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Research Paper

Experimental investigation of a mechanical vapour compression chiller at elevated chilled water temperatures

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HIGHLIGHTS

- Chiller performance improvement.
- Experimental evaluation of the chiller performance at elevated chilled water outlet temperatures.
- COP increases 37–40% and cooling capacity 40–45% using same hardware at 17 °C outlet chilled water.
- Design data of MVC system for sensible cooling.

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ABSTRACT

The performance of a Mechanical Vapour Compression (MVC) chiller is experimentally investigated under operating conditions suitable for sensible cooling. With the emergence of the energy efficient dehumidification systems, it is possible to decouple the latent load from the MVC chillers which can be operated at higher chilled water temperatures for handling sensible cooling load. In this article, the performance of the chiller is evaluated at the elevated chilled water outlet temperatures (7–17 °C) at various coolant temperatures (28–32 °C) and flow rates ($\Delta T = 4$ and 5 °C) for both full- and part-load conditions. Keeping the performance at the AHRI standard as the baseline condition, the efficacy of the chiller in terms of compression ratio, cooling capacity and COP at aforementioned conditions is quantified experimentally. It is observed that for each one-degree Celsius increase in the chilled water temperature, the COP of the chiller improves by about 3.5% whilst the cooling capacity improvement is about 4%. For operation at 17 °C chilled water outlet temperature, the improvements in COP and cooling capacity are between 37–40% and 40–45%, respectively, compared to the performance at the AHRI standards. The performance of the MVC chiller at the abovementioned operation conditions is mapped on the chiller performance characteristic chart.

1. Introduction

From the landmark introduction of the modern air conditioner by Wills Carrier in 1902 [1–3], the mechanical vapour compression (MVC) systems have been the backbone of the heating ventilation and air conditioning, (HVAC) industry especially in building sector. However, significant amount of energy is utilized in the building sector, for instance, in the U.S., 41% of primary energy consumption is accounted for this sector in 2010 whilst air-conditioning for

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heating and cooling is about 48% of the building energy consumption [4–6]. A vapour compression refrigeration cycle essentially consists of an evaporator, a compressor, a condenser and an expansion device to pump the heat from a low-temperature reservoir to a higher one using electrical work input [7–9]. In air-conditioning application, the space to be cooled is the low-temperature reservoir whilst the ambient is the higher temperature reservoir [10,11]. The refrigerants employed in the MVC systems have evolved from CFCs and HCFCs to environmental-friendly versions such as CO_2, Hydro-Fluoro-Olefin 1234yf etc. [12–15]. With technological advancements, the best available energy consumption figure for the water-cooled chiller is reported to be about 0.47 kW/ton for full-load whilst 0.38 kW/ton for the Integrated Part Load Value or the IPLV [16]. A higher COP can be attained by narrowing the temperature difference between the heat sink and heat source. Conventionally, comfort air conditioning is achieved by the removal of moisture (latent load) and lowering of the temperature of air (sensible load) simultaneously in a common exchanger to achieve suitable supply air conditions. Such a cooling and dehumidification process limits the efficiency of a chiller. The removal of moisture by dew point condensation at the evaporator is the major factor contributing to the power consumption. By decoupling dehumidification load of a chiller using a separate dehumidifier, the MVC system can be operated at elevated chilled water temperature for improved efficiencies [17].

With the emergence of the advanced and efficient dehumidification systems, it is possible to decouple the latent load from the electric-driven air conditioners [18–23]. It is reported that the theoretical COP of an advanced dehumidification system can be from 9 to 17 with corresponding compression ratios of 1.5–3 [17,24] whilst the membrane dehumidification system using a sweep gas configuration can provide the dehumidification efficiency more than 200% [25]. Thus, the mechanical vapour compression chillers coupled with a dehumidifier can be operated at the elevated chilled water outlet temperatures to handle the sensible load only. Operating at the higher evaporating temperatures for the same coolant temperature reduces the pressure ratio of the compressor. Thus, significant savings in the energy consumption are realized in addition to cooling capacity improvement. The performance of a chiller is normally assessed in accordance with the guidelines by the AHRI standards whilst several works on the chiller performance analysis and models are abundantly available in the literature with various types of refrigerants [26–29]. However, these works mainly focussed on the operating conditions suitable for the dehumidification process where a typical chilled water outlet temperature is about 7 °C [26]. No work is available on the performance of the MVC chillers at operating conditions only for the sensible load handling i.e., the performance at elevated chilled water temperatures. In this paper, the performance of the chiller, in terms of the Coefficient of Performance (COP) and the cooling capacity, is evaluated experimentally at the elevated chilled water outlet temperatures (7–17 °C) using various coolant temperatures (28–32 °C) and flow rates ($\Delta T = 4$ and 5 °C) for both full- and part-load conditions.

