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A novel environmental control system facilitating humidification for commercial aircraft

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ABSTRACT

Extreme aircraft cabin air dryness during cruise has aroused wide concern throughout the past 30 years. A new integrated system featuring air supply, pressure regulation, temperature control, water separation, and cabin humidification is proposed based on numerous field investigations, existing cabin humidification methods, and conventional aircraft environmental control systems. Cabin humidification is realized through the injection of purified water into the suction side of cabin environmental control system compressor without changing the original system structure. Another advantage of the new system is the lower demand of ram air benefitted from the decreased temperature of compressor inlet with water injection process. System analysis models and software using enthalpy parameter method are also presented. Verification experiments focused on the core parts of the integrated system show that the system analysis models agree with the experimental data well. System performance characteristic and fuel penalty are evaluated using thermodynamic analysis parameters. Results show that under 5 g/(kg·dry air) humidification, the cabin humidity increased smoothly to about 27.9% during the cruising state. The fuel penalty decreased by 1% under the new integrated system for the lower demand of ram air. The novel integrated system is effective and economy.

1. Introduction

Statistical data from the International Air Transport Association (IATA) shown that about 3.7 billion passengers traveled by air in 2016 [1]; another earlier report from the IATA forecasted that this number will nearly double by 2035, reaching 7.2 billion [2]. In addition, about 113,390 attendants and 110,500 pilots, copilots, and flight engineers were exposed to the cabin environment for an average of 900 h each year as of 2016 in the US alone [3]. Meanwhile, in order to reduce aircraft engine fuel consumption and introduce more flight corridors, the maximum cruising altitude of most modern commercial aircraft has increased to nearly 13,000 m (above 42,000 feet) during the past 40 years [4]; at this altitude, the temperature is around −56.5 °C and the humidity is near zero, as shown in Fig. 1.

During cruise, fresh atmospheric air bled from the engines of traditional commercial aircrafts or from electrically driven compressors (as in the Dreamliner Boeing 787) passes through ozone converters and air-conditioning packs to produce clean, air-conditioned air [5]. Before entering the cabin, the conditioned fresh air is mixed with filtered recirculation cabin air in order to save energy. According to reports, an aircraft cabin is drier than a typical desert, which can cause dehydration in cabin occupants [6]. An investigation conducted by the ***Committee on Airliner Cabin Air Quality*** in 1986 showed that the RH decreases from 23% to 2% under normal cabin ventilation rates [7]. Numerous subsequent studies came to similar conclusions as summarized in Table 1.

Low relative humidity (RH) in the aircraft cabin may cause a number of problems, such as skin dryness, eye irritation, and increased static electricity [19]. Additionally, low RH increases the survival time of virus such as influenza and SARS virus [20,21]. Nagda et al. (2001) strongly recommend a 5%–10% increase in aircraft cabin RH to alleviate symptoms related to dryness, and claim that such humidity enhancement is unlikely to induce microbial growth because there is no moisture condensation in the cabin interior [22]. Hisashi (2002) also asserted that cabin humidity should be kept above 3.2 g/(kg·dry air) to prevent nostril and throat pain [23]. Therefore, numerous engineers and researchers have worked on improving cabin humidity in recent years. Ceramic evaporation humidifiers were installed in Boeing 747 aircraft

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Nomenclature

h	specific enthalpy, kJ/kg
t	temperature, °C
p	Pressure, kPa
d	specific humidity, g/(kg·dry air)
Ma	Mach number
G	air mass flow rate, kg/s
NTU	number of transfer units
C^*	ratio of heat capacity
C_{min}	minimum heat capacity
A	heat transfer area, m^2
K	overall heat transfer coefficient
π	compression/expansion ratio
W	mechanical power, kW
N	number of occupants
SFC	specific fuel consumption for thrust
L	lift force, N
D	drag force, N
w	fuel consumption rate, kg/h
τ	time, h
g	acceleration of gravity, N/kg
V	flight velocity, m/s

