c-15-01

SAE The Engineering Resource For Advancing Mobility

400 COMMONWEALTH DRIVE WARRENDALE, PA 15096

AEROSPACE INFORMATION REPORT

AIR 1609

Issued 4-30-82
Revised

AIRCRAFT HUMIDIFICATION

1. INTRODUCTION: The purpose of this Aerospace Information Report (AIR) is to provide guidelines for the design of aircraft humidification systems. Physiological effects of humidity levels on crew and passengers are reviewed. Various techniques used for cabin humidification are discussed and evaluated. Various potential problems and penalties associated with humidification systems are also described.

1.1 Nomenclature: This list contains symbols used in equations, charts and descriptions in this AIR.

C_{pa} = specific heat of dry air at constant pressure, Btu/lb-°F (J/kg.°C)

C_{ps} = specific heat of water vapor at constant pressure, Btu/lb-°F (J/kg.°C)

G = water added to increase humidity, lb/min (kg/min)

h_{fg} = latent heat of vaporization at t_w, Btu/lb (J/kg)

m_p = average moisture generated per passenger, lb/min (kg/min)

m_c = average moisture generated per crew member, lb/min (kg/min)

n_p = number of passengers

n_c = number of crew members

P_c = cabin pressure, psia (kPa absolute)

P_v = saturated vapor pressure of water at the dry bulb temperature, psia (kPa absolute)

R = relative humidity, %

t_d = dry bulb temperature, °F (°C)

t_w = wet bulb temperature, °F (°C)

V = vapor recovery - percent of moisture generated in the cabin which enters the cabin atmosphere

W_a = fresh air flow rate into the cabin, lb/min (kg/min)

W_r = recirculated air, lb/min (kg/min)

x = ratio of moisture in recirculated air to moisture in cabin air

a = specific humidity, ambient, lb/lb (kg/kg) of dry air

c = specific humidity, cabin, lb/lb (kg/kg) of dry air

s = water vapor at saturation at dry bulb temperature and at the cabin pressure, lb/lb (kg/kg) of dry air

Subscripts

std = standard conditions; 14.7 psia (101.4 kPa), 59°F (15°C)

1.2 Units: All equations in this AIR, with the exception of equations (5) and (5a), may be used with conventional (US) units or SI units if consistency is maintained. Equations (5) and (5a) must use temperature in °F and °C, respectively.

2. SCOPE: This report covers the design parameters for various methods of humidification applicable to aircraft, the physiological aspects of low humidities, the possible benefits of controlling cabin humidity, the penalties associated with humidification, and the problems which must be solved for practical aircraft humidification systems. The design information is applicable to commercial and military aircraft. The physiological aspects cover all aircraft environmental control applications.

3. GENERAL BACKGROUND: World wide variations in relative humidity range from as little as 6% in desert areas to 100% when rain is falling or the temperature is equal to or just below the dew point. The absolute humidity or water content shows an equally wide variation, being less than 15 grains of water per pound of dry air (2 g/kg) in cold winter climate to as high as 200 grains per pound (29 g/kg) during summer months in tropical areas.

The majority of people who are airline passengers live in areas where the relative humidity is between 30% to 60% most of the time. Exposure to a combination of high temperature and humidity causes almost immediate discomfort. The effect of exposure to very low levels of humidity takes considerably longer to be noticeable.

4. PHYSIOLOGICAL EFFECTS OF LOW HUMIDITY: The temperature and water balance of the body is critically affected by ambient temperature and humidity. The inspired air is brought to body temperature and a saturated level prior to reaching the lungs by extracting heat and water from the mucosa lining the upper respiratory tract. This process cools and dries the surface mucosa. During expiration both heat and water are recovered from the alveolar air (37°C and 100% RH) as it contacts the colder mucosa of the nasopharynx. This net transfer of heat and moisture is dependent on ambient humidity and temperature.

4.1 Comfort: The physiological effects of low humidity are unclear. There are numerous reported instances of airline passengers and crew complaining of dry noses and throats, and "gritty" eyes. The sensation of dryness of the nose is attributed to drying out of the mucosa. Most of the evidence of discomfort related to low humidity is difficult to evaluate (Reference 1). Some investigations, under carefully controlled conditions, have concluded that there is no physiological need for humidification of air (References 2, 3).

