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Water Vapor Transmission Through Hull Material and Buoyancy of Aerostats

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An automated system for recording data during an aerostat lift-loss test includes relative humidity measurements in the helium and outside air. These data show that initially dry helium increases in water vapor content, approaching that of the outside air, following closely a theoretical prediction, and permitting computation of the overall water vapor transmissivity of the material. The effect on buoyant lift is derived, showing that water vapor in the helium increases lift while that in the outside air decreases lift. The increase in water vapor in the helium gives an artificially low lift loss rate during initial phases of the lift-loss test. A correction can be made to eliminate this error.

Nomenclature

A = area of material
D = transmissivity of material
L = gross lift of helium
P = barometric pressure
P_g = absolute pressure of He
P_s = saturation vapor pressure
P_{wa} = water vapor pressure in air
P_{wg} = water vapor pressure in He
P_0 = standard pressure, 760 mm Hg
R_a = pressure ratio of water vapor in air
R_g = pressure ratio of water vapor in helium
R_h = relative humidity, %
T = absolute temperature
T_0 = standard temperature, 288.15 K
t = time
V_g = volume of helium
γ_w = specific weight of pure water vapor
γ_{w0} = specific weight of water vapor at STP
η = lift factor for helium
κ_a = specific weight parameter for air
κ_g = specific weight parameter for helium
τ = time constant

Subscripts
a = air
g = helium

Introduction

THIS research was motivated by the desire to improve the speed and reliability of lift-loss tests that are required for checkout and acceptance of large aerostats. In this test the change in net lift over time is measured to determine the rate of helium loss. Since there are many factors that influence the buoyant lift, there is usually a significant scatter in the data and it is necessary to conduct the test over a long period of time and determine the lift loss by statistical analysis. One of the factors known to affect the buoyant lift is humidity in both the helium and the ambient air. Furthermore, it is known that water vapor penetrates modern laminated aerostat hull materials rather well.[1] Since water vapor is lighter than air it provides additional lift when the helium is moist. Moisture in the outside air reduces air density and decreases lift. These effects are usually ignored, primarily because of the difficulty of measuring humidity in the helium and the fact that the changes in lift are usually small. In the case of a lift-loss test, however, where the helium is initially dry, the influx of water vapor can cause serious error.

Recently, TCOM has initiated an automated measurement and recording system for lift-loss tests in the hangar facility at Weeksville, North Carolina. Included in the instrumentation are hygrometers and temperature sensors in the air and helium, which record relative humidity and temperature as a function of time. This has provided data to compute the rate of water vapor transmission through the hull material and to correct the lift-loss data for the effect on lift.

This article consists of two parts: 1) the theory and supporting data on the rate of transmission of water vapor into the hull of a TCOM 71M™ aerostat filled with initially dry helium and 2) the effect on lift as determined by lift-loss measurements. The barriers consist of a hull material and a lighter ballonet material. They were developed by TCOM, L.P., and the details of their construction and fabrication are proprietary. Generally, the hull material consists of a laminate of Tedlar® film with Mylar® and Dacron® fabric. For the ballonet material the Tedlar is omitted. The specifications call for a helium permeability of less than 1.0 l/m^2-day for the former and 2.0 l/m^2-day for the latter, using the procedure and conditions given in Ref. 2.

Water Vapor Transmission

Theory

Consider an aerostat initially filled with dry helium situated in humid air having a relative humidity R_h at temperature T_a. From this information the water vapor pressure of the air can be calculated using the function $P_s(T)$:

$$P_{wa} = R_h P_s(T_a)/100 \tag{1}$$

In a similar way, the water vapor pressure in the helium can be calculated.

