be up to $2kPa$ higher then external pressure. Robust fabric covering would make the airship more stable and less likely to be ripped. There are several choices for fabric made from high tensile-strength filaments. Kevlar fabric has high tensile strength, but it is prohibitively expensive. Carbon fiber is also very strong, and expensive. For instance, ACP Composites sells carbon fiber 2 by 2 twill weave fabric. Its arial density is 210 g/m^2. The carbon fiber filament composing the fabric has breaking length of 212 km. The fabric costs $143 per kg or $30 per m^2 [30].

The best choice for robust fabric covering for extremely heavy hot air airship is glass fiber fabric. There are two types of fiberglass - E-glass and S-glass. E-glass has breaking length of 128 km, while S-glass has breaking length of 170 km [31]. S-glass fabric is very expensive. Several companies offer E-glass fabric at good price. Fiberglass Supply sells Style 7725 E-glass cloth. It is a twill weave glass meaning that each yarn goes over two and then under two. The cloth has areal density 300 g/m^2. It costs $7.38 per m^2 or $24.6 per kg [32]. Fibermax Ltd sells fiberglass fabric G282P. The fabric has areal density 282g/m^2. It costs $2.82 per m^2 or $10 per kg [33]. Fibre Glast sells fiberglass woven roving. It's density is 540 g/m^2 to 625 g/m^2. The roving costs $5.60 per m^2 or $9.50 per kg [34]. In 2020, E-glass fiber cost was $2 to $3 per kg in bulk quantities. S-glass fiber cost was $16 to $30 per kg in bulk quantities [35].

An airship needs a lot of cords and cables. First, covering an airship with a high strength cord net on the outside makes it much more rip-proof. Second, cables are needed for holding the gondola. Third, in many cases, an airship may need to be moored at a high altitude, which certainly requires a very long and strong cable.

Cords available as of June 2021 are tabulated in Table 1 below. Polymer cord data is based on Erigging and US Netting [36, 37]. In Table 1 below, we use the following abbreviations. Row 2 is breaking length in . Row 3 is cost in $ per kg. Row 4 is specific cost in $ per MJ. Column 2 is Kevlar. Column 3 is UHMWPE which refers to ultra high molecular weight polyethylene. Column 5 is Polyester. Column 6 is E-glass.

Cable	Kev	UHMWPE	Nylon	PE	EGL
BL	256	162	35	27	128
Cost	460	150	18.8	13.3	10
SC	182	94	55	50	8

Table 1: Cords available June 2021.

E-glass is an obvious choice in airship applications, where degradation due to brittleness is not a problem.

Steel cable is available at $5.33 per kg. Its breaking length is 18 km. Steel is affected by fatigue and corrosion, thus it must be used with safety factor of at least 5 [36]. Even though steel wire was extensively used in Zepplins (about a century ago), it is not useful for modern airships.

Overall Cost of Extremely Heavy Hot Air Airships

Based on information presented above, it is likely that the cost of materials for constructing the airships would be of the order of $20,000 per ton airship mass. This cost would be higher for first airships which may have to use more expensive materials.

The cost of manufacturing extremely heavy hot air airship is more difficult to estimate. It is likely that assembling first airships will be expensive.

Airship and Aerostat Examples

In this section, we present two examples: the first is a low-altitude heavy transport airship and the second one is a high-altitude aerostat. The heavy transport is most suitable for cruising at 3 km altitude. Air temperatures inside and outside the airship are $T_{\text{int}} = 405^{\circ}\text{K}$ and $T_{\text{ext}} = 270^{\circ}\text{K}$. Ambient air density is $\rho_{\text{air}} \approx 0.9\ \text{kg}/\text{m}^3$. The shape factor is $C^2_{\text{Shape}} = 2$. Heavy thermal insulation has $l = 0.25\dfrac{m^4 oK}{Wk}$. In

this airship, thermal insulation makes up 20% of gross takeoff mass, thus $f_{\text{ins}} = 0.2$. Substituting these values into Equation (15) , we obtain the estimate on P_{H1} :

$$P_{\text{H1}} \approx 65\text{MW}\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{1/3}. \tag{26}$$

For a fast-moving airship, external heat transfer coefficient is low. Hence, by Equation 212, a good estimate for heat transfer resistance is $R_h \approx 0.08\dfrac{m^{2o}K}{W}$. Substituting

the above values into Equation 16 , we obtain

$$P_{\text{H2}} \approx 260MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{2/3}. \tag{27}$$

The thermal power required to keep an airship afloat can be found by substituting formulas (26) and (27) into (12) and get

$$P_{\text{Heat}} = \left\{\left[65MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{1/3}\right]^{-1} + \left[260MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{2/3}\right]^{-1}\right\}^{-1}. \tag{28}$$

The specific power requirements are calculated using (28) and collected in Table 2 below. In Table 2 below, we use the following abbreviations. Column 2 is Airship mass in tons. Column 3 is required power. Column 4 is required specific power.

M, kT	1	2	5	10	20	30
P, MW	52	68	97	125	162	187
SP, W/ kg	52	34	19	13	8.1	6.2

Table 2: Thermal power required to keep airship afloat.

