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Review

Desiccant-assisted humidity control for air refrigeration cycles

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ABSTRACT

A desiccant-assisted Brayton cooling cycle as an option for controlling humidity in air refrigeration cycles has been proposed. The modified cycle integrates a desiccant cooling cycle into an ordinary reversed Brayton cycle, using the heat rejection from the Brayton portion to drive the desiccant cooling portion, by applying a heat exchanger between the two cycles. Conversely, the cooling effect produced by the desiccant cycle is used to pre-cool the Brayton air stream, before it is admitted to the turbine. A mathematical model for the proposed cycle is developed, and its dynamic behavior is computationally simulated. The results show that the desiccant-assisted cycle can provide an effective humidity control, in addition to augmenting the cooling capacity of the cycle.

Cycles frigorifiques à air: régulation de l'humidité à l'aide d'un déshydratant

Mots clés : déshumidification à déshydratant ; refroidissement évaporatif ; conditionnement d'air ; conception thermique ; cycle hybride

1. Introduction

The adequate choice of the refrigerant plays a key-factor in a successful design of a refrigeration system, considering both the technical and environmental viewpoints. Some traditionally used refrigerants (CFCs) have been ruled out by the Montreal Protocol, as they might also exhibit a considerably high global warming potential. As a result, the use of natural refrigerants such as air and water has been increasingly investigated. Accordingly, the application of air-cycles has been readdressed, which led to the identification of opportunities beyond the aircraft air conditioning, such as drying, retail display cases, refrigerated containers and train air-conditioning (Murphy et al., 1994). Air-cycles have also been

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Nomenclature

c	specific heat, J (kg°C)$^{-1}$
COP	cycle performance coefficient
HBE	heat balance error
i	specific enthalpy, kJ (kg°C)$^{-1}$
q_H	heat rejected to environment (specific), kJ kg^{-1}
q_L	cooling load (specific), kJ kg^{-1}
w_S	supplied work (specific), kJ kg^{-1}
r_p	pressure ratio
T	temperature, °C
Y	humidity ratio, kg kg^{-1}

Greek symbols

ε	effectiveness
η	efficiency
ϕ	relative humidity

Subscripts and superscripts

ec	evaporative cooler
dw	desiccant wheel
en	environment (outside air)
hx	heat exchanger
sat	saturation state

considered for road transport refrigeration systems, exhibiting good performance at part-load operation (Spence et al., 2004). Several opportunities have also been identified in food processing and preservation (Pelsoci, 2001). The same environmental consciousness has led to a significant volume of research on sorptive cycles. Sorptive reactors are often referred to as thermal compressors, since they allow the vapor to migrate from a lower to higher level of partial pressure. In particular, desiccant cooling cycles have been significantly addressed, since they operate with water and air as working fluids (Nóbrega and Brum, 2011). Moreover, it usually demands low grade thermal energy to operate, which can be supplied by a solar collector (Grossman, 2002) or a prime mover waste heat. Adsorptive systems have also been suggested as complementary systems to vapor compression systems, in a cascade configuration (Chinnappa et al., 1993; La et al., 2011). The matching of compression and adsorptive cooling into a single cycle has also been addressed, since carbon dioxide, ammonia and HFC134a are substances which exhibit suitability for both mechanical and thermal compressions. Banker et al. (2008) investigated the performance of H134a adsorption on activated carbon followed by a mechanical compression process, obtaining an energy saving as high as 40% when compared to a single-stage mechanical compression process. Cyklis and Knator (2011) presented a cascade cycle comprised of Li–Br and water absorption cycle for the upper part and a CO_2 vapor compression for the lower temperature cycle.

Elsayed et al. (2008) suggested the recirculation of air in a warehouse loading dock area through a desiccant wheel, minimizing humidity infiltration in the storage room. The cold air for the warehouse is provided by an air-standard cycle, which uses the rejected heat to regenerate the humidity captured by the desiccant wheel. The use of a desiccant system in series with a Brayton air refrigeration cycle was first presented by Elsayed et al. (2006). The results showed improved performance when compared to the standard Brayton cycle; however, the analysis neglected the control of humidity at the turbine outlet, which is a critical operating parameter. Whenever the air stream expanding through the turbine is rich in water vapor, some condensation is bound to occur as the air temperature drops. This phenomenon is disadvantageous to cycle performance, since it reduces the work that can be recovered at the turbine. Moreover, for low temperature applications, the condensate is likely to cause icing in the turbine, which will eventually result in blockage and possible system failure (Hamlin et al., 1998).

Under this scenario, the current work proposes a hybrid cycle approach for controlling the humidity of standard air refrigeration cycles. The method consists of modifying the traditional air cycle to include a desiccant wheel for removing the unwanted moisture, a heat exchanger for providing the required regeneration temperature using heat recovered from the high-temperature condition achieved after compression, and an evaporative cooling unit for pre-cooling the air prior to admission into the heat exchanger and consequently reducing the turbine inlet temperature for a higher cooling capacity. Naturally, a secondary circuit for the regeneration air stream is also required. The proposed hybrid desiccant-assisted cycle is evaluated for different operating configurations and comparative results are presented.

2. Standard air refrigeration cycle and its limitation

The standard air refrigeration cycle, also termed the Bell Coleman cycle or the reversed Brayton cycle, is a well established cooling cycle which can be found in a couple of different forms, including both closed- and open-cycle configurations, ideally including an isentropic compression, followed by a heat rejection process, and finally by an isentropic expansion. When an open configuration is employed, the cycle is completed with a heat uptake occurring at ambient pressure, between the turbine outlet and the compressor inlet.

A problem with the standard air refrigeration cycle is that the ambient humidity level acts as a limiting factor to the maximum pressure ratio (r_p) that this cycle can be used without causing condensation or freezing in the turbine. Fig. 1 illustrates this limitation, by plotting the pressure ratio that leads to 100% relative humidity at the turbine outlet for an open-cycle with different ambient condition. Also shown in this figure is the minimum supply air temperature that can be attained with the maximum pressure ratio. As can be seen, for ambient relative humidities above 40%, pressure ratios above 1.2 lead to condensation or freezing in the turbine outlet. In addition, when looking into the minimum supply air temperatures one notices that for $\phi \geq 30\%$, only temperatures