2. Experimental setup and procedures

A water-cooled MVC chiller with cooling load and temperature rating facilities is constructed for performance evaluation tests. In the rating facilities, the required set points are achieved by mixing water from the cooling tower, the evaporator and the condenser using PID controller for the supply and bypass valves whilst Table 1 lists the operating conditions. The AHRI Standard 551/591 is adopted for the chiller rating where the standard conditions are 7 °C and 0.0478 L/(s·kW) for the chilled water and 30 °C for cooling water [4]. Table 2 furnishes details on the measuring instruments installed on the test facility. The facility can give the control accuracy of ±0.1 °C and ±0.45 LPM. Fig. 1 gives the pictorial views of the test facility.

Table 1
Summary of test conditions.

Parameter	Range
Chilled water outlet temperature (°C)	7.0–17.0
Cooling water inlet temperature (°C)	28.0–32.0
Load profile	Full load–part load
Coolant ΔT (°C)	4 and 5

Note: The test standard is according to AHRI Standard 551/591.

A data acquisition protocol was developed using the LabVIEW environment where the acquired data are processed using thermo-physical properties of the refrigerant R134a. The steady state conditions were maintained at least 45 min for each set point. The superheat and sub-cooling were maintained at 6.5 ± 0.5 °C and 3.5 ± 0.5 °C, respectively. The cooling capacity and the heat rejection at the condenser are calculated as,

$$q_{Evap} = \dot{m}_{Ch} \times c_p \times (T_{Ch,In} - T_{Ch,Out}), \quad (1)$$

$$q_{Cond} = \dot{m}_{Cw} \times c_p \times (T_{Cw,Out} - T_{Cw,In}), \quad (2)$$

where q_{Evap} is the cooling capacity in kW, $\dot{m}_{Ch}$ is the chilled water flow rate, c_p is the specific heat capacity, $T_{Ch,In}$ and $T_{Ch,Out}$ are the inlet and out temperatures of the chilled water. Similarly, q_{Cond} is the heat rejection at the condenser in kW, $\dot{m}_{Cw}$ is the coolant flow rate to the condenser, $T_{Cw,In}$ and $T_{Cw,Out}$ are the inlet and out temperatures of the coolant. The energy balance of the system is evaluated as,

$$EB = (q_{Evap} + P_{Com} - q_{Cond})/q_{Cond}. \quad (3)$$

Here EB is the energy balance and P_{Com} is the compressor power which is directly acquired using a power meter. The coefficient of performance (COP) of the system is calculated as,

Table 2
Details of the components of the MVC test rig.

No.	Name of the component	Specifications
1.	MVC System	Nominal capacity 10.0 kW
2.	Compressor	COPELAND Scroll compressor, model ZR81 KC-TFD-522, with a nominal 6.8 horsepower
3.	Evaporator	SUS304, shell and tube type, 4 passes, refrigerant in tube-side, water in shell-side
4.	Condenser	SUS304, shell and tube type, 4 passes, refrigerant in shell-side, water in tube-side
5.	Expansion device	TXV (EMERSON TXV, model HFES 8HC), EXV (EMERSON PWM EX-2 EXV with EC2-39 Controller)
6.	Refrigerant flow meter	KROHNE, Model 29/RR/M9/es; Range: 36–360 L/hr; Accuracy: 1.6% F.S
7.	Energy meter	HIOKI, Model 3184, measures the electrical power consumption of the whole chiller system, with an accuracy of ±0.01 kW
8.	Variable speed drive	VLT2875, 7.5 kW, 10 HP, 16 A
9.	Pressure transducers	Gems Sensors Pressure Transducer Model:1200BGB1001A3UA/1200BGB2501A3UA; Output: 4–20 mA, two wire, Range: 0–10/25 bar G, Accuracy: 0.5% F.S
10.	Temperature sensors	4 wire RTD, PT100, 1/10 DIN
11.	Control valve and actuator	CV216 RGA DN25 TA-MC100, 0.15 or 0.5 VDC, S3-50% ED c/h 1200 EN 60034-1
12.	Water flow meters	Siemens, MAG3100 (sensor), MAG6000 (Transmitter) (0.2% ±1 mm/s of rate)