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Investigation of energy-efficient strategy for direct expansion air-cooled air conditioning systems

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HIGHLIGHTS

- Combined theoretical–empirical models for performance prediction of the DX air conditioning system.
- Field tests conducted for a real building's air-cooled DX rooftop package.
- Numerical algorithm developed and implemented in transient simulation software.
- Liquid pressure amplification method appears to be effective for the study.
- About 25.3% in average and up to 42% drop in energy consumption.

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ABSTRACT

This paper addresses the energy saving significance of air-cooled direct expansion (DX) air conditioning systems using liquid pressure amplification (LPA) technology along with proposed theoretical–empirical models for the system components. This method utilizes a refrigerant pump in the liquid line to allow the system operation at lower condensing pressure. An actual DX rooftop package is used for data collection. The performance of the proposed method is simulated using transient simulation software. Simulation tool was validated by comparing predicted and measured power consumption of the rooftop package. Results show that up to 42% power savings can be obtained using this approach.

1. Introduction

The increasing energy consumption of heating, ventilating and air-conditioning (HVAC) systems in buildings has triggered a great deal of research aimed at developing energy-saving systems, processes and tools. The increased use of HVAC systems is a result of an ever-increasing demand for occupant comfort; HVAC systems have therefore become a common appliance, accounting for almost 50% of the energy consumed in a standard building and around 10–20% of total energy consumption in developed countries [1]. However, direct expansion (DX) air conditioning systems are common; they are simpler in configuration and more cost-effective to maintain than central cooling systems that use chillers and cooling towers [2,3]. Therefore, DX systems have a wide application in small- to medium-sized buildings. The performance of these systems can be improved by applying effective configurations of existing system components [4–6]. One proven way of achieving energy efficiency in the vapor compression refrigeration systems is to reduce the compressor discharge pressure [7] which decreases the compression ratio of the compressor and in turn causing to less electricity consumption which is the focus of our study.

In the context of energy optimization, a lot of research has been dedicated to various methods for reducing the compressor head pressure. For example pre-cooling the ambient air before it reaches the air-cooled condenser of the vapor compression cooling systems can reduce the condensing temperatures which drop the condensing pressure. Yu and Chen [8] investigated how the COP of air-cooled chillers can be improved by using mist pre-cooling. Their results estimated that around 18% decrease in the annual electricity usage could be achieved with mist pre-cooling of air entering the air-cooled condenser of chiller, serving a hotel in a sub-tropical

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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
inj	injected
r	refrigerant
sat	saturated
sh	superheated
suc	suction
sup	supply

climate. Hwang et al. [9], compared the performance of an evaporative-cooled condenser with that of a conventional air-cooled condenser for a split heat pump system. In their design, the condenser tubes were immersed in a water bath where ambient air was blown across rotated wheel submerged in the water bath. Their experimental results showed that the capacity and coefficient of performance (COP) of LPA system can be increased by 1.8–8.1% and 11.1–21.6% respectively. Naphon [10] presented the performance of an air-conditioner with 12,000 Btu/h when combining with three set of heat pipe for cooling air before entering the condenser. For the indoor design temperature kept at 25–26 °C, their results indicated that the proposed design could increase the COP of the system by 6.4%. As reported in Ref. [11], the COP of a ground source heat pump was higher than that of air source heat pump by 74% due to lower condensing temperature in the ground source heat pump system. However, there are few published studies that have addressed the effects of floating condensing temperature using liquid pump amplifier on the overall energy consumption of the DX air conditioning systems.

The objective of this study is to explore the influence of an optimal strategy on energy consumption of an existing direct expansion air conditioning system. For this purpose, the existing DX rooftop package of a real-world commercial building located in a hot and dry climate zone is used. Field tests were conducted to quantify and determine the variables of the system. Both inputs and outputs of the existing plant are measured from the field monitoring in one typical week in the summer. The measured data obtained from the actual DX rooftop package is used to calibrate a model, which, in turn, is used to estimate the performance of the LPA system. The system models were obtained by using a Theoretical–empirical approach, from which the proposed strategy is formulated. In the proposed strategy, a liquid pressure amplification pump (LPA) is located in the liquid line between the condenser and expansion valve to allow the condensing temperature to fluctuate with ambient temperature changes. Therefore, the condensing pressure is reduced and system consumes less electricity. In other words, the LPA pump increases pressure of the liquid refrigerant before it enters the expansion valve. Additionally, around 5% of the sub-cooled refrigerant mass flow rate is injected into the discharge line of the compressor to cool the discharge gas, reduce the condenser heat rejection and thus cope with higher load demand.

Along with the formulated strategy, a numerical algorithm is developed to obtain the system transient performance using an iterative loop. To deal with complexity of the heat transfer process, building-dependency of the HVAC system, and the increased cumbersome computation due to a small time interval (hourly), a transient simulation software package, TRNSYS [12] is used to predict the HVAC system performance under a variety of operating conditions. Mathematical models, experimental data and proposed algorithm are coded and implemented within the TRNSYS environment so that dynamic predictions of all main equipment in the system can be performed simultaneously. Performance predictions were then compared with actual performance measurements to verify the mathematical model. Results indicate the validity of our modeling approach and serves as convincing evidence for the energy savings claim. Results also show significant energy saving potential as a result of proposed approach.

2. System modeling

Many models for DX rooftop package air conditioning system have been developed using various principles [13–15]. In the followings a combined theoretical–empirical modeling approach will be developed for these components. A single stage vapor compression direct expansion air conditioning system consists of four major components, namely a rotary scroll compressor, an air-cooled condenser, an expansion valve and a DX evaporator. Fig. 1 shows a schematic block diagram of the conventional and developed DX air conditioning system while their pressure–enthalpy diagram is shown in Fig. 2. In the conventional system cycle starts with a mixture of liquid and vapor refrigerant entering the evaporator (point 1). The DX evaporator in 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 by an DX evaporator 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:

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

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

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

where $T_{eva,r,sh}$ is the temperature of superheated vapor refrigerant leaving the evaporator which was measured during the