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ORIGINAL PAPER

Long permanence high altitude airships: the opportunity of hydrogen

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Abstract

Introduction MAAT cruiser/feeder airship system is a transport system financed by European 7th Framework programme 2011. The project aims to realize a cruiser/feeder airship system, which can connect major populated centres worldwide. The MAAT cruiser feeder system is based on two different airships, the cruiser, which remains airborne for long times, and the feeder, which connects the cruiser with the ground and vice versa. This paper traces a detailed bibliography about MAAT project showing the actual state of the art of the project. This bibliographic review allows understanding the level of innovation related to this project.
Methods Starting from the results of the preceding literature, the authors present a model of the cruiser, in terms of both mass and energy. According to the preceding studies, they have assumed the following minimal set of hypothesis: the buoyant gas is hydrogen; the shape of the cruiser is a discoid; operative altitude is in the range 15-17 km. It is well known that the major showstopper to actual diffusion of airships is related to the initial costs related to the use of Helium. The problem is more accentuated in Europe than in USA and Russia, because of higher unitary prices. An economic comparison with the possibility of using Hydrogen has produced. A further comparison has performed in terms of operations, focusing on the necessity of replacing the gas, which disperses in the external atmosphere because of the porosity of the tissues of the balloon system. The on board generation of hydrogen as an energy system is very convenient on long permanence airships because the replacement buoyant gas can be produced on board. It has been also traced a complete energy balance of the cruiser airship assuming it as discoid. On one side it has been evaluated the hydrolysis process against batteries showing that an hydrolyser/fuell cell cycle has a lower efficiency in comparison of batteries but it looks less expensive and presents a lower weight than any battery type.
Results This paper has clearly demonstrated that the use of hydrogen is much more convenient than the uoiuse of Helium, even if it require an accurate design to minimize the risks related to hydrogen potential flammability. It demonstrates the necessity of using hydrogen as buoyant gas in long endurance airships because of the easiness of replacement. An estimation of the necessary energy requirements for a discoid airship has produced demonstrating clearly that a discoid shaped airship is energetically inefficient. These results force to consider a different and more efficient cruiser system.
Conclusions In conclusion this paper demonstrates clearly the necessity of using hydrogen to allow possible future airship renaissance, which could be a fundamental option for the future because of airships are the most energetically efficient aerial vehicles. This research activity has also clearly demonstrated that the initial discoid shaped cruiser hypothesis is not feasible on energetic point of view.

Keywords Airship · Photovoltaic · Hydrogen · Dispersion · Energy balance

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Definitions and Abbreviations

A	Surface [m^2]
a, b, c	Semi axes of an ellipsoid [m]
c_p	specific heat at constant pressure [kJ/kg °C]
D	Diffusion coefficient [cm^2/s]
d	diameter [m]
E	Energy [kWh]
H	Altitude [m, km]
M	Mass [kg, ton]
p	Pressure [Pa]

P	Permeation coefficient $[\mathrm{cm}^3_{(273.15\mathrm{K};\ 1.013\times105)}/(\mathrm{cm}\times\mathrm{s}\times\mathrm{Pa})]$
R	Gas constant 8,3144 10^{-3} kJ/K mol
S	Solubility coefficient $[\mathrm{cm}^3_{(273.15\mathrm{K};\ 1.013\times105)}/(\mathrm{cm}^3\times\mathrm{Pa})]$
s	thickness [mm]
T	Temperature [K]
t	Time [s, h]
V	Volume [m^3]
v	Wind velocity [m/s]

Acronyms

MAAT	Multibody Advanced Airship for Transport
PV	Photovoltaic

1 Introduction: the MAAT project

MAAT, Multibody Advanced Airship for Transport, aims to investigate aerial transportation possibility by airship based cruiser-feeder system [1–5]. MAAT is composed by two modules: The cruiser, named PTAH, (acronym of Photovoltaic Transport Aerial High altitude system); the feeder, named ATEN (Aerial Transport Elevator Network feeder), is a VTOL system (Vertical Take Off and Landing) which ensure the connection between the cruiser and the ground. They can lift up and down by the control of buoyancy force and displace horizontally to join to cruiser.

The project aims to:

1. identify and design the most functional cruiser/feeder airship architecture based on a discoid innovative airship able to remain airborne for long periods and to travel great distances;
2. design the best type of propulsion both for cruiser and feeder so they can contribute together to the propulsion of an innovative modular airship;
3. minimize the environmental air transport impacts by annulling the fossil fuels energy consumption by designing both cruiser and feeder are energetically autonomous by photovoltaic energy and innovative electric propulsion.
4. study the different possible ways of approaching and joining between ATEN and PTAH, and consequently, the release of ATEN from PTAH.
5. design the best procedure of docking operations thus identified in order to obtain the minimum disruption to passengers and the maximum safety for themselves and for goods
6. study the different architectures of PTAH and Athens, in such a way that :
    a. the lift up capacity guaranteed by the buoyancy force, may be integrated with the power of the engines;
    b. effective and safe procedures for docking;

Table 1 Atmospheric data

Altitude [m]	Temperature [K]	Pressure [Pa]	Density [kg/m3]	Pressure H2 [Pa]
0.00	288.15	101325.00	1.2250	106391.25
1000.00	281.65	89874.57	1.1116	94368.30
2000.00	275.15	79495.22	1.0065	83469.98
3000.00	268.65	70108.54	0.9091	73613.97
4000.00	262.15	61640.24	0.8191	64722.25
5000.00	255.65	54019.91	0.7361	56720.91
6000.00	249.15	47181.03	0.6597	49540.08
7000.00	242.65	41060.74	0.5895	43113.78
8000.00	236.15	35599.81	0.5252	37379.80
9000.00	229.65	30742.46	0.4663	32279.58
10000.00	223.15	26436.27	0.4127	27758.08
11000.00	216.65	22632.06	0.3639	23763.67
12000.00	216.65	19330.41	0.3108	20296.93
13000.00	216.65	16510.41	0.2655	17335.93
14000.00	216.65	14101.80	0.2268	14806.89
15000.00	216.65	12044.57	0.1937	12646.80
16000.00	**216.65**	**10287.46**	**0.1654**	**10801.83**
17000.00	216.65	8786.68	0.1413	9226.02

Bold indicates the valuesat optimal altitude

    c. ATEN can land and take off from Airport Hubs named AHA located in major populated centres
    d. PTAH satisfies the better possible aerodynamic performances possible for the dimensions and the operative mission.

