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Experimental investigation of air conditioning system using evaporative cooling condenser

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ABSTRACT

This paper presents an experimental investigation of the Coefficient of Performance (COP)'s augmentation of an air conditioning system utilizing an evaporative cooling condenser. The experimental facility consisted of four major components, which are, the compressor, the evaporator, the thermal expansion valve, and the condenser. An evaporative cooling unit was located upstream from the condenser. Thermal parameters, such as relative humidity, dry bulb temperature, and wet bulb temperature were measured to evaluate the effect of in-direct evaporative cooling on the system's COP. The results indicated an inverse relation between the condenser inlet dry bulb temperature and the COP. The changes in specific enthalpy of the air across the evaporative cooled condenser were due to latent heat transfer and sensible heat exchanges, whereas the specific enthalpy changes for the conventional condenser were primarily caused by sensible heat exchanges. By using the evaporative cooling condenser to pre-cool the air, the saturation temperature drop through the condenser increased from 2.4 °C to 6.6 °C. It also resulted in an increase of the mass flow rate of refrigerant that went into the evaporator. This mass increase of liquid entering the evaporator consequently resulted in the increase of COP from 6.1% to 18%. A power reduction up to 14.3% on the compressor was also achieved. The result reveals the relation between water consumption and compressor energy saving regarding to their costs. Although greater power reductions were fulfilled at higher dry bulb temperatures, in this circumstance, the cost-optimal applicable temperature is around 33.1 °C.

1. Introduction

The continuous increase in energy demand and the decline in global energy supply have resulted in high energy costs. In 2008, it was reported that 20% of total energy in the USA and 17% of the total global energy were consumed in air conditioning [1,2]; hence, the enhancement of the COP of air conditioning system will contribute to the reduction of global energy consumption.

The condensing units in air conditioning systems have significant influence on the compressor discharge pressure. Most condensers are air cooled and their performances are governed by heat transfer to the surrounding air. The thermal stability of air-cooled condensers fluctuates throughout the year, especially during the summer when surrounding air temperature is high. The refrigerant flowing through the condenser may not fully condense in a high temperature environment resulting in a mixture of liquid and vapor entering the Thermal Expansion Valve (TXV) and consequently decreasing COP. The key to COP enhancement is to reduce the average surrounding air temperature. Vrachopoulos et al. [3] investigated a water evaporation system to an air-cooled condenser by spraying water mist into the air flow upstream to the condenser. They reported a COP enhancement of 210% and the need for an installation of a water droplet collector to avoid condenser erosion and a subsequent ventilation power increase. Hasan and Siren [4] tested two evaporative heat exchangers with fin-tube and bare-tube. Their model and experiment revealed that the fin-tube had a higher thermal efficiency than the bare-tube. The dry-fin surface had greater fin efficiency than wetted-fin surface, which indicated the weakness of a water-spray system when the mist adheres on fin surface. Hajidavalloo and Eghtedari [5] and Aglawe et al. [6] performed a test on a window-air-conditioner with evaporative cooling media surrounding the condensing coil. Experimental result showed a 16% decrease in power consumption. Manske et al. [7] investigated the control strategy on an industrial refrigeration system with an evaporative condenser model. Their simulation demonstrated an 11% annual reduction in energy consumption.

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Nomenclature

CV	conventional air conditioning system
COP	coefficient of performance
COP_{DEC}	coefficient of performance with DEC
COP_{CV}	coefficient of performance without DEC
DEC	directive evaporative cooling
g	gravity
h_{ai}	enthalpy of air at DEC inlet [kJ/kg]
h_{fg}	enthalpy of evaporation [kJ/kg]
$h_{ao,DEC}$	enthalpy of air at DEC outlet [kJ/kg]
$h_{ao,c}$	enthalpy of air at condenser outlet [kJ/kg]
$h_{r,ci}$	enthalpy of refrigerant at condenser inlet [kJ/kg]
$h_{r,co}$	enthalpy of refrigerant at condenser outlet [kJ/kg]
h_x	specific enthalpy, $x = 1, 2, 3, 4$ represent the location [kJ/kg]
$\dot{m}_{ai}$	mass flow rate of vapor at DEC inlet [kg/h]
$\dot{m}_{ao,DEC}$	mass flow rate of vapor at DEC outlet [kg/h]
$\dot{m}_{ao,c}$	mass flow rate of vapor at condenser outlet [kg/h]
$\dot{m}_r$	refrigerant flow mass flow rate [kg/h]
$\dot{m}_{w,e}$	evaporation rate of water [kg/h]
P_c	refrigerant pressure at discharge [kPa]
P_{sat}	refrigerant pressure saturation pressure [kPa]
$\dot{Q}_{evap}$	cooling capacity [kW]
ΔQ	water consumption [ml/h]
ΔS_{DEC}	refrigerant entropy change through condenser with DEC [kJ/kg-K]
ΔS_{CV}	refrigerant entropy change through condenser without DEC [kJ/kg-K]
TXV	thermal expansion valve
T_{dbi}	dry bulb temperature of air at DEC inlet [°C]
T_{dbo}	dry bulb temperature of air at DEC outlet [°C]
T_{wbi}	wet-bulb temperature of air at DEC inlet
T_{wi}	inlet water temperature [°C]
T_{wo}	drained water temperature [°C]
$T_{sat,DEC}$	refrigerant saturate temperature with DEC [°C]
$T_{sat,CV}$	refrigerant saturate temperature without DEC [°C]
$\dot{W}_{isen}$	isentropic work of compressor [kW]
$\dot{W}_{act}$	actual work of compressor [kW]
$\dot{W}_{irr}$	irreversible work of compressor [kW]
ΔW	work difference of compressor [kW]
$\dot{W}$	work of compressor [kW]
W_p	power consumption of water pump [kW]
η	COP enhancement
Φ	cost ratio of $\frac{\text{Price of water comsupiton}}{\text{Price of total engery saved}}$
ξ_e	price of electricity [\$/kW-hr]
ξ_w	price of water [\$/m^3]
q	flow capacity [m^3/h]
ρ	density of fluid [kg/m^3]
h	differential head [m]
η_p	pump efficiency
φ	relative humidity ratio