The water vapor transmission is a function of the partial pressure of the gaseous water in the air and helium:

$$\frac{dw}{dt} = DA\left(\frac{P_{wa}}{P} - \frac{P_{wg}}{P_g}\right) \tag{2}$$

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Equation (2) can be simplified by ignoring the small pressure differential between the air and helium:

$$P_g \cong P \quad (3)$$

$$\frac{dw}{dt} = \frac{DA}{P}(P_{wa} - P_{wg}) \quad (4)$$

The water vapor inside the hull can be expressed in terms of the partial pressure ratio or volume concentration of water vapor. Thus,

$$w = V_g \gamma_w (P_{wg}/P) \quad (5)$$

where

$$\gamma_w = \gamma_{w0}(PT_0/P_0T_g) \quad (6)$$

Differentiating Eq. (5) and combining with Eq. (3), we have

$$\frac{dP_{wg}}{dt} = \frac{DA}{V_g \gamma_w}(P_{wa} - P_{wg}) \quad (7)$$

Assuming the water vapor pressure of the outside air remains constant, the solution to Eq. (7) is

$$P_{wg} = P_{wa}(1 - e^{-t/\tau}) \quad (8)$$

$$\tau = \frac{V_g \gamma_w}{DA} \quad (9)$$

Experimental Data

Lift-loss data were recorded on a TCOM 71M aerostat over a period of 22 days in the TCOM hangar facility in Weeksville, North Carolina. The aerostat and hangar environment were instrumented and the following parameters automatically recorded: data, time, barometric pressure, air temperature, air relative humidity, aerostat weight, net lift, ambient air temperature (at the midline of the aerostat), helium temperature (about 15 ft down from the top at the maximum diameter), helium purity, ballonet pressure differential, and helium relative humidity.

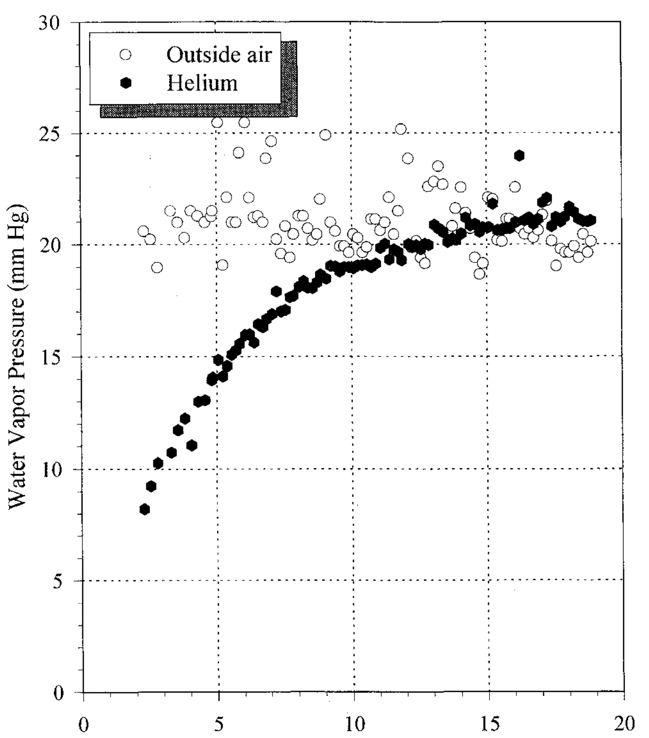

Fig. 1 Vapor pressure of water in helium and air during lift-loss test.