To study the transfer operations between ATEN and PTAH of goods and people and vice versa, to:

1. minimize distress conditions for passengers,
2. maximize performances especially for goods;

Table 2 Airship system weight

	Number of persons	Mass (kg)
Passengers	480	48000
Crew	20	2500
Freight		12000
Total passengers and freights		62500
Structure		150000
Energy conversion		60000
Energy storage		50000
Propulsion		40000
Total System Weight		300000
Total Weight		362500

Table 3 Volume comparison H_2 vs. He

Altitude [m]	Density H_2 kg/m3	Density He kg/m3	V(H_2) [m3]	Veff (H_2) [m3]	V(He) [m3]	Veff (He) [m3]
0.00	0.08953	0.17777	319251	351176	346150	380765
1000.00	0.08125	0.16132	351806	386986	381448	419593
2000.00	0.07356	0.14606	388561	427417	421300	463430
3000.00	0.06644	0.13193	430176	473194	466421	513064
4000.00	0.05987	0.11887	477437	525181	517665	569431
5000.00	0.05380	0.10682	531278	584406	576042	633647
6000.00	0.04821	0.09573	592821	652104	642771	707048
7000.00	0.04308	0.08555	663413	729754	719310	791241
8000.00	0.03838	0.07621	744681	819149	807425	888168
9000.00	0.03408	0.06767	838607	922467	909265	1000192
10000.00	0.03016	0.05989	947603	1042364	1027446	1130190
11000.00	0.02660	0.05281	1074645	1182109	1165191	1281710
12000.00	0.02272	0.04511	1258196	1384016	1364208	1500629
13000.00	0.01940	0.03853	1473098	1620408	1597218	1756939
14000.00	0.01657	0.03291	1724708	1897178	1870027	2057029
15000.00	0.01415	0.02811	2019282	2221211	2189421	2408363
16000.00	0.01209	0.02401	2364179	2600597	2563378	2819716
17000.00	0.01033	0.02050	2767981	3044779	3001202	3301323

3. enhance safety of these operations to maximum possible level.

The objectives described are congruent with each other and to achieve this study of the system and components must be highly structured.

2 MAAT design activity

This project has started by a preliminary conceptual design activity. The historical milestone references for any author who approaches the design of airships are certainly Lewitt [5] and Warner [6]. Kreider [7] has defined the most

Table 4 Reference values for calculation

Altitude [m]	c(H_2) [m]	c(He) [m]	A [m^2]	A_{front} (H_2) [m^2]	A_{front} (He) [m^2]	d_{id} (H_2) [m]	d_{id} (He) [m]	V^2/3(H_2) [m^2]	V^2/3(He) [m^2]	V^1/3(H_2) [m^2]	V^1/3(He) [m^2]
0.00	4.28	4.64	124920	1881.30	2039.81	5.02	5.41	4977.56	5253.37	70.55	72.48
1000.00	4.71	5.11	125016	2073.14	2247.82	5.50	5.92	5310.44	5604.70	72.87	74.86
2000.00	5.21	5.64	125130	2289.73	2482.66	6.02	6.49	5674.15	5988.56	75.33	77.39
3000.00	5.76	6.25	125268	2534.97	2748.56	6.61	7.12	6072.39	6408.86	77.93	80.06
4000.00	6.40	6.94	125435	2813.47	3050.52	7.27	7.83	6509.37	6870.06	80.68	82.89
5000.00	7.12	7.72	125637	3130.75	3394.54	8.01	8.62	6989.99	7377.31	83.61	85.89
6000.00	7.94	8.61	125883	3493.41	3787.76	8.84	9.51	7519.88	7936.57	86.72	89.09
7000.00	8.89	9.64	126185	3909.40	4238.79	9.78	10.50	8105.59	8554.72	90.03	92.49
8000.00	9.98	10.82	126557	4388.30	4758.04	10.83	11.63	8754.71	9239.82	93.57	96.12
9000.00	11.24	12.18	127018	4941.79	5358.17	12.02	12.89	9476.20	10001.28	97.35	100.01
10000.00	12.70	13.77	127592	5584.09	6054.59	13.36	14.32	10280.47	10850.11	101.39	104.16
11000.00	14.40	15.61	128311	6332.73	6866.31	14.87	15.93	11179.91	11799.40	105.74	108.63
12000.00	16.86	18.28	129439	7414.37	8039.08	16.98	18.16	12419.21	13107.37	111.44	114.49
13000.00	19.74	21.40	130884	8680.76	9412.17	19.35	20.66	13795.89	14560.33	117.46	120.67
14000.00	23.11	25.06	132731	10163.46	11019.80	21.97	23.43	15325.17	16174.36	123.79	127.18
15000.00	27.05	29.33	135089	11899.34	12901.95	24.89	26.49	17023.93	17967.24	130.48	134.04
16000.00	**31.68**	**34.34**	**138091**	**13931.77**	**15105.62**	**28.09**	**29.86**	**18911.04**	**19958.91**	**137.52**	**141.28**
17000.00	37.09	40.21	141901	16311.32	17685.66	31.61	33.53	21007.31	22171.34	144.94	148.90

Table 5 Reference photovoltaic plant considered for hydrogen production

Module Properties	poly-Si	
Module	Unit	Value
Power capacity	W	200
Efficiency	%	13.50 %
Area	m^2	1.48
Nominal operating cell temp.	°C	45
Temperature coefficient	%/°C	0.40 %
Plant and Conversion Properties		
Plant	Unit	Value
Miscellaneous losses	%	5.00 %
Inverter	Unit	Value
Efficiency	%	95.00 %
Capacity	kW	1
Distribution Losses	%	5.00 %

comprehensible mathematical modeling of an High Altitude Balloon and allowed to predict the Performance during flight.

The fundamental guidelines about airship designs has synthesized by Khoury and Gillett [8].

The actual aeronautic guidelines has been defined by Raymer [9], with the conceptual design for innovation method. This methodology can be partially reassumed by the acronym KISS that means "keep it simple, stupid". It is not a simple joke. In any breakthrough innovation it is important to adopt a step by step design starting from very basic model and then introducing individual modification, which can be tested individually inside the system.

