Chinese Journal of Aeronautics, (2015), 28(3): 712–719

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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A novel environmental control system based on membrane dehumidification

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Received 10 October 2014; revised 17 March 2015; accepted 30 March 2015
Available online 20 April 2015

KEYWORDS

Aircraft;
Cooling performance;
Environmental control system;
High pressure de-water;
Membrane dehumidification;
Sweep ratio

Abstract This paper conducts a simulation study of a novel aircraft environmental control system based on membrane dehumidification (MD-ECS), and compares the system with the up-to-date four-wheel high pressure de-water system (4WHPDW-ECS). Mathematical models for the two systems are established, and a system simulation using a numerical technique is performed to analyze and compare the cooling performance of the two systems. Simulation results show that the cooling capacity of MD-ECS is much higher than that of 4WHPDW-ECS under the same working conditions, indicating that the novel system is theoretically feasible and promising. The effects of the sweep ratio of the membrane dehumidifier on the dehumidification and cooling performance of the system is also investigated.

1. Introduction

Vapor compression refrigeration (VCR) is the most common cooling technology widely applied in heating, ventilation and air conditioning (HVAC), ice making, food storage, etc. However, its performance strongly depends on ambient conditions, and the vapor compressor may become the main drawback because of the oil scavenging problem in some severely moving circumstances such as ships, high speed trains and aircrafts. In contrast, air cycle derived from inverse Brayton cycle has been developed as the main cooling technology in aircrafts after the earliest application in the fighter during 1940s, with the advantages of light weight, few components and easy maintenance. In particular, air cycle consumes almost no electric power, and is proved to be the best cooling technology before the development of all-electric aircraft (AEA).

With the development of wide-bodied airliners and rapid increase of the power of the avionics equipments, the basic air cycle system mainly consisting of only an air compressor and a turbine[1,2] has to be modified gradually to meet the increasing demand of cooling capacity. It is found that the humidity drastically limits the cooling capacity. Especially on the ground or at low flight height where the ambient humidity

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.04.016
1000-9361

is relatively high, the refrigeration temperature cannot be too low, otherwise dewing and even freezing may take place at the turbine exit. Consequently, high pressure de-water (HPDW) system is currently widely applied.[3] Before entering the turbine, the pressurized humid air is cooled by a condenser and the condensate water droplets are then separated by a water separator. Compared with low pressure de-water (LPDW) system,[4,5] HPDW has many advantages including:[6] (A) the water vapor is condensed more easily due to higher dew point temperature at high pressure; (B) high pressure breeds high density and therefore low air velocity, so the condensate droplets are big enough to promote the separation efficiency, while the mist caused by high air velocity is hard to be removed in LPDW; (C) HPDW system can obtain significant cooling capacity by achieving low enough temperature at the turbine exit, free from freezing risk. Currently, the most advanced environmental control system (ECS) is the four-wheel type (4WHPDW-ECS) system consisting of a compressor, a fan (sometimes replaced by another compressor to further increase the pressure) and two turbines, which has been applied in B777 and A380 airliners. In such a system, the water vapor is condensed in the condenser by the cold dry air discharged from the primary turbine and is then removed by the water separator. Finally, the cold dry air enters the secondary turbine for further expansion to obtain even lower temperature. The primary turbine achieves a low refrigeration temperature above the ice point of the airflow, so the possibility of condenser freezing is eliminated. Therefore, the 4WHPDW-ECS system is superior to three-wheel system which has only one big turbine.[3,7,8] Moreover, two-stage low-intensity expansions reduce the turbine energy loss, compared with one-stage high-intensity expansion within the same overall expansion ratio.

However, the 4WHPDW-ECS also has disadvantages including higher weight and more complex structure in comparison with former ECS types. The water vapor removal fundamental hardly changes from LPDW to HPDW, as water vapor removal is achieved by successive condensation and mechanical separation. The de-water systems have to consume much cooling capacity of turbine(s) to lower the air temperature below the dew point. Totally different from the conventional water vapor removal method, a novel environmental control system based on membrane dehumidification is proposed in this study to replace the group of the condenser and water separator[9] used in HPDW-ECS. In this novel system, the water vapor transfers across membranes from the high pressure feed air to the low pressure purging air without phase change. Therefore, the latent cooling capacity is totally reserved, and the cooling capacity supplied to the cabin is greatly promoted.

2. System description

2.1. Four-wheel high pressure de-water ECS

The schematic process of a typical 4WHPDW system is depicted in Fig. 1, the bleed air of high temperature and pressure is first cooled by the primary heat exchanger HX1, and is then further pressurized by the compressor, which also causes a temperature rise. After being compressed, it is further cooled by the secondary heat exchanger HX2. The ram air at low temperature flows at the cold sides of HX1 and HX2, propelled by the fan. It has been known that the high pressure air can be cooled remarkably through expansion. To prevent it from freezing, in the 4WHPDW-ECS, the bleed air is pretreated by a de-water process before entering the turbine. A condenser and a water separator are arranged before the primary turbine to remove the water vapor from the high pressure bleed air, where the cold source for condensation is the cold and dry air exhausted from the primary turbine. The latent heat is recycled by spraying the condensed water to the ram air side of HX2. A heat recuperator is used to increase the bleed air temperature properly to reduce the freezing risk during the following expansions. Then the cold and dry air flows across the cold side of the condenser and is cooled by the secondary turbine successively. Having met the supply air quality requirements, the product dry air is finally supplied to the cabin. Four rotary devices including the fan, the compressor and two turbines are coaxial with a power adaption and allocation mechanism, which is the reason for the naming of "four-wheel" system.

Compared with the traditional ECS, the 4WHPDW-ECS achieves a greater cooling capacity by utilizing high pressure de-water process, and the two-stage expansion reduces the possibility of freezing and turbine efficiency loss. Various heat recovery procedures, including pre-cooling by HX1 and HX2, heat recuperator and water spraying, promote the heat transfer efficiency of the whole system.

2.2. Membrane dehumidification ECS

However, the complexity of the 4WHPDW-ECS, as well as higher weight than that of the traditional systems, confines its application regardless of its advanced performance. To overcome these drawbacks, an original membrane dehumidification environmental control system (MD-ECS) is proposed, using a "shell-and-tube" type hollow fiber membrane dehumidifier to replace the metal-made group of the condenser and water separator. The schematic flowchart of the MD-ECS is shown in Fig. 2. With the same flow procedure before expansion as the 4WHPDW-ECS, the bleed air is propelled into the feed side (tube side) of the membrane dehumidifier, and is dehumidified by a certain ratio of the dry product air sweeping back in the permeate side (shell side). Since the outlet pressure of the feed side is still relatively high, this paper proposes a minor turbine for the sweep air before sweeping back, so as to obtain a greater trans-membrane water vapor partial pressure difference. The temperature of the sweep air decreases by expansion, so the dehumidification process is combined with a heat transfer process. After dehumidification, the sweep air is mixed with the ram air, flowing across the cold sides of HX1 and HX2. Apart from this proportion of sweep air, the remaining dry product air from the membrane dehumidifier is cooled down by expansion in the main turbine, and is supplied to the cabin finally.

In this novel system, the membrane dehumidifier is a key component. As a widely applied technology in the fields of separation and purification of compressed air and natural gas,[10,11] membrane dehumidification works on the principle of water vapor permeation under partial pressure difference across the microporous membrane, which is highly selective for water vapor with respect to dry air. Here, polyethersulfone (PES)