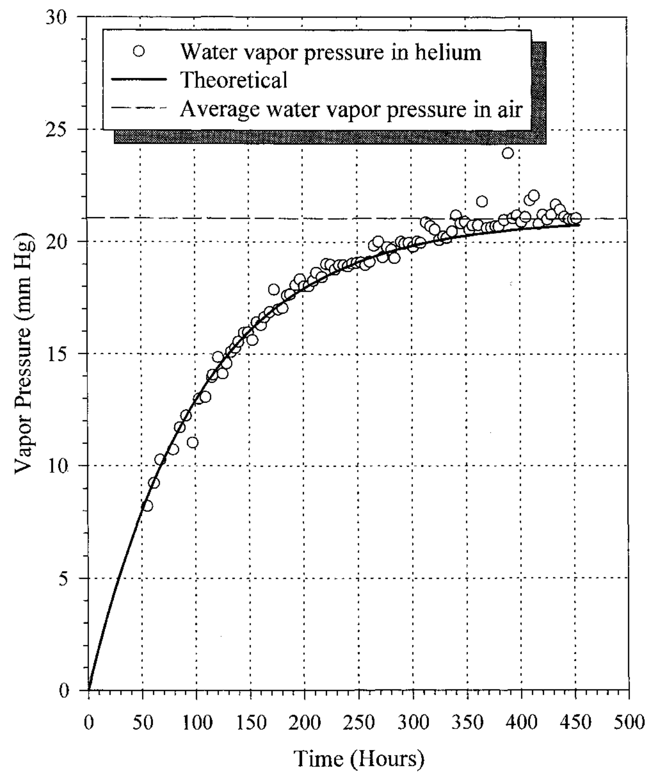

Fig. 2 Vapor pressure of water in helium as a function of time showing theoretical curve with a time constant of 105 h.

Altogether, 105 recordings of all the previous parameters were taken over the sampling period. The temperature and relative humidity of the air and the helium were used to compute the water vapor partial pressure using a computer program with a subroutine to compute $P_s(T)$ by interpolation from a table. The resulting data are plotted in Fig. 1.

In Fig. 1 the water vapor pressure of the ambient air shows considerable scatter, reflecting transient weather patterns and diurnal effects. These effects are not seen in the confined environment of the helium. It is apparent that the water vapor pressure in the helium increased approximately as predicted by Eq. (8), approaching that of the outside air in about 10 days. This is shown more clearly in Fig. 2, where the average water vapor pressure in the outside air of 21.04 mm Hg is shown as a dashed line and Eq. (8) with a time constant of 105 h is shown as a solid curve through the data.

Transmissivity

From the time constant and other parameters of the system, Eq. (9) can be used to compute the water vapor transmissivity of the material:

$$D = V_g \gamma_w / A\tau \quad (10)$$

The helium volume was calculated from the measured gross lift and the material area, including the hull and ballonet, from the geometry of the system:

$$\tau = 105 \text{ h}$$

$$V_g = 10{,}246 \text{ m}^3$$

$$A = 4280 \text{ m}^2$$

Pure water vapor cannot exist under standard conditions; however, its specific weight can be calculated from theory:

$$\gamma_{wo} = 0.7620 \text{ kg/m}^3$$

Adjusting for an average temperature of 29.4°C gives

$$\gamma_w = 0.7252 \text{ kg/m}^3$$

Using these values in Eq. (10), the water vapor transmissivity is

$$D = 0.0165 \text{ kg/m}^2\text{-h-atm at } 29.4°\text{C}$$

Effect of Water Vapor on Lift

Theory

In Ref. 1, a nomograph is presented, showing the lift ratio of moist helium-to-dry helium as a function of the dew point of the helium and the ambient air; however, no derivation or formulation was offered. The lift of dry helium in dry air is given by the relation

$$L = V_g(\gamma_a - \gamma_g) \tag{11}$$

Denoting the moist condition by primes, the lift of moist helium in moist air is

$$L' = V_g'(\gamma_a' - \gamma_g') \tag{12}$$

and the lift factor is defined as

$$\eta = L'/L \tag{13}$$

Using Dalton's law of partial pressures, the specific weight of moist air and moist helium and the volume of the moist helium can be calculated:

$$\gamma_g' = \gamma_g(1 - R_g) + \gamma_w R_g \tag{14}$$

$$\gamma_a' = \gamma_a(1 - R_a) + \gamma_w R_a \tag{15}$$

$$V_g' = V_g/(1 - R_g) \tag{16}$$

where

$$R_a = P_{wa}/P_a \tag{17}$$

$$R_g = P_{wg}/P_g \tag{18}$$

Substituting Eqs. (11), (12), (14), (15), and (16) in Eq. (13), and collecting terms yields

