Airship Lift By Hot Air From Its Engines

Introduction

Airships use helium. To go up the bag (sometimes called the envelope) is filled. To go down some helium is compressed into small bags, called ballonets. Helium is getting scarce and expensive, and there are problems associated with the use of other gases. Hot air can be used instead of helium and such ships use a gas burner to heat the air. Here it is shown that airships can use air which is heated by the engines.

To ensure that the values used are realistic an example airship is used, currently made by HAV, the Airlander 10. Specifications are given in the appendix.

The engines of this airship are diesel, and a general rule of thumb is that the energy consumed by such engines is distributed thus: 35% power output, 35% exhaust & 30% water jacket. The power output of the example engines (four are used) is 1MW. This means that the heat from the water jacket is 895kW. This heat is available in the air leaving the engine radiators. Allowing for the inaccuracy of the rule of thumb, and for losses, assume that only 400kW is available.

Figure 1 shows how the air from the radiators can be directed into the bag, to raise the temperature of the air in the bag. The pressure in the bag is maintained at ambient pressure by a pressure relief valve releasing air from the top of the bag, so the density of that air is decreased, and the bag becomes buoyant.

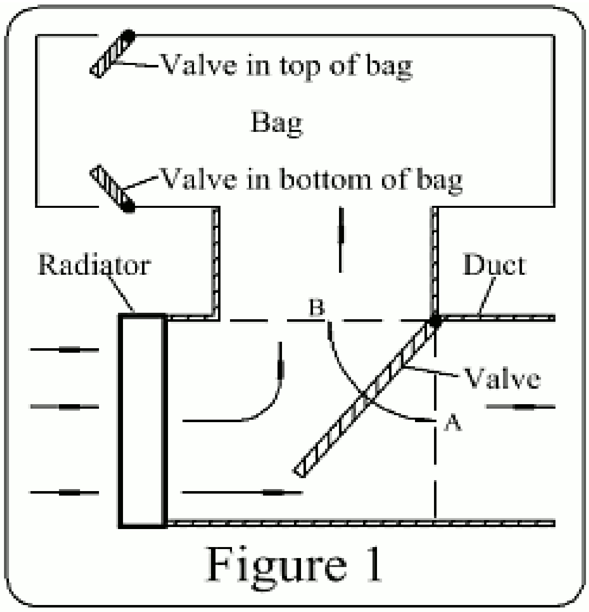

Figure 1

Ambient air is drawn through the radiator as in normal practice. From the radiator the air, instead of escaping to atmosphere as normal, enters a duct. In the duct is a valve which can take any position between its extents A & B. At A all the air is directed into the bag. At B, the air is vented to the atmosphere. Any position between A & B can can be selected to control the rate of ascent.

To descend, the valve at the top of the bag can be opened and a valve at the bottom of the bag can be opened, thus letting ambient (cooler) air into the bag.

ICAO, for the ambient air in the troposphere	
P_{sl}	Standard pressure at sea level = 101325Pa
T_{sl}	Standard temperature at sea level = 288.15K
ρ_{sl}	Standard density at sea level = 1.225kg/m^3
H_t	Height of tropopause = 11000m
L	Temperature lapse rate = (T_{sl} -T_t) / H_t = 0.0065K/m
P_t	Pressure at tropopause = 22633Pa
T_t	Temperature at tropopause = 216.65K
g	9.80665m/s^2
R	Universal gas constant = 8.31447J/mol.K
M	Molar mass of dry air = 0.0289644kg/mol
R_s	Specific gas constant = R / M = 287.048J/kg.K

$$T = T_{sl} - LH$$

$$P = P_{sl} \left(1 - \frac{LH}{T_{sl}}\right)^{\frac{g}{R_s L}}$$

$$\rho = \frac{PM}{RT} = \frac{P}{R_s T}$$

In the lower stratosphere (constant T): H_s = Height above H_T

$$P = P_t \, e^{\left(g \frac{(H_t - H_s)}{R_s T_s} \right)}$$

a	ambient
b	air in bag
f	final
i	ingoing air
o	out
m	mass = V.ρ kg
V_b	Volume of bag
V_s	Volume of ship, say = V_b
W_b	Weight of air in bag = $V_b.\rho_b.g$
W_s	Weight of (rest of) ship
W_t	$W_b + W_s$
ρ_s	Density of ship = W_t / V_b
C	specific heat, kJ/kg.K
T	temperature, K
V	volume