The intrinsic difficulties related to the project has forced to produce a large conceptual and design innovation in different field starting from the basic principles. Krausman [10] has investigated various parameters affecting altitude performance of tethered aerostats. Colozza [11, 12] have studied several models of high altitude airships. In particular he has investigated the possibility of realizing high altitude photovoltaic airships. This studies has inspired the PSICHE project about photovoltaic energy production and conversion at high altitude [13], and the energetic design based of high-altitude airships by Dumas [14]. PSICHE can be considered the original cruiser/feeder high altitude system which has been the origin of the MAAT project constituted by two very specialized systems. The cruiser needs to be designed an airship with cruising capability, while the feeder is conceived by simplicity as an aerostat with possibility of control by propulsion. Similar results has been produced by Aglietti and others [15], who have studied the feasibility of solar power generation using high altitude platforms. Dumas and Trancossi [16] has formulated an improved mathematical model used for PSICHE energetic evaluation, estimating the photovoltaic energy, which can be produced at high altitude by an horizontal photovoltaic plant, both in terms of electric energy or hydrogen and oxygen. In particular this method has been also recently improved [17] by a more complete estimation of the plants and their energetic effects on the system.

Pascoa [17] has produced an effective analysis of possible propulsion concepts which can be adopted on unconventional airships defining an effective state of the art which can be starting point for future development of future airship design modes.

Trancossi and others [18] has presented a variable shape airship configuration, which permits to reduce both the risk of fire and presents also a variable frontal section increasing volume with altitude, such as a traditional aerostat. Dumas and others [19, 20] have presented two different studies on this airship concept, verifying also its optimal mission profile and its feasibility.

The difficulties related to the energetic balances related to unconventional high altitude airships has been analysed by Pshikhopov [21, 22] and confirmed by Dumas [23, 24] and Khoshnoud [20, 25]. The exigency of producing an effective optimization of the plants and the consequent design guidelines have been demonstrated by Smith [26, 27]. This problematic part of the project has been an exceptional opportunity for the future of the project development opening the road to a series of methodological innovations.

Two directions has then started: a traditional disciplinary process which aims to improve the results on the basis of specific disciplinary needs which has been produced an interesting series of minor improvements starting from the very interesting stability analysis by Voloshin [28]. Neydorf [29] has analysed the Stability issues of MAAT feeder airship

Table 6 Considered geographic locations and climatic data

	Lat. deg	Air temperature °C	Relative humidity %	Daily solar radiation* $kWh/m^2/d$	Wind speed m/s	Earth temperature °C
Bjornoya Island	74.5	−1.3	88.3 %	1.81	7.0	3.0
Oslo	60	5.7	73.4 %	2.41	2.6	4.5
Torino	45	11.6	69.5 %	3.67	1.5	7.3
Cairo	30	21.4	58.1 %	5.38	4.0	24.5
Asmara	15	24.6	53.3 %	5.93	4.0	27.6
Singapore	0	26.7	83.3 %	4.45	1.7	26.6

* Average daily solar radiation on a horizontal plane

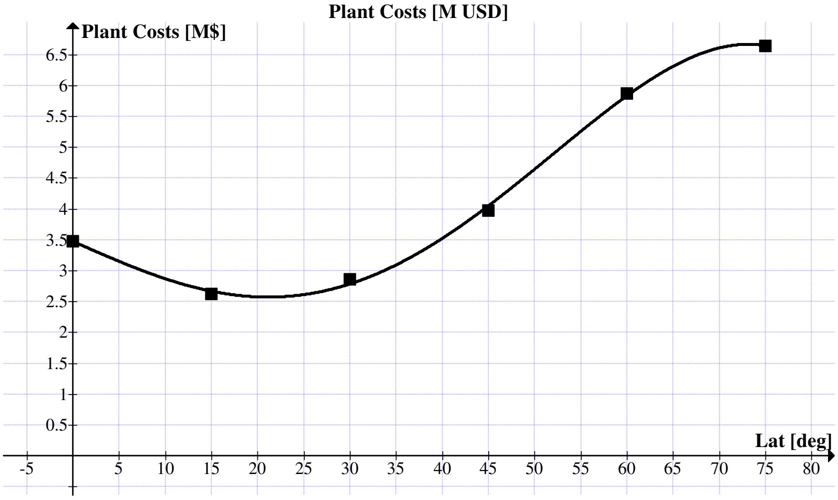


Fig. 1 Cost of the plant at different latitudes and interpolating third order curve

during vertical movements with wind disturbances. Pshikhopov[30] has considered planning of energy-efficient trajectories for the feeder with implementation of evolution algorithms.

Vizinho [31] has performed an effective computational analysis of the propulsive nacelle which needs to be used for the MAAT cruised propulsion. Vucinic, Gaviraghi and others [32] have analysed in depth the connection system and passenger exchange modes between cruise and feeder.

Another direction of development of the project is looking at methodological issues such as optimization systems. Ceruti [33] is analyzing multi-disciplinary design optimization with Heuristic Algorithms. Cerruti [34] analyses also how to apply innovatively rapid prototyping tools to facilitate wind tunnel testing of unconventional unmanned airships. Tuveri [35] is developing an innovative mesh based approach for the estimate the added masses to an unconventional unmanned airship.

On the other side Trancossi [36] has focused on the conceptual design methodologies to perform an effective system design optimization. Starting from the generalized formulation of the second principle defined by Adrian Bejan and defined Constructal Law [37, 38], he have developed a novel design method which can overcome the theoretical limits of the bottom-up design approach. He has finally proposed final formulations based on a dual cycle design method with a preliminary design method: the first aims to the definition of the optimal system on the basis of Constructal principle and second principle of Thermodynamics, the second aims to produce an effective optimization of the internal subcomponents of the system. This design methodology - defined Constructal Design for Efficiency – aims to finalize an optimal design which can solve the energetic issues related to the MAAT cruiser-feeder system. It has been previously applied to transport airship shapes with interesting results [39, 40] and on MAAT system [41, 42]. In particular, Trancossi is also working inside standardization committees on photovoltaic focusing on the characterization of photovoltaic modules for extreme conditions [43].