$$\eta = \frac{1 - \kappa_a R_a - \kappa_g R_g}{1 - R_g} \tag{19}$$

where

$$\kappa_a = (\gamma_a - \gamma_w)/(\gamma_a - \gamma_g) \tag{20}$$

$$\kappa_g = (\gamma_w - \gamma_g)/(\gamma_a - \gamma_g) \tag{21}$$

The ratios of the specific weights are constants, and so

$$\kappa_a = 0.4384$$

$$\kappa_g = 0.5616$$

Lift-Loss Test

The lift-loss test to determine the integrity of the material and seals is an important part of acceptance testing for large aerostats such as the 71M. This test is conducted in the TCOM hangar facility in as benign an environment as can be arranged. A carefully calibrated load cell automatically records the net lift, which is added to the aerostat weight to give gross lift as a function of time. These measurements are carried out over a period of days to determine the helium lift-loss rate. The results always show considerable scatter that cannot be accounted for, even though corrections are made in the individual readings for the hull pressure differential (superpressure) and

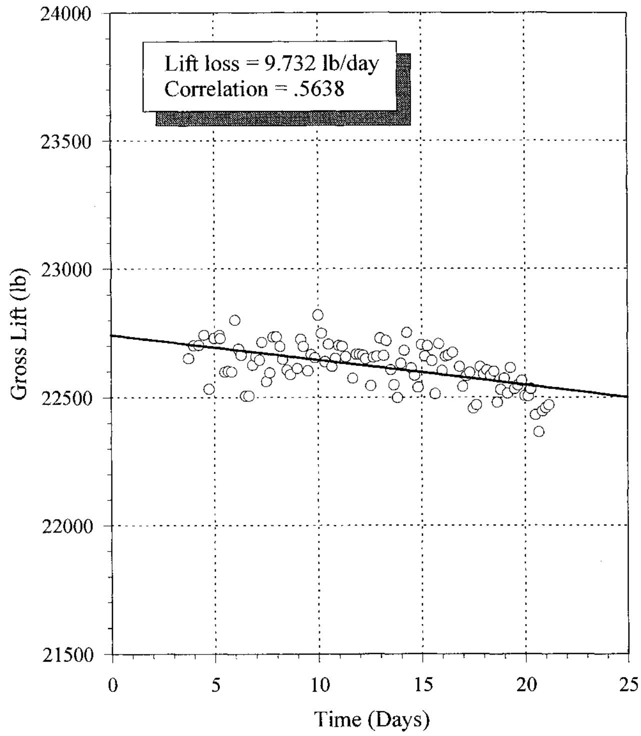

Fig. 3 Lift-loss data showing gross lift, corrected for superheat and superpressure only, as a function of time.

