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A comparative study on the effect of different strategies for energy saving of air-cooled vapor compression air conditioning systems

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ABSTRACT

This paper investigates and compares the energy saving potential of air-cooled vapor compression air conditioning systems by using liquid pressure amplification (LPA), evaporative-cooled condenser (ECC) and combined LPA and ECC strategies. The applicability, limitation and energy performance of these strategies are discussed. For the purpose of this study, an existing direct expansion rooftop package of a commercial building is used for experimentation and data collection. The system under investigation is extensively equipped with a number of instrumentation devices for data logging. Theoretical–empirical mathematical models for system components were developed first, while a numerical algorithm together with monitored data and a mathematical model implemented on a transient system simulation tool is used to predict the performance of each strategy under transient loads. The integrated simulation tool was validated by comparing predicted and measured power consumption of the rooftop package. Comparing between LPA and ECC methods shows that for the ambient temperatures less than 27 °C the LPA is more effective method while for ambient temperature greater than 27 °C the ECC system is more efficient. Our results also demonstrate average energy savings of 25.3%, 18.3% and 44.2%, respectively for LPA, ECC and combined LPA and ECC methods.

1. Introduction

Heating, ventilation and air conditioning (HVAC) systems typically account for around 40% of total electricity consumption of buildings [1]. In addition, energy use in the built environment is predicted to increase by 34% in the next 20 years, or an average of 1.5% per year [2]. HVAC also dominates peak building electricity demand and therefore energy-efficient methods can reduce HVAC peak energy demands, which currently cost power companies millions of dollars a year in infrastructure investments. The cost of these investments is one of the underlying causes of increasing electricity prices. In recent years, hotter weather has resulted in peak energy demand growing much faster than base power demand. This routinely overwhelms the capacity of the electrical grid. As a result, finding novel ways to reduce energy consumption in buildings without compromising comfort and indoor air quality is an ongoing research challenge. This study demonstrates a range in which novel configurations of existing HVAC system components are used to improve the energy consumption rates of air conditioning systems [3–6].

Many studies report that reduced compressor discharge pressures and the corresponding reduction of compression ratios in a refrigeration cycle are advantageous when it comes to reducing HVAC energy consumption and increasing system life. There are however some solutions which will allow compressor discharge pressures to be significantly lowered whilst preventing the occurrence of flash vapor. Comparing the influence of different methods on compressor discharge pressure shows that using evaporative-cooled condenser (ECC) and floating system condensing temperature using liquid pressure amplification (LPA) pump are the most effective methods. In the evaporative-cooled air condenser system, the ambient air entering the condenser cools when it passes the wet media installed at the upstream of the condenser coil. A controlled water flow is dripped across the media, lowering the condensing temperature and thereby reducing the discharge pressure and subsequent energy consumption of the compressor. The application of LPA to air-cooled air conditioning systems can assist in achieving a considerable reduction in compressor discharge pressure. LPA is achieved by a hermetically sealed, magnetically driven liquid refrigerant pump which is installed in the liquid line between the condenser and expansion valve [7]. The LPA pump increases the pressure of the liquid refrigerant before

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Nomenclature

COP	coefficient of performance
C_p	heat capacity (kJ/kg °C)
h	enthalpy (kJ/kg)
k	polytropic index of the refrigerant vapor
$\dot{m}$	mass flow rate (kg/s)
P	power consumption (kW)
p_{dis}	discharge pressure (kPa)
p_{suc}	suction pressure (kPa)
T	temperature (°C)
Q_b	building cooling load (kW)
V_D	displacement volume of the compressor (m^3/s)
ϑ_{suc}	specific volume of the refrigerant at the compressor inlet (m^3/kg)
W_{in}	electrical power consumption of the compressor (kW)
η_{comp}	total efficiency of the compressor
η_v	volumetric efficiency of the compressor

Subscripts

a	air
amb	ambient
comp	compressor
con	condenser
cond	condensing
dis	discharge
eva	evaporator
i	inlet
r	refrigerant
sat	saturated
sh	superheated
suc	suction
sup	supply

it enters the expansion valve. This method allows the condensing temperature to fluctuate with ambient temperature changes, reducing the condensing pressure and lowering overall energy consumption.