Table 7 Photovoltaic plant dimensions

Latitude	Hydrogen productivity	Number of PV modules	Electric Power	Effective PV area
Deg.	m^3/m^2 year	–	kW	m^2
Deg.	m^3/m^2 year	–	kW	m^2
0	36.6	6959	1391.6	10298.69
15	48.5	5251	1050.2	7771.79
30	44.5	5723	1144.6	8470.38
45	32.1	7934	1586.8	11742.43
60	21.7	11737	2347.2	17370.14
75	19.2	13265	2652.8	19631.88

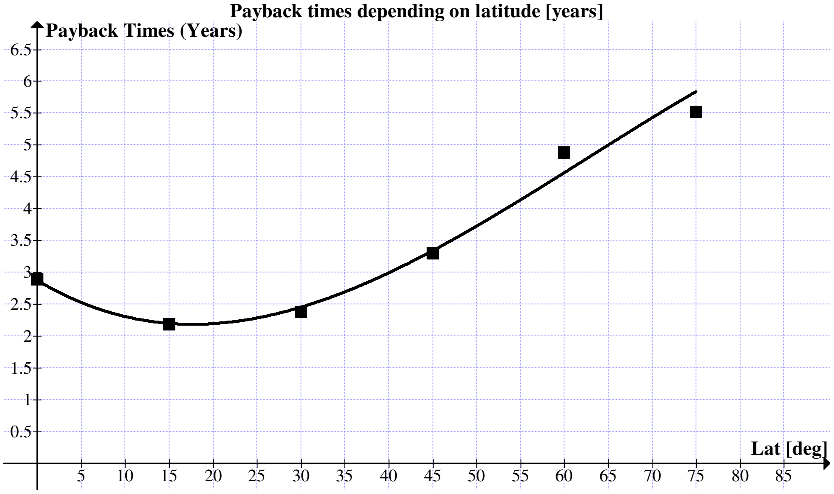
3 Hydrogen use as buoyant gas

The use of hydrogen as buoyant gas is a defined technical choice of the MAAT project. This technical choice is necessary especially for airships with a long airborne permanence, because of simple replacement of the gas which disperses into the environment.

It is possible to evaluate the convenience of hydrogen use both as buoyant gas and as energy storage system comparing it to helium and batteries for a large electrically propelled airship.

It has been considered a high altitude long permanence airship, which is a part (cruiser) of the MAAT cruiser-feeder architecture. Three phenomena have considered initial volume inflating (at ground), energy production and storage, gas replacement during service. It has been also evaluated the energy balance of the system for the initial reference discoid shape. Safety considerations has been also taken into account.

Fig. 2 Payback times at various latitudes and interpolating curve



4 General data

This paper considers a large airship with the capacity to lift 300 passengers plus baggage and 20 people crew at 16 km. An overall weight of 125 kg for passenger has estimated. A 5 % buoyant gas overpressure has estimated in the balloon to maintain the shape, even in presence of wind. The operative altitude has estimated at 16 km and maximum ceiling of the system at 17 km.

Atmospheric data have reported in Table 1.

Main physical parameters of the airship have been evaluated in Table 2. An overpressure about 5 % has considered ensuring the possibility of the balloon system to keep the shape.

Both Hydrogen and Helium balloons has been estimated and it has been observed that helium balloons results about 1.084 times larger than hydrogen ones. The hydrogen mass has also been evaluated in 29.44 tons while helium mass in about 61.53 tons. A parameter, defined V_{eff}, has defined for hydrogen and helium airships. It considers that the external volume of the system is larger than the volume of gas strictly necessary for buoyancy. A coefficient 1.1 has adopted in this evaluation because of the system is a cruiser/feeder. It presents more empty spaces than any other traditional airship system because of this architecture.

Changing shape airship architecture such as the ones evaluated in [19, 20] has evaluated. It has also evaluated an ellipsoid shape, which is characterised by the following relations:

$$V = \frac{4\pi}{3} \cdot a \cdot b \cdot c \tag{1}$$

$$A \simeq 4 \cdot \pi \cdot \left(\frac{a^k b^{\mathrm{k}} + a^k c^k + b^k c^k}{3} \right)^{1/k} \tag{2}$$

Area expressed by Eq. 2 is expressed by the Knud Thomsen formula which has a maximum error of 1,061, where k is a numerical constant equal to 1.6075.

It is possible to compare Helium and Hydrogen volume. The comparison is reported in Table 3. The following conventions have assumed: V is the useful volume of buoyant gas for lift and V_{eff} the effective volume used for aerodynamic calculations. The two semi axes on the horizontal plane (x, y) have been assumed $a = b = 150\ m$. The constant c is considered variable with altitude. By this assumption, it is possible to evaluate the reference values used for calculation (Table 4).

Table 8 Estimated costs for the plant

Photovoltaic modules	$/kW	1,000
Back-up system	$/kW	300
Installation	$/kW	200
Transmission lines	$/kW	300
Inverter	$/kW	100
Electrolysers	$/kW	200
Compression plant and Storage	$/kW	400
Total	$/kW	2,500

5 Initial airship inflation

The initial inflation can be evaluated by assuming the masses of both helium and hydrogen.

In 2011, the Helium 99.9 % the average market price in the U.S. [44, 45] can be estimated between 50 and 70 USD/MCF. It means a price between 1.77 and 2.47 USD/m^3. For such a volume of hydrogen it is necessary an initial expense between 613000 USD and 855000 USD excluding losses. Some China suppliers have similar prices also. Prices exclude storage

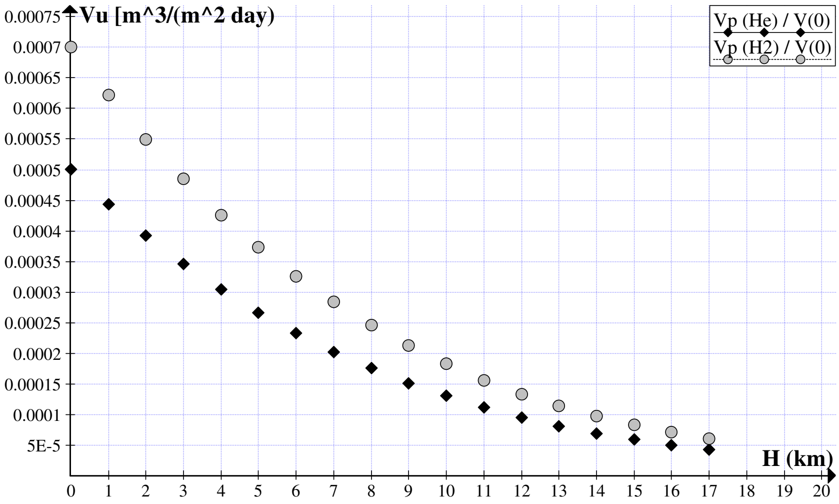


Fig. 3 Unitary losses as a function of operative altitude with high quality fabric

cylinders and delivery costs, which lead in Europe to much higher prices.

In a preceding paper, Dumas [43] has estimated that the necessary hydrogen can be produced in one year with a large photovoltaic facility with the characteristics reported in Table 5. It has evaluated the economic feasibility of photovoltaic hydrogen production that making a conservative hypothesis on the prices of hydrolytic hydrogen (evaluated one-fifth of average helium cost). For advanced solid polymer or alkaline electrolyser, the electric efficiency [46] of the industrial process overcomes 75 %.