It should be noted that in cold climates, the relative humidity inside buildings can be quite low. For example, if the outside air is saturated at 20°F (-6.7°C), the RH at 75°F (23.9°C) is only 11%. Many people are exposed to such humidity levels for long durations, apparently without significant adverse effects or discomfort. However, some asthmatics may have discomfort when humidity is less than 30% or more than 60%.

4.2 Performance: No adverse effect of low humidity on performance has been established. USAF School of Aerospace Medicine experiments showed that environments of 0.5 mm Hg (66.5 Pa) vapor pressure and/or simulated 8000 ft (2.44 km) barometric pressure (a moisture content of about 4 gr/lb (0.6 g/kg)) had no adverse effects on performance during four 36-hour chamber exposures (Reference 4). DOT-FAA investigations have been conducted to evaluate any performance effects of low humidity. These studies concluded that the information presented with regard to humidity effects did not show that low humidity had safety implications (Reference 5).

4.3 Respiratory Infections: Many medical practitioners believe that low winter humidities predispose towards infection and have recommended humidification for those who suffer respiratory troubles. The dispersal of bacteria is affected by humidity, in that bacteria are carried on small dust particles (Reference 6). Increasing relative humidity encourages the particles to agglomerate which will increase the rate at which they settle out of the atmosphere. Humidification systems may, therefore, be desirable in military airplanes used as mobile hospitals.

Some epidemiological investigations have been made which point to low atmospheric humidities as a factor in increasing the incidence of infection. Although these investigations support each other, none can really be considered conclusive (Reference 1).

4.4 Effective Temperature: The Effective Temperature (ET*) is an index which combines into a single value the effects of dry-bulb temperature, relative humidity and air velocity on the sensation of comfort (Reference 3). It is similar to the older Effective Temperature (ET) used earlier by ASHRAE, but it is based upon more current tests on effects of environment on human comfort. As would be expected, the index shows that as humidity is decreased, dry bulb temperature must be increased to achieve the same sensation of warmth. The index indicates that at 75°F to 80°F (24°C to 27°C) range, a shift of relative humidity from 50% to 10% requires about 2°F (1°C) increase in dry bulb temperature to achieve the same comfort.

4.5 Exposure Time: Any effects of low humidity are not immediate. The incidence of passenger complaints tends to be associated with flights of 3-4 hours or longer, increasing with flight time.

For military applications, crew discomfort is more prevalent due to their more frequent and longer duration exposure to low humidity conditions. Military crews on flights lasting up to approximately 24 hours have experienced discomfort and weight loss due to low humidities.

5. HUMIDITY LEVELS IN PRESSURIZED AIRCRAFT: The normal cabin and flight station humidity is a function of the ambient humidity, ventilation rate per occupant, moisture generated in the cabin and the temperature of the cabin or flight station.

The specific humidity of air in the cabin can be calculated using the general equation (1) given below. The vapor recovery factor (V) in equation (1) is the percent of occupant moisture generated in the cabin that contributes to the relative humidity. Some of the expired moisture may be lost overboard before it can diffuse into the cabin atmosphere. In the absence of available data on the value of the recovery factor, the value used is one. The recirculation factor is included to cover systems where recirculated air may be treated by passing through charcoal or other chemical filters which may remove some of the moisture.

Where air recirculation is not used or where air recirculation is used without moisture removal, the denominator in equation (1) becomes simply W_a.

The rate of moisture generation by passengers and crew members depends upon the cabin temperature, and can be determined from Figure 1. The moisture generated in galleys has not been included since it is generated intermittently and usually is vented overboard.

$$\omega_c = \frac{W_a \omega_a + V[n_p m_p + n_c m_c]}{W_a + W_r (1 - x)} \qquad (1)$$

5.1 Measurement of Cabin Humidity: Cabin specific and relative humidities can be measured using wet and dry bulb thermometers or dew point measuring devices.

5.1.1 Wet Bulb and Dry Bulb Temperatures: The use of these measurements is the simplest way to determine humidities and if done carefully, will yield satisfactory results.

The wet bulb measurement is critical and can only be obtained accurately when air is drawn over the temperature sensor at a high velocity. The reading then approaches the temperature of adiabatic saturation.

The wet bulb temperature may be measured using a sling psychrometer or specially designed instruments which draw the air sample over dry and wet temperature sensors.