The compressor is the largest power consumer in a vapor compression system. As a result, many previous studies have investigated the influence of various technologies on the compressor performance to enhance the operating and energy efficiency of vapor compression refrigeration systems [8]. However, compared with water-cooled air conditioning system, air-cooled cycles are less energy efficient [9]. Wang et al. [10] studied the impact of two performance improvement techniques applied to a compressor with different refrigerants. The first option involved cooling the compressor motor via external means and the second option was to make the compression process isothermal by transferring heat from the compressor chamber. Their results showed that these approaches could reduce the power consumption of the compressor by up to 16% for the external cooling method and 14% for the isothermal compression. In another study the effect of suction gas bypass on the scroll compressor modulating of an air-conditioner was investigated by Wang et al. [11]. They found that this method can reduce the cooling capacity of the air-conditioner by up to 39% in cooling mode. Some researchers have also showed that floating the condensing temperature closely above the ambient dry-bulb temperature can maximize the COP of the air-cooled air conditioning systems. Sarntichartsak and Thepa [12] showed that the better improvement on the system performance of R410A inverter air-conditioner can be performed using an evaporative-cooled condenser. By using this method, the COP of their tested system was increased by 18.32%. A comparative study between heat recovery and floating condensing temperature was carried out by Arias and Lundqvist [13] to evaluate the potential of their energy savings. Their simulation results indicated that the highest potential of energy saving can be obtained via the combination of both approaches. Furthermore, they showed that at 40 °C condensing temperature, the energy consumption of the system with floating condensing temperature is about 50% of a conventional refrigeration system.

The objective of this paper is to address and compare the reduction of the energy consumption of a DX air-cooled rooftop package by using the evaporative-cooled air condenser method, liquid pressure amplifier method and integration of both methods. For this purpose, an actual air-cooled rooftop package air conditioning system of a real-world commercial building located in a hot and dry climate zone was used for experimentation and data collection. Field tests were conducted to quantify and determine the variables of the system. System models were obtained by using a theoretical–empirical approach, from which the proposed strategies were formulated. In order to take into account the nonlinear, time varying and building-dependent dynamics of the HVAC system, a transient simulation software package, TRNSYS 16 [14] was used to predict the HVAC energy usage. The cooling plant was tested continuously to obtain the operation parameters of system components under different conditions. On the basis of the TRNSYS codes and using the real test data, a simulation module for the cooling plant was developed and embedded in the software. In this model, a commercial building was equipped with the rooftop package allowing dynamic simulation of all main equipment in the whole system to be performed simultaneously. Performance predictions were then compared with actual performance measurements to verify the mathematical model and compare the performance of the three strategies. Findings detailed in this paper show energy savings of 39%, 28% and 56% are possible as a result of using LPA, ECC and the LPA/ECC combined model, respectively.

2. System modeling

A single-stage vapor compression DX air-cooled air conditioning system consists of four major components: a compressor, an air-cooled condenser, an expansion valve and a DX evaporator. Fig. 1 shows a schematic block diagram of the conventional DX air conditioning system while its pressure–enthalpy diagram is shown in Fig. 2. In the conventional system the cycle starts with a mixture of liquid and vapor refrigerant entering the evaporator (point (1)). The DX evaporator in the plant is of the rectangular finned tube type of heat exchanger in which the refrigerant and air are assumed to be counter-flow. The heat from warm air is absorbed using the evaporator DX coil. During this process, the state of the refrigerant is changed from a liquid to a gas and becomes superheated at the evaporator exit. Superheat is required to prevent slugs of liquid refrigerant from reaching the compressor and causing any serious damage. The supply air temperature can be estimated by:

$$T_{\text{sup}} = T_{\text{eva},a,i} - \frac{\dot{m}_r}{\dot{m}_{\text{eva},a} C_{p,a}}(h_2 - h_1), \qquad (1)$$

where h_2 is the enthalpy of the refrigerant leaving the DX evaporator and are determined as:

$$h_2 = h_{\text{eva},r,\text{sat}} + C_{p,r}(T_{\text{eva},r,\text{sh}} - T_{\text{eva},r,\text{sat}}), \qquad (2)$$

where $T_{\text{eva},r,\text{sh}}$ is the temperature of superheated vapor refrigerant leaving the evaporator which was measured during the experimentation, $h_{\text{eva},r,\text{sat}}$ and $T_{\text{eva},r,\text{sat}}$ are respectively the enthalpy and temperature of saturated refrigerant vapor at the evaporating pressure and can be calculated using the refrigerant thermodynamic