A possible market price of hydrogen for airship inflation can be estimated (prudentially) the 25 % of average helium cubic meter prices. It means that a cubic meter of Hydrogen is about 0.5 \$/m^3 (a low price considering actual market standards). Considering that about 5 kWh are necessary to produce 1 m^3 of compressed hydrogen, it means the price of electricity can be considered 0.1 \$/kWh.

Compressed hydrogen productivity has estimated in different locations and at different latitudes (Table 6). In particular sample locations has assumed on the northern hemisphere at 15° step.

The hydrogen average annual productivity on a flat horizontal plan has estimated in terms of compressed hydrogen [20, 23, 24] and shown as a function of latitude in Fig. 1.

It has also evaluated the plant dimensions (Table 7) according to the unitary costs specified in Table 5. The costs (Fig. 1) and payback times (Fig. 2) have been estimated. The dimensions have evaluated on the possibility of filling a large airship such as the one considered with the electrical production of a year.

Considering European costs of Energy a similar photovoltaic plant, even if very large, can have a very similar payback time considering the possibility of selling the electricity on the market at the same evaluated price of 0.1 USD/kWh.

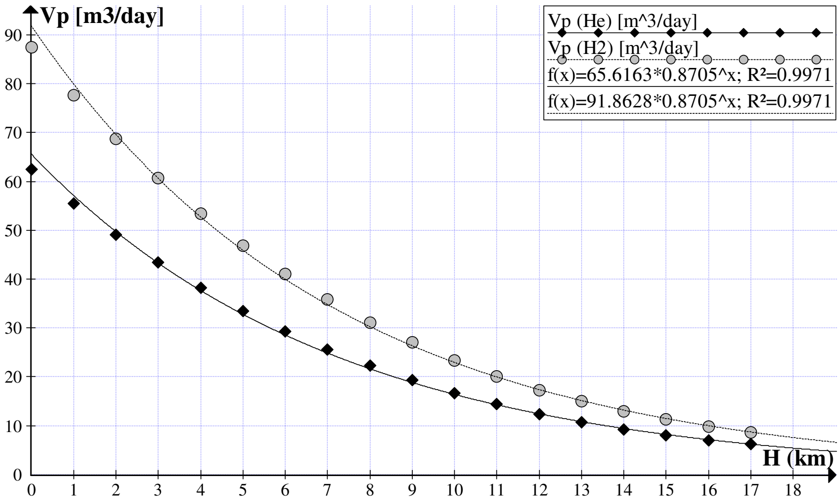


Fig. 4 Losses [m^3/day] as a function of operative altitude with high quality fabric and interpolating functions

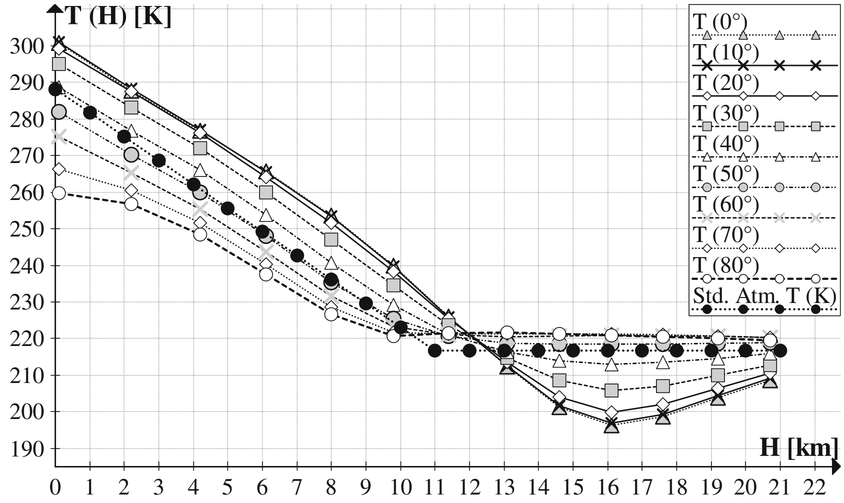


Fig. 5 Temperature CIRA 86 average annual values vs. Standard Atmosphere values

6 Buoyant dispersion

6.1 Permeability

An airship has continuous losses of gas by permeability. In scientific literature, different expressions can be found to describe permeability processes. The simplest way is to adopt the permeability coefficient [47], which can be defined as:

$$P = \frac{(quantity\ of\ permeant) \times (film\ thickness)}{(area) \times (time) \times (pressure\ drop\ across\ the\ film)}$$

This representation of permeability is very comfortable for an initial evaluation and especially because it permit a temperature dependent formulation. The case of a high altitude airship can be described by temperature dependent coefficients, because of the extreme variation of thermal conditions during missions.

Table 9 Permeability coefficient of various materials

	P(He)	(P(H2)	P(O2)
Poly(ethylene) density 0.914 g/cm^-3	7.40E-13	3.70E-13	2.20E-13
Polyvinilecloride plasticized 10 %	1.30E-13	–	3.83E-16
Polyvinilacetate	4.95E-13	2.99E-13	1.36E-14
Poly(trifluorochloroethylene) film 30 % cristallinity	7.05E-14	5.10E-13	3.00E-15
Mylar A	4.88E-14	2.44E-14	3.00E-15
Nylon 6	–	3.98E-14	2.85E-15
Nylon 11	1.34E-13	1.46E-13	–
Cellophane (relative humidity 43 %)	1.20E-15	–	5.36E-16

The permeation of molecules through flawless polymers is the combination of two effects: the solution of a permeant in the polymer and diffusion of the dissolved permeant. The permeability coefficient is the product of the diffusion coefficient D and the solubility coefficient S:

$$P = D \cdot S \tag{3}$$

The permeability coefficient P, the diffusion coefficient D, and the solubility coefficient S can vary as a function of temperature, and exponential relations can express these relations:

$$P = P_0 \cdot e^{-\frac{E_p}{RT}}; D = D_0 \cdot e^{-\frac{E_d}{RT}}; S = S_0 \cdot e^{-\frac{E_s}{RT}} \tag{4}$$

where E_p is the activation energy of permeation, E_d the activation energy of diffusion, and E_s the heat of solution that have in SI units the dimension [kJ/mol]. Those data are tabled for many polymers and for many gasses and liquids. P_o, D_o and S_o are the multiplicative factors. R is the gas constant; T is the temperature.

The permeability coefficient is determined for a given temperature by means of the multiplicative factor P_o and the activation energy of permeation E_p. These data have been tabled by Pauly [47].

This permeability evaluation is important. Joints and defects need an accurate evaluation. In particular, data for some materials of interest for balloons are reported in Table 8.