The error in wet bulb depression for different air velocities is approximately as follows:

AIR VELOCITY (fpm)	(m/sec)	ERROR IN WET BULB DEPRESSION - PERCENT
0	0	-15
500	2.54	-4.5
1000	5.08	-2.7
2000	10.16	-1.5
4000	20.32	-0.8
5000	25.40	-NIL

The Carrier equation can be used to calculate specific humidity given wet bulb and dry bulb temperatures (Reference 8). It is shown below as equation (2).

$$\omega = \frac{h_{fg} \cdot \omega_s - C_{pa}[t_d - t_w]}{h_{fg} + C_{ps}[t_d - t_w]} \qquad (2)$$

Relative humidity can be calculated by:

$$R = \frac{\omega_c \cdot P_c}{(0.622 + \omega_c) \cdot P_v} \times 100 \qquad (3)$$

The saturated water content at cabin (or any) pressure can be calculated by:

$$\omega_s = \frac{0.622 \cdot P_v}{P_c - P_v} \qquad (4)$$

The specific heat of water vapor is:

$$C_{ps} = 0.4423 + 0.00018\ t_d \text{ where } t_d \text{ is } ^\circ F \qquad (5)$$

$$C_{ps} = 0.4481 + 0.00032\ t_d \text{ where } t_d \text{ is } ^\circ C \qquad (5a)$$

The units of specific heat are Btu/lb-°F or cal/g°C for both equations. To convert specific heat to SI units (joules/kg.°C) multiply the value obtained in (5) or (5a) by 4.184.

The dew point can be measured directly using electronic instruments or carefully observing the temperature at which moisture condenses on a chilled surface. The humidity ratio (ω_s) at the measured dew point at cabin pressure may be obtained from standard moisture tables and corrected for absolute pressure by:

$$\omega_s = \frac{\omega_{std} \cdot P_c}{P_{std}} \qquad (6)$$

6. HUMIDITY IN AIRCRAFT AT HIGH ALTITUDE: Humidification may be desirable in aircraft which cruise for long periods at high altitude. It might be thought reasonable to set up a supply of water so engineered as to result in a cabin relative humidity most frequently within the range of 30% to 60%, preferably at the low end so as to minimize the water required. In practice, however, this level of humidity has been found too great due to the condensation which occurs. Inevitably at high altitude the aircraft structure of subsonic aircraft becomes so cold that the local temperature even inside the thermal insulation is inconveniently low. Thus, the water in the cabin air "migrates" to these cold areas and condenses. When the relative humidity is around 35%, condensation can occur on smooth surfaces of the cabin furnishing which are close to major structural members.

Drainage of this condensed moisture leads to its collection in the bottom of the fuselage between the insulation or cargo floor and the skin. Since the temperatures are so low in this region, the water droplets freeze and the ice thus collected may not melt during turnaround between flights and so the water drains cannot function. Further flights lead to more condensate and ice accumulations totalling several inches thick arise. This excess and unaccounted weight could cause operating problems.

It has been observed that in a typical transport the onset of condensation on the windscreen pillars coincides with a relative humidity of about 30% and that taking this as a maximum and switching off humidifiers when it occurs helps to avoid an excess of condensate drainage. Taking a margin on this figure is advisable as use of the humidifier at lower altitudes where ambient moisture content may be greater can result in exceeding 30% relative humidity.

Based on the above considerations, a practical design objective for a humidification system is to maintain 20% relative humidity with a full passenger load. Consideration should also be given to operating the humidification system only towards the end of the cruise flight regime. This reduces the amount of water usage, and the amount of any condensed moisture, while at the same time providing some relief from any possible physiological effects of low humidity.

6.1 Water Requirements: The amount of water which must be added to the cabin to maintain a given water content in the air depends on the fresh air ventilation rate, the moisture produced by passengers and crew, the water content of the ambient air and the desired relative humidity.

For a given relative humidity, the specific cabin humidity may be calculated by rewriting equation (3):

$$\omega_c = \frac{0.622\ P_v \cdot R}{100\ P_c - R \cdot P_v} \qquad (7)$$

The water which must be added to maintain a given specific humidity is:

$$G = (\omega_c - \omega_a)\ W_a - V\ (n_p\ m_p + n_c\ m_c) \qquad (8)$$

Figure 2 illustrates the effect of fresh air ventilation rate on water requirements for humidification. The ventilation rate is the total fresh air supplied to the cabin divided by the actual number of passengers aboard. Thus, at low load factors, passenger ventilation rate becomes quite high unless inflow can be reduced. For one wide bodied aircraft with a passenger load of 400 persons, the water required to maintain 20% relative humidity would be 40 lb/hr or 180 kg over a 10-hour flight.