Buoyancy

Upthrust = $\rho_a\ g\ V_b$

Acting against this is W_t

So total buoyancy force = $\rho_a\ g\ V_b$ - W_t

Maintenance of Constant Height

For constant height: $\rho_a\ g\ V_b = W_t$

$$\frac{P_a\ g\ V_b}{R_s\ T_a} = W_b + W_s = V_b\ \rho_b\ g + W_s = \frac{V_b\ P_b\ g}{R_s\ T_b} + W_s$$

$$\frac{V_b\ P_b\ g}{R_s\ T_b} = \frac{P_a\ g\ V_b}{R_s\ T_a} - W_s$$

$$V_b\ P_b\ g = \frac{R_s\ T_b\ P_a\ g\ V_b}{R_s\ T_a} - R_s\ T_b\ W_s$$

$$= T_b \left(\frac{P_a\ g\ V_b}{T_a - R_s\ W_s} \right)$$

$$T_b = \left(\frac{V_b\ P_b\ g}{\left(\frac{P_a\ g\ V_b}{T_a - R_s\ W_s} \right)} \right)$$

As stated above, $P_b = P_a$.

Example: required height = 500. From HAV's Airlander 10, V_b = 38000 & W_s = 20000.

$$P_b = P_a = P_{sl} \left(1 - \frac{LH}{T_{sl}} \right)^{\frac{g}{R_s L}}$$

$$= 101325 \left(1 - \frac{0.0065 \times 500}{288} \right)^{\frac{9.80665}{287 \times 0.0065}}$$

$$\underline{= 95458 Pa}$$

$$T_a = T_{sl} - LH = 288 - 0.0065 \times 500$$

$$\underline{= 285K}$$

$$T_b = \left(\frac{38000 \times 95458 \times 9.80665}{\left(\frac{95458 \times 9.80665 \times 38000}{285 - 287 \times 20000} \right)} \right)$$

$$\underline{= 299K}$$

If the bag is internally lined with Aerofoam or survival blanket material, then the thermal conductivity, λ, of the bag will be 0.044W/m^2.K:

$$\text{Heat loss} = \text{Surface area} \; . \; \delta T \; . \; \lambda$$

$$\simeq 15050 \times 11 \times 0.044$$

$$\underline{= 7.3kW}$$

Example: required height = 6000.

$$P_b = P_a = P_{sl} \left(1 - \frac{LH}{T_{sl}}\right)^{\frac{g}{R_S L}}$$

$$= 101325 \left(1 - \frac{0.0065 \times 6000}{288}\right)^{\frac{9.80665}{287 \times 0.0065}}$$

$$\underline{= 47154Pa}$$

$$T_a = T_{sl} - LH = 288 - 0.0065 \times 6000$$

$$\underline{= 249K}$$

$$T_b = \left(\frac{38000 \times 47154 \times 9.80665}{\left(\frac{47154 \times 9.80665 \times 38000}{249 - 287 \times 20000} \right)} \right)$$

$$\underline{= 271K}$$

Heat loss = 11.3kW

Example: required height = 11000.

$$T_b = \left(\frac{38000 \times 22633 \times 9.80665}{\left(\frac{22633 \times 9.80665 \times 38000}{217 - 287 \times 20000} \right)} \right)$$

$$\underline{= 255K}$$

Heat loss = 25.2kW

As shown above, 400kW is available. This is ample.

<u>Rate of ascent</u>

Regarding the air from the radiator: $C_{air} \simeq 1$.

$V_b = 38000$.

At sea level: $\rho_a = 1.225$, $m_b = 46550$.

So the air from the radiator can raise the bag temperature by

$$\frac{400000}{46550} \underline{= 8.6K/s}$$

At a temperature of 288 + 8.6,

$$\rho = \frac{P}{R_s T} \underline{= 1.19}$$

$$H' = \frac{T_{sl}}{L} \left(1 - \left(\frac{\rho R_s T}{P_{sl}} \right)^{\frac{R_s L}{g}} \right)$$

$$= \frac{288}{0.0065} \left(1 - \left(\frac{1.19 \text{ x } 287 \text{ x } 296.6}{101325} \right)^{\frac{287 \text{ x } 0.0065}{9.80665}} \right)$$

$$\underline{= 2.26}$$

In other words, a climb rate of 136m/min.

At H = 500: P_a = 95458 & T_a = 285

$$\rho_a = \frac{P}{R_s T}$$

$$= \frac{95458}{287 \text{ x } 285}$$

$$\underline{= 1.167}$$

m_b = 44346.

So the air from the radiator can raise the bag temperature by

$$\frac{400000}{44346} \underline{= 9K/s}$$

At a temperature of 285 + 9,

$$\rho_a = \frac{P}{R_s T} \underline{= 1.13}$$

$$H' = \frac{285}{0.0065} \left(1 - \left(\frac{1.13 \text{ x } 287 \text{ x } 294}{95458} \right)^{\frac{287 \text{ x } 0.0065}{9.80665}} \right)$$

$$\underline{= 9.7}$$

In other words, a climb rate of 582m/min.

At H = 11000

P_a = 22663

T_a = 217

$$\rho_a = \frac{22663}{287 \text{ x } 217} \underline{= 0.364}$$

m_b = 13828.