Assume that a high altitude aerostat is moored at 14 km altitude. Air temperatures inside and outside the airvehicle are $T_{\text{int}} = 315^{\circ}\text{K}$ and $T_{\text{ext}} = 210^{\circ}\text{K}$. Ambient air density is $\rho_{\text{air}} \approx 0.24\ \text{kg}/\text{m}^3$. The shape factor for the spherical aerostat is $C_{\text{Shape}} = 1$. Light thermal insulation has $l = 0.45\dfrac{m^4\ \text{K}}{W\ \text{kg}}$. In

this airvehicle, thermal insulation makes up 20% of gross takeoff mass, thus $f_{\text{ins}} = 0.2$. Substituting these values into Equation (15), we obtain the estimate for P_{H1} :

$$P_{\text{H1}} \approx 85MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{1/3}. \tag{29}$$

For almost stationary balloon, we take the value of $R_h = 0.36\dfrac{m^2K}{W}$ from Equation 3. Substituting the values

above into Equation (16), we obtain the estimate for P_{H2} :

$$P_{\text{H2}} \approx 79MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{2/3}. \tag{30}$$

Thermal power required to keep high altitude aerostat afloat is found by substituting estimates (29) and (30) into (12):

$$P_{\text{Heat}} = \left\{\left[85MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{1/3}\right]^{-1} + \left[79MW\left(\frac{M_{\text{airvehicle}}}{1000\text{ tons}}\right)^{2/3}\right]^{-1}\right\}^{-1}. \tag{31}$$

requirements are calculated using (31) and collected in Table 3 below. We use the following abbreviations. Column 2 is Airship mass in tons. Column 3 is required power. Column 4 is required specific power.

M, *KT*	1	2	5	10	20	30
P, *MW*	41	58	89	122	165	196
SP, *W/* kg	41	29	18	12	8.3	6.5

Table 3: Thermal power required to keep high altitude aerostat afloat.

From Equations (28) and (31) , it follows that for extremely heavy airvehicles, heating power requirement is proportional to $M^{1/3}_{\text{airvehicle}}$ and for light airvehicles, heating power requirement is proportional to $M^{2/3}_{\text{airvehicle}}$. Specific power requirements for extremely heavy airvehicles and light airvehicles are proportional to $M^{-2/3}_{\text{airrehicle}}$ and $M^{-1/3}_{\text{airrehicle}}$ respectively.

A high altitude aerostat using N95H5 instead of air would have internal temperature of 290°K (which is 17°C) instead of 315° K. This temperature can be sustained by a heat pump rather than resistive heating. If this aerostat is a part of the

Hoos mega power tower mentioned in the Introduction, then internal heat can be sustained with considerably lower energy expenditures.

Conclusion

Very heavy and extremely heavy airvehicles are feasible. As summarized in Tables 2 and 3 thermal energy requirements for insulated airvehicles are not unreasonably high. Specific power requirements for airvehicles decrease rapidly with the increase of airvehicle gross takeoff masses. Low mass airvehicles filled with hot air incur prohibitive energy expenses. Replacing hot air by hot nitrogen or hot mixture of 94.5% nitrogen and 5.5% hydrogen by volume reduces heating power requirements by 10% and 24% respectively.

For airships, the lifting gas can be heated by the engine exhaust. For aerostats, the lifting gas can be heated by a heat pump, in which electric power is supplied from the mooring point on the surface. Very heavy and extremely heavy airvehicles, which are efficient and not extremely costly, will be developed and constructed in the near future.

Latin Notations

$A_{\text{airvehicle}}$ – airvehicle surface area;

C_{Shape} - factor depending on airvehicle shape; if denotes volume, then the following relation holds:

$A_{\text{airvehicle}} = 5C_{\text{Shape}}V_{\text{airvehicle}}^{2/3}$;

d_{ins} – insulation thickness;

f_{ins} - fraction of airvehicle gross mass composed of thermal insulation;

h_{ext} – heat transfer coefficient between atmosphere and airvehicle wall;

h_{int} – heat transfer coefficient between internal hot air and airvehicle wall;

h_{wall} – heat transfer coefficient through airvehicle wall;

$M_{\text{airvehicle}}$ – airvehicle mass;

P_{Heat} - heating power needed to sustain airvehicle afloat;

P_{H1} – thermal power requirement for an airvehicle with no heat transfer resistance;

P_{H2} - thermal power requirement for an airvehicle with no insulation;

R_h - heat transfer resistance of uninsulated airvehicle;

$r_T > 1$ – the ratio of the temperatures inside and outside the airvehicle;

r_ρ - the ratio of the density of a given gas to air density at the same pressure and temperature;

T_{ext} - air temperature outside airvehicle;

T_{int} - air temperature inside airvehicle;

T^*_{int} – temperature inside airvehicle filled with lifting gas slightly less dense then air;

$V_{\text{airvehicle}}$ – airvehicle volume.

Greek Notations

ý - specific insulation;

κ - factor by which thermal power requirement of an aerostat is decreased if it is filled with a gas slightly lighter than air;

κ_{ins} – thermal conductivity of thermal insulation;

ρ_{ins} – density of thermal insulation;

ρ_{air} – air density.