Applied Energy 213 (2018) 31–44

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Thermodynamic feasibility evaluation of hybrid dehumidification – mechanical vapour compression systems

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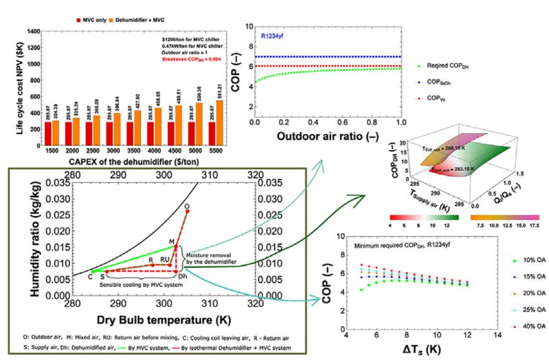
HIGHLIGHTS

- Breakeven COP for the coupled dehumidifier of dehumidifier + MVC system is evaluated.
- MVC at higher $T_{chilled}$ is studied using Carnot, endoreversible and ideal cycle methods.
- Three refrigerants (HFC-R134a, HFC-R32 and HFO-R1234yf) for MVC are analysed.
- The coupled dehumidifier needs COP at least 4 to batter conventional MVC systems.
- LCC_NPV affirms separate dehumidifier is viable for low outdoor air ratio operations.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Breakeven COP
Chiller efficiency
Decoupling latent heat
Isothermal dehumidification
Mechanical vapour compression

ABSTRACT

Air conditioning approach using two separate units for latent heat and sensible heat removal opens up opportunities and challenges for improved efficiency. In such systems, the dehumidification device removes moisture from the air stream usually without condensation whilst the remaining sensible load is handled by a conventional mechanical vapour compression (MVC) machine. This article investigates the thermodynamic feasibility of such hybrid dehumidifier + MVC systems as potential replacements for the conventional MVC devices. We shed some light on the minimum efficacy requirement in terms of COP or simply the breakeven COP for the coupled dehumidification system. Thermodynamic investigation has been conducted using classical Carnot, endoreversible technique and the experimental approaches. The breakeven COPs for a dehumidifier + MVC system where the latter using HFC-R14a, HFC-R32 and HFO-R1234yf as refrigerants have been investigated at assorted outdoor air ratios. Performance enhancement in terms of COP and the cooling capacity at elevated temperatures for sensible cooling are accounted for. It is observed that the breakeven COP for the dehumidification system ranges from 9 to 17 (Carnot approach) and 4.3 to 6.8 (Ideal cycle) in order to be realistically competitive with the current efficiency offered by a MVC system for the both dehumidification and sensible cooling. The life cycle cost (LCC) analysis is further performed to assess the fresh air-handling systems using a

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https://doi.org/10.1016/j.apenergy.2018.01.024
Received 25 October 2017; Received in revised form 5 January 2018; Accepted 6 January 2018

Nomenclature

A_s	cross sectional area [m^2]
h	specific enthalpy [kJ/kg]
K	heat capacitance [kW/K]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [Pa]
q	specific energy [kJ/kg]
Q	thermal energy [kW]
r_p	pressure ratio [–]
r_H	outdoor air ratio [–]
T	temperature [K]
T_{db}	dry bulb temperature [K]
w	specific work [kJ/kg]
W	work [kW]
$\Delta T_{Chilled}$	temperature difference of the chilled water across the evaporator [K]
$\Delta T_{Cooling}$	temperature difference of the cooling water across the condenser [K]

Greek symbols

ρ	density [kg/m^3]
ψ	contraction coefficient [–]
γ	isentropic expansion factor [–]
ω	humidity ratio [kg of water/kg of dry air]
λ	heat of condensation [kJ/kg]

Subscripts

C	cooling coil
comp	compressor
DH	dehumidification
DHMVC	dehumidification mechanical vapour compression
Dis	discharge
Evap	evaporator
Evap,in	evaporator inlet
l	latent
O	outdoor air
s	sensible
SeDh	sensible cooling with dehumidification
S	supply air
Sus	suction
VC	vapour compression
VolCooling	volumetric cooling

conventional MVC system and a dehumidifier + MVC system. The unprecedented improvement in the performance of the MVC systems further raises the ceiling for the breakeven COP of the dehumidification systems.