7 Permeability evaluation of materials

The above-enunciated theory about permeability allows an effective application to the airship shape, both for helium

Table 10 Evaluation of dispersions for different polymers

Loses for a 20 μm membrane	Ground			16 km		
	V(H_2) [m^3gas/m^2 h]	V(He) [m^3gas/m^2 h]	V(0_2) [m^3gas/m^2 h]	V(H_2) [m^3gas/m^2 h]	V(He) [m^3gas/m^2 h]	V(0_2) [m^3gas/m^2 h]
Poly(ethylene) density 0.914 g/cm^-3	7.13E-05	3.56E-05	2.12E-05	1.07E-05	5.34E-06	3.18E-06
Polyvinilecloride plasticized 10 %	1.25E-05		3.69E-08	1.88E-06		5.53E-09
Polyvinilacetate	4.77E-05	2.88E-05	1.31E-06	7.15E-06	4.32E-06	1.96E-07
Poly(trifluorochloroethylene) film 30 % cristallinity	6.79E-06	4.91E-05	2.89E-07	1.02E-06	7.37E-06	4.33E-08
Mylar A	4.7E-06	2.35E-06	2.89E-07	7.05E-07	3.52E-07	4.33E-08
Nylon 6					5.75E-07	4.12E-08
Nylon 11	1.29E-05	1.41E-05		1.94E-06	2.11E-06	
Cellophane (relative humidity 43 %)	1.16E-07		5.16E-08	1.73E-08		7.74E-09

and hydrogen. It can be assumed that the gas dispersion for permeability can be expressed as:

$$M_p = \frac{P \cdot A \cdot t \cdot \Delta p}{s} \tag{5}$$

Gas dispersion for the three critical gasses has calculated for 1 m^2 of balloon surface and per hour of steady service.

The choice of material must be a good compromise of mechanical properties and gas dispersions. The best compromise solutions between mechanical properties and porosity are Mylar A and or Nylon rip-stop-polyurethane dual layer balloons.

It is possible to find on the market high-quality proprietary fabrics. For example, it can be cited 3-ply rip-stop nylon 108.5 g/m^2 made on rigorous standards with internal polyurethane balloon. It has not the typical problems of the polyurethane: the pinholes and the difficulties in reparation.

This material allows evaluating daily losses in STP conditions. Helium losses are about 2.5 10^{-4} m^3 (273.15 K; 1,013×10^5 Pa)/(m^2 day). Hydrogen losses about 3.5 10^{-4} m^3 (273.15 K; 1,013×10^5 Pa)/(m^2 day). The cited values do not consider an entire airship in service including losses due to the junctions among different textile sheets (Blimpworks Airship – USA). The considered overpressure is higher than the usual one 1–3 %).

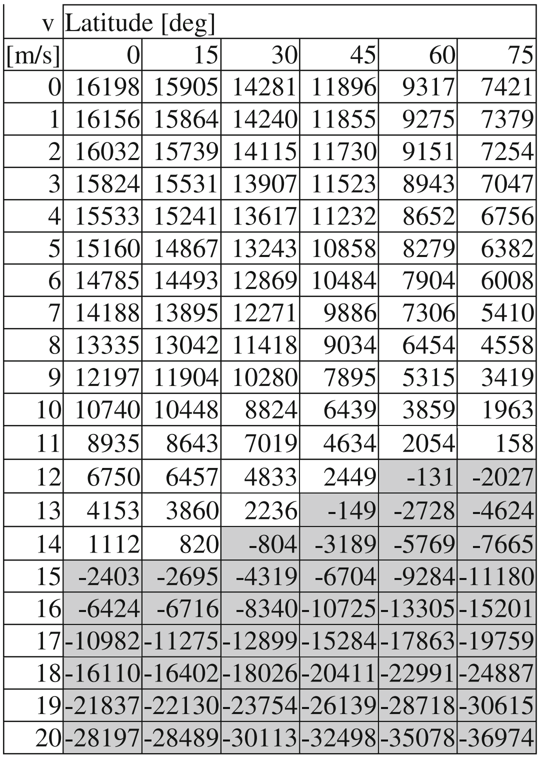
Table 11 Example of massif regulation in the case of a thermal excursion in gas temperature±10°between day and night

Hydrogen	T [K]	V [m^3]	ΔV [m^3]	ΔM gas [kg]
	206.65	2368397	−114609	1446
	216.65	2483006	0	0
	226.65	2597616	114610	−1318
Helium	T [K]	V [m^3]	ΔV [m^3]	ΔM gas [kg]
	206.65	2579995	−124849	2865
	216.65	2704844	0	0
	226.65	2829692	124848	−3142

8 Gas dispersion evaluation in service

The volume and surface defined in Table 4 allow evaluating the dispersion into service. An airship including junctions

Table 12 Difference of average energy productivity and energy used for propulsion [kW]



v	Latitude [deg]					
[m/s]	0	15	30	45	60	75
0	16198	15905	14281	11896	9317	7421
1	16156	15864	14240	11855	9275	7379
2	16032	15739	14115	11730	9151	7254
3	15824	15531	13907	11523	8943	7047
4	15533	15241	13617	11232	8652	6756
5	15160	14867	13243	10858	8279	6382
6	14785	14493	12869	10484	7904	6008
7	14188	13895	12271	9886	7306	5410
8	13335	13042	11418	9034	6454	4558
9	12197	11904	10280	7895	5315	3419
10	10740	10448	8824	6439	3859	1963
11	8935	8643	7019	4634	2054	158
12	6750	6457	4833	2449	-131	-2027
13	4153	3860	2236	-149	-2728	-4624
14	1112	820	-804	-3189	-5769	-7665
15	-2403	-2695	-4319	-6704	-9284	-11180
16	-6424	-6716	-8340	-10725	-13305	-15201
17	-10982	-11275	-12899	-15284	-17863	-19759
18	-16110	-16402	-18026	-20411	-22991	-24887
19	-21837	-22130	-23754	-26139	-28718	-30615
20	-28197	-28489	-30113	-32498	-35078	-36974