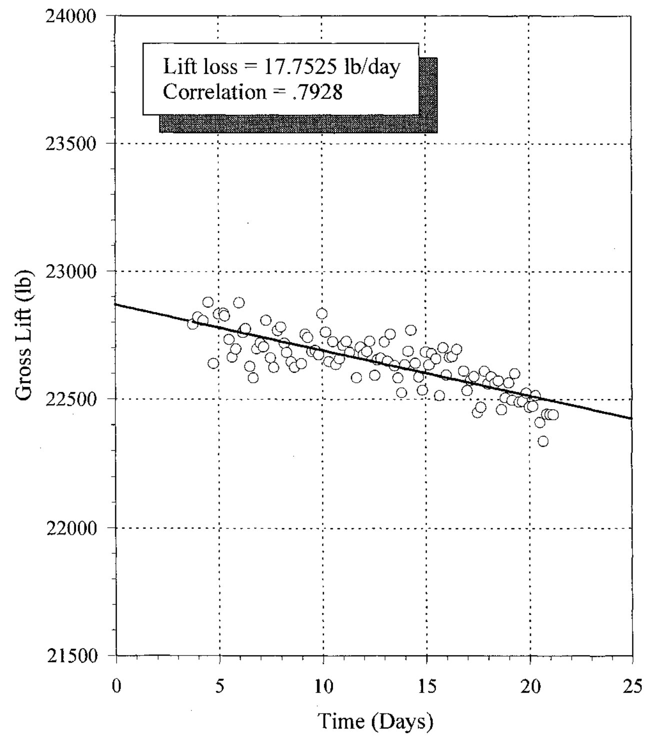

Fig. 4 Lift-loss data showing gross lift corrected for superheat, superpressure, and humidity as a function of time.

temperature differential (superheat) resulting from temperature gradients in the hangar. These corrections for superheat and superpressure are given in Ref. 1. Because of the inevitable scatter, it is necessary to take a large number of readings and determine the lift loss by linear regression analysis. These readings were taken simultaneously with the humidity data previously discussed. The purpose of this analysis is to show how the humidity correction given in Eq. (19) affects the lift-loss results.

Lift-loss data corrected for superheat and superpressure only are plotted in Fig. 3, which shows a lift-loss rate (slope of the curve) of 9.73 lb/day with a correlation coefficient of 0.564.

In Fig. 4, each data point has been corrected using the relation

$$L = L'/\eta \tag{22}$$

This gives a lift-loss rate of 17.75 lb/day with a correlation coefficient of 0.793. This difference is accounted for by the increasing water vapor content of the initially dry helium, increasing its lift and causing the lift-loss rate in Fig. 3 to appear lower than it actually is. The correction for humidity not only eliminates this effect, but also improves the correlation of the data with a linear relationship.

Comparison with Helium Permeability

The corrected lift-loss rate can be compared with the helium permeability specifications for the hull and ballonet materials. The latter would give the minimum value of helium loss rate if there were no pinholes or imperfections in the material. For the hull material the specification is 1.0 l/m^2-day and for the ballonet, 2 l/m^2-day, both at 23°C. Reference 2 gives a temperature relationship for helium permeability of laminated materials. Using those data and extrapolating to the average temperature of the lift-loss test (29.4°C), the values are 1.3 and 2.6 l/m^2-day, respectively. The calculated areas exposed to helium in the test were hull material = 2900 m^2 and ballonet material = 1380 m^2.

Calculating the volumetric loss of helium through these areas and converting to lift-loss, one obtains for permeability alone, 16.3 lb/day. This is surprisingly close to the lift-loss rate corrected for humidity of 17.75 lb/day and is far more than the 9.73 lb/day obtained before humidity correction.

Conclusions

Experimental measurements of the relative humidity and temperature in a 71M aerostat initially filled with dry helium show that the water vapor content of the helium increases with time, approaching that of the outside air with a transmission rate of 0.0165 kg/m^2-h at an average temperature of 29.4°C. For the test vehicle, the time constant was 105 h.

Theory predicts that water vapor in the helium will increase lift and in the outside air will decrease lift. Thus, the asymptotic rise in water vapor content of the helium during lift-loss tests will give an artificially low lift-loss rate by causing the helium to gain lift. Correcting the gross lift for humidity gives a lift-loss rate for the 71M aerostat very close to that predicted by the helium permeability specifications for the hull and ballonet materials. Furthermore, the correlation coefficient of the data in linear regression analysis is improved by the correction.

References

[1]Jones, S. P., "Tethered Aerostat Performance Modeling," *AIAA 7th Conference on Sounding Rockets, Balloons and Related Space Systems*, AIAA, Washington, DC, 1986, pp. 180–185 (AIAA Paper 86-2567).

[2]Ashford, R. L., Bata, B. T., and Walsh, E. D., "Measurement of Helium Gas Transmission Through Aerostat Material," AIAA Paper 83-1996, July 1983.