Subscripts

a	air
c	condenser
db	dry bulb
e	evaporation
evap	evaporator
i	inlet
o	outlet
r	refrigerant
w	water
wb	wet bulb

EI-Dessouky et al. [8] carried out experiments on a two-stage evaporative cooler with Direct Evaporative Cooling (DEC) and Indirect Evaporative Cooling (IEC). Their work revealed that DEC performed better than IEC under the same condition by using air temperature drop as the evaluation parameter. Youbi-Idrissi et al. [9], in their work on simulation of a spray evaporative condenser, reported an 11% increase in capacity and also revealed an upper theoretical limit of the spray rate to assure efficiency. Pongsakorn et al. [10] studied an inverter air conditioner with an evaporative cooled condenser. They tested the system under multiple water spray rates and frequencies with three different temperature scales in fixed ambient temperature. As a result, up to 35% increase of COP was achieved at a lower water spray rate of 100 L/h and a higher frequency of 80–90 Hz. Delfani et al. [11] applied IEC to a packaged unit air conditioner. Under local conditions, they were able to achieve an increase in a cooling load up to 75% and a reduction in electrical energy consumption of 55%.

Review of the above literature revealed that the thermal enhancement of air conditioning systems can be achieved using an evaporative cooling device, with very strong results. However, there is a lack of study of commercial sized system as well as their real applications. Moreover, very limited work has been reported on the pressure–enthalpy (p–h) or temperature–entropy (T–S) relationship of the overall hybrid DEC-condenser system. This information is important in order to gain the insight of the impact of evaporative cooling on major air conditioning components such as thermal expansion valve, compressor, and evaporator. Furthermore, the DEC evaporation efficiency and the cost-benefit analysis of an evaporative cooling condenser system have received minimal attention. This information is needed for efficient design, performance characterization, and application of DEC-Condenser to air conditioning systems. In this paper, an experimental investigation was conducted on hybrid DEC-condenser located in a full-scale air-conditioning system. The DEC was located upstream to the condenser. The condenser fan was set equal to residential condenser air speed. Thermodynamic properties such as relative humidity, dry-bulb and wet-bulb temperature, and water temperature were measured under steady-state condition for various simulated outside air temperature conditions.

Unlike other studies, the experiments in this paper were carried out using residential sized condenser and evaporator. All the experimental parameters, such as, air velocity, water flow rate, and dry-bulb temperature, were set consistent with design standards and commercially available air conditioning system. Therefore, results obtained from this study has practical engineering relevance and could be directly used in HVAC design. The water temperature were controlled such that the heat transfer process was dominated by latent heat exchange as is the case in practical DEC systems. The cost–benefit analysis performed in this paper provides information to HVAC designers attempting to integrate DEC into a conventional air conditioning system to increase cooling capacity and lower power consumption.

2. Experimental apparatus

The experimental system could be split into two parts: a conventional air-cooled refrigeration system using R-410A coolant and an evaporative pre-cooling system with a temperature control device. The combination of condenser and evaporative pre-cooling system was regarded as the outdoor unit, while the evaporator was considered as the indoor unit, as depicted in Fig. 1. The refrigeration unit was driven by a 7.4 kW scroll compressor, with an evaporator capacity of 5.3 kW to 7 kW. The dimension of the evaporator was 48 cm × 61 cm × 2 rows × 3.15 FPCM, while the capacity of the condenser was 11 kW and its dimension was 63.5 cm × 76.2 cm × 2