1. Introduction

Thermal comfort requires conditioning the outdoor air to control the dry-bulb temperature and moisture content [1]. Conditioning the dry-bulb temperature of the air is associated with the sensible load whilst the humidity control is achieved by handling the latent load. Willis H. Carrier made some landmark discoveries in HVAC; (i) the relationship and technique to control the temperature and the humidity in 1902 [1], and (ii) the law of constant dew-point depression in 1906 [2–4]. With such breakthrough discoveries, conditioning of air and commercial chillers, from small- to mega-scale, has become a reality and HVAC systems are now important equipment for the modern society. Generally, air conditioning is achieved by lowering the air temperature to the dew point for moisture removal followed by the sensible heating/cooling process. The required cooling energy to reduce the air temperature is usually produced by an electricity-driven mechanical vapour compression (MVC) system. These MVC systems are employed either to directly condition the air or to produce chilled water, as in most commercial chillers. Thus, the operation cost (OPEX) of a HVAC system is largely associating with the performance of the MVC chiller. On the other hand, the efficacy of a cooling device or a chiller is usually assessed in terms of the coefficient of performance (COP) or the kW of electricity per ton of refrigerant (simply the kW/ton) or the energy efficiency ratio (EER) [5]. Since commencement, the performance of chillers has been improving while the COP of today's MVC systems is approaching the limit dictated by the laws of physics i.e., the Carnot COP. The efficiency value of 0.45 kW/ton (at full load) becomes a BAU (business-as-usual) case [6,7] while this efficiency figure can be as low as 0.296 kW/ton for the integrated part-load value (IPLV) [8]. According to the U.S. Federal Energy Management Program, the minimum efficiency requirement for a water-cooled chiller is stated to be as low as 0.56 kW/ton for full-load and 0.50 for IPLV [9]. Moreover, the Procurement of Energy Efficient Products Required by the Energy Policy Act of 2005 states that the best available energy consumption for a water-cooled chiller is about 0.47 kW/ton for full-load and 0.38 kW/ton for IPLV [10].

Despite such high efficiency, performance improvement in the HVAC system, especially the MVC unit, is always desirable since even a small or marginal efficiency gain will amplify tremendously on a global scale. However, pushing the efficiency of the MVC system further towards the thermodynamic limit involves multi-dimensional challenges such as breakthrough in the compressor technology and the minimization of parasitic irreversibilities in the heat exchange process and to name a few. Moreover, the MVC systems utilize some chemical compounds as working fluids, commonly known as the refrigerants. Those refrigerants significantly contribute to the global warming and are potential hazards due to toxicity, asphyxiation and flammability [11]. At the same time, greater awareness in the brunt of the environmental issues and global warming applies further pressure to the conventional MVC systems. However, next generation refrigerants have been continuously developed with some salient features such as environmentally benign and low GWP while maintaining or improving the

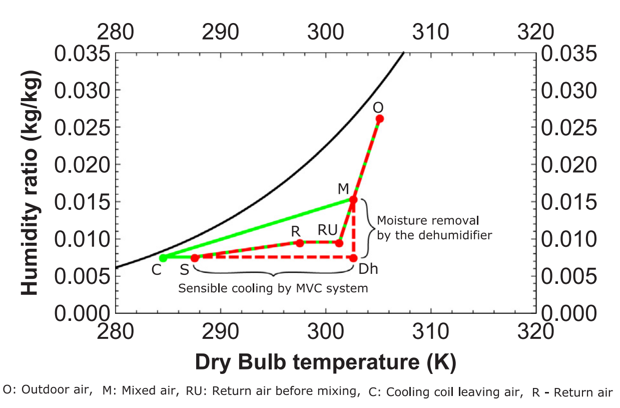

Fig. 1. Psychrometric processes for air-conditioning by a conventional MVC and a dehumidifier + MVC system.