6.2 Methods of Humidification: A number of different techniques have been developed and used to humidify aircraft.

6.2.1 Spray Atomization: One of the simplest methods of humidification for aircraft is by means of a spray device in which a jet of water is broken up into small droplets by a high velocity stream of air. The many small droplets provide a large surface area of water; thus, evaporation can take place provided that the air conditioning supply is not too cold.

The spray type humidifier consists of a water nozzle with an air nozzle arranged such that the axes of flow of the two fluids are at 90° to each other. With water supplied at 12 psig (83 kPa) and air at a similar or greater pressure, a fine spray of droplets is formed.

Two units are used, one located in one of the main distribution feeds to the passenger cabin and the other in a similar position just upstream of the tapping to the flight deck. If it is possible to locate a single unit such that all areas are adequately supplied with humidified air, then a larger water orifice can be used with advantage.

The supplies of water and air are controlled by simple solenoid valves switched from the flight deck.

6.2.2 Mechanical Aerosol Generators: The aerosol generator is used in a number of aircraft humidification applications. In this system a high speed electrical motor drives a disc which induces a flow of water over the disc. The high velocity causes the water to break up into very fine droplets. The same disc has ventilation blades which generate a moderate airflow toward the fixed vanes and evacuate the aerosol mist into the aircraft ambient air or distribution ducting.

6.2.3 Vapor Injection: Water vapor may be injected into the air distribution system to eliminate problems of non-vaporization which occur with liquid water injection. There is no buildup of contaminates in ducts or in the cabin. However, a vapor generator requires significant amounts of power to vaporize the water. In addition, the generator must handle the buildup of contaminates which will be deposited on the vaporizing surfaces.

6.2.3.1 Electric Heaters: Heaters will require about 18 kilowatts for each lb/min (27.2 kg/hr) of water vaporized. Heaters must be periodically cleaned. A contaminate buildup insulates the heaters leading to higher heating element temperatures and early failure.

6.2.3.2 Bleed Air: Engine bleed air which is usually available at 250° to 400°F (120° to 200°C) has been used to supply the heat of vaporization. Although the contamination buildup is the same, mixing the water and bleed air in an evaporator with a large surface area for contaminate buildup can provide reasonable maintenance intervals.

In this system, water and bleed air are injected into a canister containing a large number of horizontal plates. The air-water mixture circulates over the plates where the water is vaporized. The water flow is controlled to maintain a constant discharge temperature of 150°F (65°C) at the exit of the canister. Bleed air flow is regulated as a function of the bleed air temperature. This provides a relatively constant amount of thermal energy and the water required to cool the mixture to a fixed temperature is similarly constant. The process of mixing bleed air with water can be considered adiabatic if the canister is well insulated and can be analyzed on the basis of the air and water enthalpies.

Water must not be injected directly into high pressure bleed ducts unless it has been demineralized or distilled and all dissolved solids removed.

6.2.4 Humidity Controls: Humidity sensors are available which can modulate or cycle the moisture input although such controls tend to be complex and expensive. Simple manual on-off controls are adequate to maintain cabin humidity within the comfort band over a wide range of passenger loads.

6.3 Humidification Problems: The major problems in aircraft humidification are contaminate buildup, incomplete vaporization of the water, recondensation in ducts, condensation in insulation batts, and corrosion.

6.3.1 Contaminate Buildup: Potable water is normally used for humidification. Carbonates and other dissolved solids contained in the potable water build up wherever evaporation takes place.

Where atomized water is sprayed into ducts, residual contaminates, largely calcium carbonate, occur on the internal surfaces of ducts. They spread through the system and after some years of aircraft operation begin to appear at air outlets as a fine dust. All items within ducts exposed to the humidifier spray are affected. Valves eventually seize and items such as temperature sensors gradually suffer an increase in time constant which eventually leads to malfunction of the temperature control system. Regular removal and cleaning is necessary. The deposits can be removed by dissolving in acetic acid, which must first be shown to be compatible with the material of the components affected.

Where avionics are cooled using cabin air, these salts can create a corrosion problem if they become trapped in the avionics boxes and subsequently hydrolize. ARP 987 discusses control of humidity in avionics cooling in more detail. (Reference 9)

6.3.2 Vaporization and Condensation: Where cold vapor or atomized water systems are used, inadequate heat to vaporize the water permits water to collect in ducts and eventually leak out or spurt out through the outlets.