So the air from the radiator can raise the bag temperature by

$$\frac{400000}{13828} = \underline{29K/s}$$

At a temperature of 217 + 29,

$$\rho_a = \frac{P}{R_s T} \underline{= 0.32}$$

$$H' = \frac{217}{0.0065} \left(1 - \left(\frac{0.32 \times 287 \times 246}{22663} \right)^{\frac{287 \times 0.0065}{9.80665}} \right)$$

$$\underline{= 19.7}$$

In other words, a climb rate of 1184m/min.

The engine power will decrease with altitude, but power reduction is not considered here.

So far the heat from the water jacket has been considered, but more heat is available from the exhaust. It is not suggested that the exhaust is vented into the bag, which would cause contamination of the bag material and internal components. Instead, the heat from the exhaust can be used as shown in Figure 2.

The exhaust pipe is part of a duct with a valve which works as explained in Figure 1. With the valve in position B the exhaust is vented to atmosphere. When the exhaust is directed into the bag the flow is then through a heat exchanger and then is vented to atmosphere.

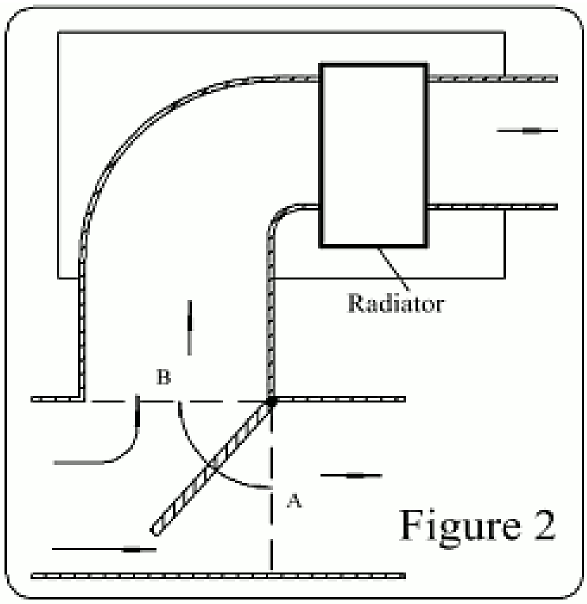

Figure 2

First Conclusion

The use of heat from diesel engines is a practical proposition.

The Future

As airship speeds increase the use of jet engines will become practicable.

The Turboprop

An example of a current engine of the required power output is the General Electric CT7. This has an air flow rate of 4.5kg/s, and the exhaust temperature will be ≃ 1073K. With four engines, and letting C = 1, the heat power available is 14.4MW. From Maintenance of Constant Height it can be seen that this is sufficient for the ceiling of the Airlander, 6000m. Figure 3 shows how to achieve the heat exchange.

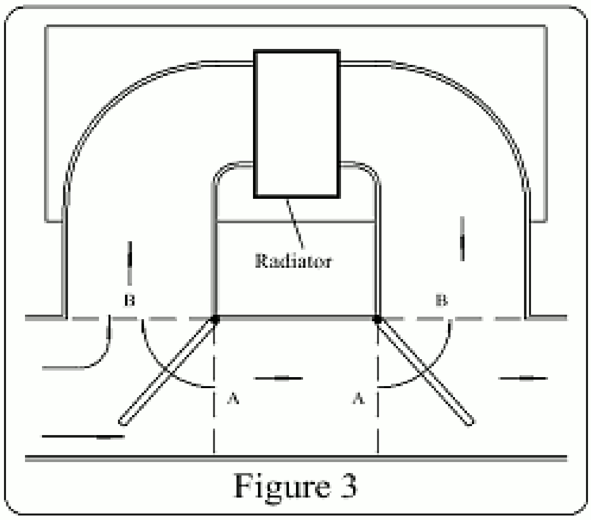

Figure 3

The exhaust is ducted. The duct has two interconnected valves. With the valves at B the exhaust is vented to atmosphere. With the valves at A the exhaust heat is directed into the bag, the flow then being through heat exchanger and then to atmosphere.

Another way of getting heat from a jet engine, turboprop, turbofan or turbojet, is to take air from the compressor, as shown in Figure 4.

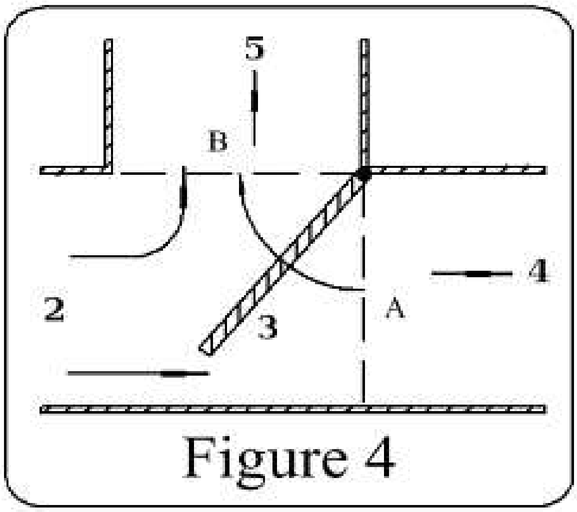

Figure 4

Some air is bled from the compressor outlet into a duct, 2, containing a valve, 3, which can move between the extents A & B as before. With the valve at B the air is redirected back to the engine, 4. With the valve at A the air is directed to the bag, 5.