Gray cells indicates negative values

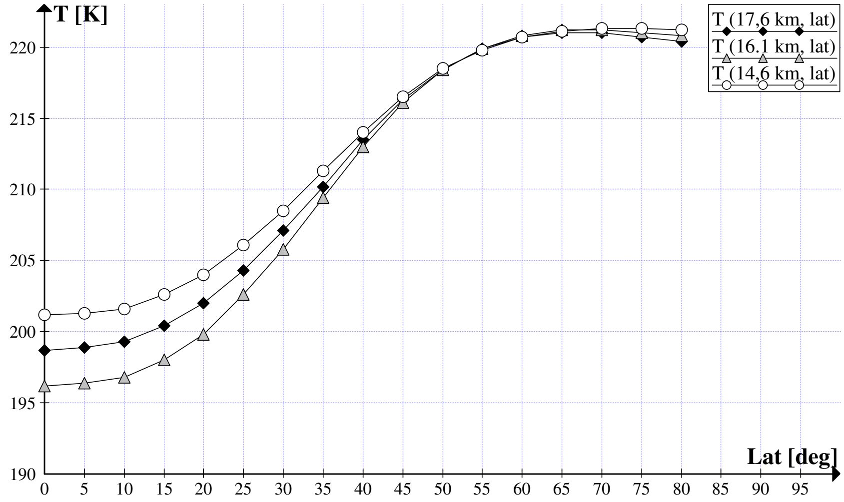


Fig. 6 Average temperature excursion around operative altitude of 16 km (North hemisphere)

among sheets of the high-quality mentioned materials has been evaluated. Figure 3 shows the results. The overpressure has increased to 5 % instead 1 % evaluated by the producer.

By the results in Figs. 4 and 5 it is possible to see that long permanence airships with mission times longer than a week it losses can be significant.

The calculations show the losses because of permanence at high altitudes for a month. Helium losses are about 210 m^3 and Hydrogen ones about 290 m^3. These preliminary evaluations force to consider the impossibility to preserve the necessary overpressure and the shape geometry without any refill of gas. The losses increase also consistently in case of a lower quality fabric.

9 Daily thermal excursion effects

Another important volumetric effect is the daily thermal excursions and to location changes during travel. They have, with solar irradiance, large effects on the temperature and density of the buoyant gas. To compensate these daily thermal effects is necessary to preserve the operative altitude. The reference temperature of Standard Atmosphere model at stratospheric altitudes is about −56 °C.

The simplest regulation of the volume against temperature variations is to vary the mass of gas in the balloon. The same pressure and volume preceding the thermal variation can be restored and preserved. Thermal controls have often used but volumetric are less expensive and less complex. They need only a sufficient reserve of gas.

For example, Tables 9, 10, 11 and 12 shows the results of the calculations considering a thermal excursion of ±10°. This example shows clearly that it is necessary a gas reserve also in mass to keep the volume by buoyant gas addition or subtraction.

This strategy of preserving the volume is interesting for hydrogen, because it is possible to avoid thermal actions on hydrogen lowering energetic costs and lessening the risks related to hydrogen thermal treatment plant.

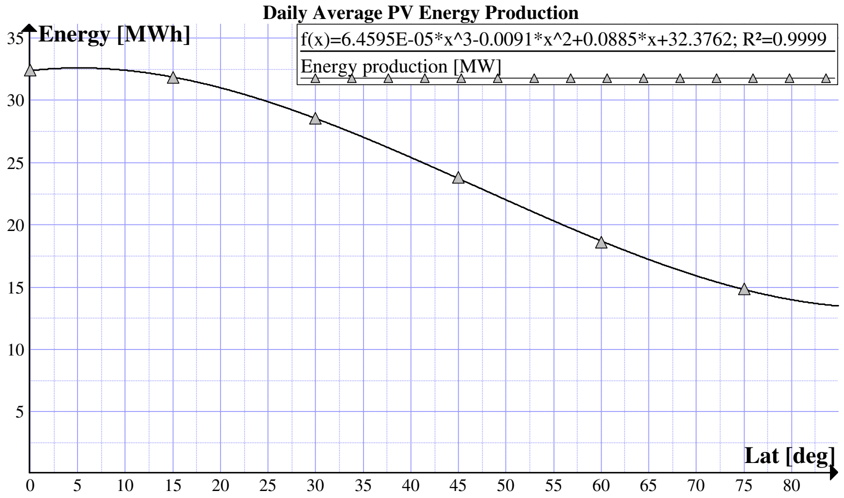


Fig. 7 Electric Energy Production average daily value [MW] for different latitudes at an altitude of 16 km a

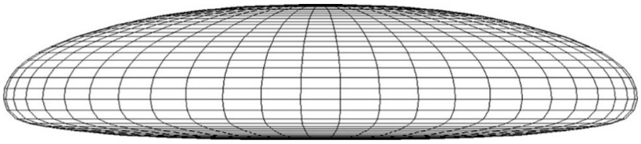


Fig. 8 The configuration of the reference shape

Another thermal effect needs a serious evaluation: the changes in air temperature and density, moving from one location to another. Figure 5 shows average temperature by Standard Atmosphere model and average temperature at different latitudes by CIRA Model.

Figure 6 shows the temperature variation around the operative altitude.

It shows clearly that an average temperature jump about 25° must be considered. The daily thermal excursion has estimated in 10–12 ° C by considering data that are more accurate. By these values, the thermal effects on the system have estimated for this preliminary calculation.

In this case, the volume control by buoyant gas variation is easier than any other operation and much convenient for hydrogen airship.

10 Energy needs for flight

The energy production has estimated in a precedent paper [20] for square meter of photovoltaic surface at various latitudes. The photovoltaic surface has estimated about 61,000 m^3. Daily average production has shown in Fig. 7 against latitude.

The considered discoid airship shape at 16.000 has shown in Fig. 8. The coefficient of drag of the shape C_D and drag D has evaluated as a function of wind velocity at different diameters in a preceding paper [24]. It can be assumed conservatively a $C_{d,V}$ about 0.125 even if a lower one has been evaluated in the cited paper including their variation as a function of Reynolds number.

Following the method presented in such paper the aerodynamic forces and necessary power has estimated. Figure 9 presents the needed power at 16 km against relative velocity of the airship and third order interpolating function.

The held values allow verifying the average production of photovoltaic energy. The use of compressed hydrogen storage and fuel cells for conversions, together with batteries for emergency has assumed. A reference efficiency of the energy caption, storage and conversion has considered about 50 %.

Calculations have realised for 24 h of service at the annual mean relative speed of the considered airship. The energy needs have evaluated and subtracted to the needs for daily operations at constant velocity. The values are reported at an altitude of 16 km for different relative velocities. It has noted that the system must preferably move in the main direction of high altitude winds. In other cases, it can only remain in hovering conditions or being moved by high altitude winds passively.

The results force to consider a conservative hypothesis. The airship can move at an average velocity. It is equal to the average wind velocity in the selected location plus a seasonal value depending on photovoltaic energy high altitude caption.