Water condensation in insulation batts with increased humidity levels can be a problem unless the batts are designed to be self draining and the material is non-wicking.

Unless proper insulation is provided, condensation and freezing on cold surfaces can add uncontrolled weight to the aircraft. AIR 1204 discusses control of condensation on structure. (Reference 10)

6.3.3 Corrosion: Corrosion can arise with water providing a medium for electrolytic action. The problems of corrosion can be minimized if the contaminates are contained or otherwise eliminated.

7. PENALTIES OF HUMIDIFICATION: The addition of a humidification system to an aircraft imposes significant penalties to the operator which must be balanced against the benefits of increased cabin humidity.

The main penalties are:

- o Weight. The system is characterized by a high weight in relation to its complexity and operational necessity, mainly because of the weight of water which has to be carried. This represents a continuous fuel penalty.

- o Maintenance. The maintenance burden of the system might be considered disproportionately high relative to its operational function. In addition to the condition monitoring of the system components, regular servicing is necessary to prevent buildup of contaminates. Also, the total extent of vulnerable areas which would have to be inspected, e.g., ducting, other systems and structure may not be determined until the aircraft has been in service some time.

- o Operation. The failure modes of a humidification system must be considered and must not create a health hazard or seriously affect ancillary systems such as cabin temperature control and potable water supply. Some degree of automatic control of cabin humidity would probably be necessary if only to be consistent with other aircraft systems (it might be inappropriate to rely on crew to monitor operation by observation of condensation and to activate controls accordingly on todays' sophisticated aircraft). Such external factors tend to complicate what would be considered technically a simple system.

8. WATER TREATMENT:

8.1 Health Requirements: Water used for humidification must meet all requirements for potable water. Waste water of any type cannot be used for humidification unless it is cleaned and sterilized.

8.2 Dissolved Solids: A great many of the chemical impurities in water are in the form of dissolved mineral salts. Demineralization can be accomplished by passing the water through synthetic resins which exchange H+ (cation) and OH- (anion) ions for ionized impurities. This technique can produce water with a resistance of 50,000 ohms to 10 megohms. Demineralized water of this quality is used to cool klystrons, magnetrons, and traveling wave tubes in the electronic industry.

Table I shows the variation in total dissolved solids in some typical cities in the United States and London.

TABLE I TOTAL DISSOLVED SOLIDS (TDS) AND CARBONATE HARDNESS IN WATER (Ca CO_3) - VARIOUS SOURCES

Location	TDS (PPM)	Ca CO_3 (PPM)
New York City - Catskill Supply	31	12
Middleburg, Florida	66	11
Niagara Falls, N.Y.	165	95
Missouri River (Ave)	426	165
London (Heathrow)	440	
Dayton, Ohio	432	287
Saugus, California	820	465

It is apparent that the amount of contaminate buildup is dependent primarily on the quality of the water used.

Demineralizing the water used in humidification would for the most part solve problems of contaminate buildup; however, the cost of this type of treatment is very high and some residual non-ionizable materials would be deposited. A 3 3/8 in. (8.5 cm) diameter demineralization cartridge about 17 in. (43 cm) long weighing 4 1/2 lbs (2 kg) has a capacity of 1050 grains (68 g) (CA CO_3). If typical London-Heathrow water were to be used (Table I) having 400-450 ppm total dissolved solids (TDS) an ion exchange cartridge would process about 45 gallons (170 ℓ) of water. This would represent about nine hours of operation.

Dissolved foreign matter can be eliminated by suppyling demineralized water with a separate tank installation. In spite of the extra weight and servicing problems involved, it may well be a cost effective alternative.

9. REFERENCES:

1. D. A. McIntyre, Indoor Climate, Applied Science, 1980.
2. Ib Anderson, MD; Gunnar R. Lundquist, MSC; Preben L. Jensen; Donald F. Proctor, MD; Human Response to 78 Hour Exposure to Dry Air, Arch. Environmental Health, Vol. 29, December, 1974.
3. ASHRAE Handbook, Fundamentals Volume, 1977.
4. Storm, W. F. etal: Effect of Low Humidity on Human Performance, USAF School of Aerospace Medicine, Brooks AFB, Texas. SAM-TR-73-3, Feb. 1973.
5. Dille, J. R., MD: Further Information Concerning Humidity Control for Aircrew Performance. FAA-CAMI Oklahoma City, OK. File AC-100 Oct. 1970.