The Compressor

The compression is isentropic and a CR of 4 is typical of current engines. γ for air = 1.4.

$$\frac{P_a}{P_o} = \left(\frac{V_o}{V_a}\right)^{\gamma}$$

So $P_o = P_a(4^{\gamma})$

$$\frac{T_o}{T_a} = \left(\frac{P_o}{P_a}\right)^{\left(1 - \frac{1}{\gamma}\right)}$$

So $T_o = T_a \left(\frac{P_o}{P_a}\right)^{\left(1 - \frac{1}{\gamma}\right)}$

$$\rho_o = \frac{P_o}{R_s T_o}$$

At sea level: T_a = 288 & P_a = 101325.

At 500m: T_a = 285 & P_a = 95458.

For an ascent between these heights let T_a & P_a be the median values, ie, 286.5 & 98392.

From the compressor: P_o = 685238, T_o = 499 & ρ_o = 4.78

From Maintenance of Constant Height:

$$T_b = \left(\frac{V_b\, P_b\, g}{\left(\frac{P_a\, g\, V_b}{T_a - R_s\, W_s} \right)} \right) \underline{= 299}$$

For a mixture of two masses of air at different temperatures:

$$T_f = \frac{m_1\, C_1\, T_1 + m_2\, C_2\, T_2}{m_1\, C_1 + m_2\, C_2}$$

$$C_1 \simeq C_2 \simeq 1, \text{ so } T_f = \frac{m_1\, T_1 + m_2\, T_2}{m_1 + m_2}$$

Once the masses are mixed the composition will be:

$$(V_a - V_i)\ @\ 288K + V_i\ @\ 499K$$

$$\text{So } T_f = \frac{288 \times 1.225\, (V_a - V_i) + 499 \times 4.78V_i}{1.225\, (V_a - V_i) + 4.78V_i}$$

$$= \frac{288 \times 1.225V_a - 288 \times 1.225V_i + 499 \times 4.78V_i}{1.225V_a - 1.225V_i + 4.78V_i}$$

$$= \frac{288 \times 1.225V_a + 2032V_i}{1.225V_a + 3.56V_i}$$

$$T_f\, (1.225V_a + 3.56V_i) = 288 \times 1.225V_a + 2032V_i$$

$$1.225V_aT_f + 3.56V_iT_f = 288 \times 1.225V_a + 2032V_i$$

$$2032V_i - 3.56V_iT_f = 1.225V_aT_f - 288 \times 1.225V_a$$

$$V_i\, (2032 - 3.56T_f) = 1.225V_a\, (T_f - 288)$$

$$V_i = \frac{1.225V_a\, (T_f - 288)}{2032 - 3.56T_f}$$

$$V_i = \frac{1.225V_a \times 38000\, (299 - 288)}{2032 - 3.56 \times 299}$$

$$\underline{= 529}$$

The work required $= \gamma R_s \left(\frac{T_o - T_i}{\gamma - 1} \right)$

$$= 1.4 \times 287 \left(\frac{499 - 285}{0.4} \right)$$

$$\underline{= 214963\ J/m^3}$$

To match the rate of ascent accomplished by the radiator air of the diesel-powered ship, V_i must be supplied in 221s.

So the compressor power $= 214963 \times \frac{529}{221}$

$$= 515kW$$

$$\underline{= 139kW / engine}$$

(presuming four engines). Such an engine can be made.

Second Conclusion

The use of heat from a jet engine is a practical proposition.

Comparison With Helium

For maintenance of height there is no difference. For rate of climb, the density of helium at STP is 0.179kg/m^3, so helium is far superior. The other advantage of helium becomes apparent when considering a cold start. When using air, first the engines must be warmed up and then the air in the bag must be heated. There is a patent covering the use of engines to heat the gas in the bag, but I suspect that the cold start is the reason that hot air is not used.

Appendix

HAV Airlander 10	
Bag volume	38000
Length	92
Width	43.5
Height	26
Endurance	5 days manned
Altitude	6100
Engines	4 x 261kW, 4 litre, turbocharged diesels
Total weight	20000
Payload	10000
Speed	cruise 41, loiter 10

GE CT7 turboprop engine	
SHP	1100kW
Air flow	4.5kg/s