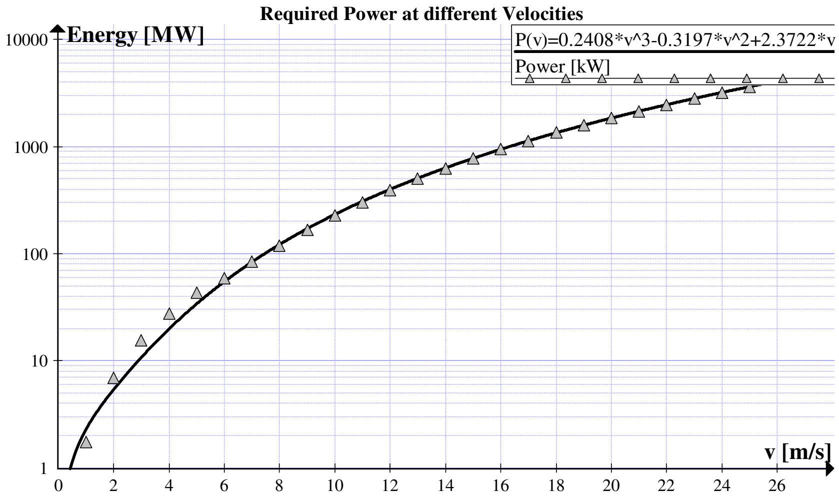
Average speeds have evaluated by the results of these elementary calculations. Detailed calculations could be performed on daily, weekly or monthly photovoltaic productivity.

The operative velocity can then be plotted in Fig. 10 on average annual basis, taking data by the values of the velocity of winds by CIRA model.

11 General considerations and future advances

This paper presents a problem and analyses it drawing a methodological model of work for the future activities related to the MAAT project.

Fig. 9 Required power kW at different relative velocities



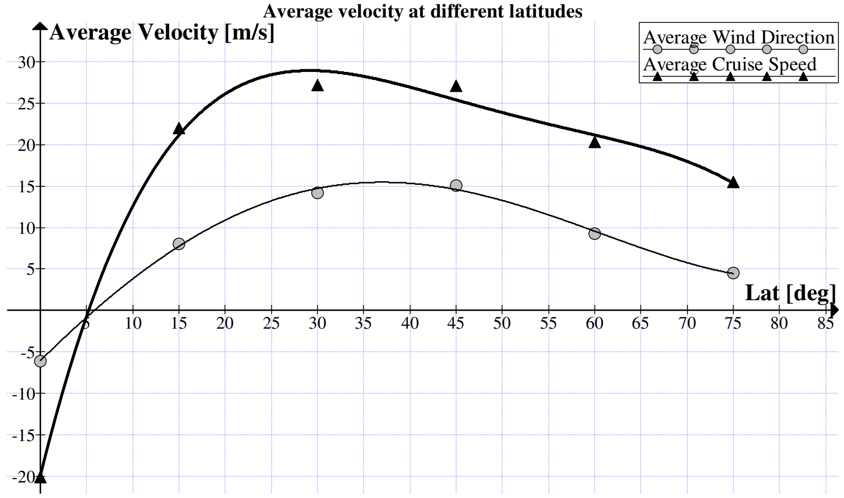


Fig. 10 Average velocity at an altitude of 16 Km at different latitudes

The mission profiles require a more accurate analysis of the velocities of the winds at different altitude and an effective mapping of the jet streams. It will be one of the primary efforts of further activities, which will define the ideal shape of the cruiser and the mission profiles.

The optimization of the shape and operation connected problems. They are the core of the development of the MAAT cruiser/feeder project. This paper present a method for the calculations necessary to minimize of energy needs and volume through an effective step by step optimisation.

Future activity will require also a detailed study of adiabatic phenomena that takes place during vertical movements, especially relating the feeder behaviour. An airship is subject during vertical movement to heating and cooling phenomena. Considering the vertical motion of an airship or of a balloon, it can be easily demonstrated that it changes its average temperature during expansion/compression processes. Some hypothesis are required. They are in brief:

1. thermal exchanges of the balloon during the vertical movement are negligible,
2. the balloon can be considered as an air parcel.
3. changes in temperature result from either expansion or contraction

Such a process can be described by the first principle of thermodynamics and its governing equations are:

$$\mathrm{dq} = 0 \Rightarrow \begin{cases} \mathrm{V} = \mathrm{cost} \rightarrow \mathrm{c_v dT} + \mathrm{p d}\alpha = 0 \\ \mathrm{P} = \mathrm{cost} \rightarrow \mathrm{c_p dT} - \alpha \mathrm{dP} = 0 \end{cases} \qquad (6)$$

In particular it can be considered an adiabatic process described by Poisson Eq. (7), which can be obtained by ideal gas equation:

$$\frac{\mathrm{T_{final}}}{\mathrm{T_{initial}}} = \left(\frac{\mathrm{p_{final}}}{\mathrm{p_{initial}}}\right)^{\mathrm{R_d}/\mathrm{c_p}} \qquad (7)$$

Using numerical interpolations of the Standard Atmosphere values it is possible to evaluate the theoretical adiabatic temperature reached by the balloon. It relates the initial conditions of temperature and pressure to the final temperature and pressure. In calculations it can be assumed the hydrogen gas constant $R_d = 4124\ J/kg\ K$ and the specific heat $c_p = 14.25\ J/kg\ K$. It is in particular necessary to define an adequate model of the system and the heating/cooling apparatus to maintain the temperature of the gas in an acceptable range.

Adiabatic heating/cooling processes together with the heat transfer processes between the internal gas and the exterior one is an argument which needs to be analysed in depth. This activity will be interesting in the future especially to create an exact model of the vertical motion of the feeder.

Together it is necessary the job on controls.

12 Conclusions

This paper aims to show that hydrogen is fundamental for the future of airships. They are suffering large problems because of high costs of helium.

Hydrogen, which can be produced on board, simplifies the management of airship during long missions. It ensures the possibility of a continuous refilling of spread gas, even if hydrogen has higher dispersions than helium.

It has demonstrated that today prices of the photovoltaic hydrogen are the most economic choice for airship filling. Estimating a cost of electricity up to 0.1 USD/kWh it has shown that a photovoltaic plant for hydrogen production ensures a valid alternative to helium.

It has demonstrated that a mix of storage technologies can perform the best performances and flexibility. Hydrolyser and fuel cells can perform the basic needs and batteries ensure a fast acting and flexible system. Together they ensure acceptable performances even with non-optimised shapes.

In this paper it has been considered the possibility of using hydrogen for airship volume. It is another important development for the future hydrogen airships. It is necessary because it is needed to increase system safety by removing any air ballonet inside the volume of the hull.

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