Subscripts

sat	saturated value
c	cold side
h	hot side
in	inlet
out	outlet
C	compressor
T	turbine
WS	water separator

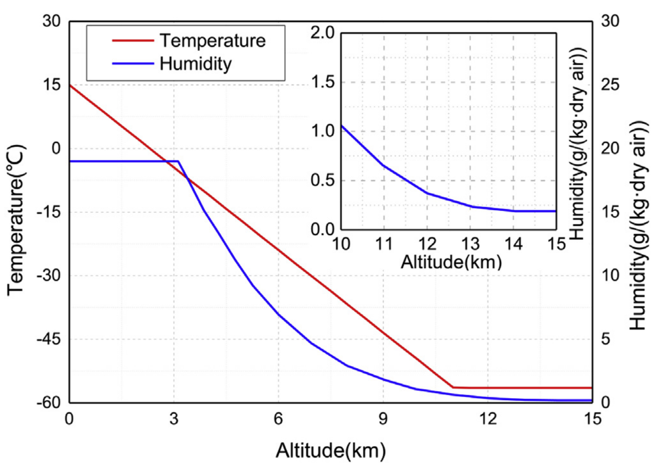

Fig. 1. Temperature and humidity in standard atmosphere.

without any measurable increases in cabin air microorganisms; however, the efficiency of these humidifiers is limited by technical problems, resulting in continued passenger complaints [24,25]. Strøm-Tejsen et al. (2007) proposed a new idea to balance fresh air supply and humidity by reducing the fresh air supply [26]. Unfortunately, complaints of headache, dizziness, and other uncomfortable conditions intensify owing to increased levels of contaminants under lower air flow rate and higher RH. Hisashi presented a new environmental control system concept for civil aircraft using a desiccant rotor, which can recycle water vapor, the humidity of the cabin supply air can be increased from nearly 0 to about 3.2 g/(kg·dry air) at a cruising altitude of 12,800 m [23]. Zhang et al. (2010) [27] proposed a new under-aisle air distribution system in which channel inlets along the sidewalls supply conditioned fresh dry air and under-floor aisle inlets supply mixed humidified air. This system was found by a validated CFD program to be capable of boosting the RH from 10% to 20% with a water consumption of 0.05 kg/(h·person). Airbus invented an individual humidification apparatus which makes available a conditioning fluid to be ejected into the cabin from a nozzle [28], or even use a box filled with water vapor for breathing zone humidification [29]. Honeywell (formerly Allied Signal Inc.) published a humidification method through the trim air supply using a spray bar with a water tank and other accessories [30]. Humidification devices have been equipped in newly developed aircraft cabins and crew rest compartments including the Airbus 380, Boeing 787, and Airbus 350 during recent years [31]. A novel humidification system installed in the first class cabin of commercial Lufthansa aircrafts increased the RH from 5%~15% to 20%–25% [32].

Table 1
Summary of published inflight cabin relative humidity measurements.

Aircraft type		Relative humidity (%)		Reference
		Minimum	Average	
B727/737/767/DC9/etc.		5–38	15.5 or 21.5	Nagda (1992) [8]
B777		8.8–27.8	12.9 or 16.5	Pierce (1999) [9]
B747-400		5.8–42.5	10.0	Lee (1999) [10]
A340		6.7–50.6	14.4	
A320		5.4	<10 (17out of 21 flights)	Haghighata (1999) [11]
B767		2.33	<10 (4 out of 5 flights)	
B747/A330/A340		6.7	14.3	Lee (2000) [12]
B747-400 (KLM)		3–59	8.3–11.7	Hans de Ree (2000) [13]
MD-80		10.5–18.6	11.4	Spicer (2004) [14]
B767	Business Class	10–14	12	Norbäck (2006) [15]
	Tourist Class	10–12	11	Lindgren (2007) [16]
	Cockpit	6–15	10	
A319		8.7–55	17.9–27	Giaconia (2013) [17]
Boeing 737		15.4–20.8	Not Given	Cui (2017) [18]