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Modeling and optimal control of an energy-efficient hybrid solar air conditioning system

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The paper addresses the modeling and optimal control problem of a new hybrid solar-assisted air conditioning system developed for performance enhancement and energy efficiency improvement. To regulate the mass flow rate of the refrigerant vapor passing through a water storage tank for increasing the refrigerant's sub-cooling process at partial loads, we propose a new discharge bypass line together with an inline solenoid valve, installed after the compressor. In addition, to control the air flow rate, a variable speed drive is coupled with the condenser fan. For the control purpose, a lumped parameter model is first developed to describe the system dynamics in an explicit input–output relationship; then, a linear optimal control scheme is applied for the system's multivariable control. The system has been fully-instrumented to examine its performance under different operation conditions. The system model is then validated by extensive experimental tests. Based on the obtained dynamic model, an optimal controller is designed to minimize a quadratic cost function. Numerical algorithms, implemented in a simulation tool, are then employed to predict the energy performance of the system under transient loads. The experimental results obtained from implementation with PLC demonstrate that the newly-developed system can deliver higher system efficiency owing to amelioration of the refrigeration effect in the direct expansion evaporator and adjustment of its air flow rate. The development is thus promising for improvement of energy efficiency, enhancement of the system performance while fulfilling the cooling demand.

1. Introduction

Heating, ventilating and air conditioning (HVAC) systems consume significant amounts of electricity. Among energy consumption of commercial and residential buildings, HVAC systems account for over 50% of the total energy usage [1]. They also lead to the reduction of the valuable fossil fuel sources and production of the greenhouse gases which are known to cause ozone layer depletion [2]. In addition, a recent energy overview predicts that energy use in the built environment will grow by 34% in the next 20 years at an average rate of 1.5% [3]. However, it is noted that the major part of the energy usage still comes from fossil fuels [4]. Therefore, the overall attainable reduction in energy consumption and enhancement of human comfort in buildings are dependent on the performance of HVAC systems. The possibility of cooling via the use of renewable energy has been intriguing on how to combine air conditioning systems with free energy sources so as to reduce their power consumption. In recent years, due to world energy shortage, different types of cooling technologies in combination with solar thermal energy have been explored. For this, most efficient among the sources is perhaps the solar thermal energy. Solar energy is clean and accessible all over the world, especially feasible in regions with high solar radiation. It has been estimated of around 35–45% reduction in the total system cost for solar thermal cooling by 2030 [5]. Technically, solar energy is applied to air conditioning systems either by photovoltaic panels or heat driven sorption systems. Applying solar energy on various types of HVAC systems has proven its potential for energy usage reduction. However, solar radiation is a highly time-dependent energy source and it does not necessarily match with the building demand. This problem can be addressed by regulating the storage and release of thermal energy according to the building load. Therefore, an appropriate control method should be employed by solar-assisted HVAC systems to adjust the transient building demand with the stored solar thermal energy. In construction automation, building energy management and the necessity to reduce overall energy consumption are becoming an increasingly important topic, given with highly dynamic environments in association with frequently varying conditions of the building setting and its occupancy [6]. For air conditioned buildings, an important problem is energy optimization, for example using a reliable model for predicting the whole building heat and moisture transfer [7]. In the building and energy context, the application of modeling and control engineering has proved to be promising [8].

Among different types of HVAC systems, the direct expansion (DX) wall-mounted air-conditioner with a vapor compression cycle is commonly-used. This system that uses energy obtained by fossil fuels can output two to six times thermal energy through absorption from

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renewable energy sources [9]. However, air-cooled air conditioning systems are less energy efficient than water-cooled air conditioning system [10] and thus finding novel ways to reduce its energy consumption without compromising comfort and indoor air quality is an ongoing research challenge. A large number of theoretical and experimental investigations on solar-assisted HVAC systems have been reported. The feasibility of using different photovoltaic systems for supplying the electricity of a window-type air conditioner was investigated in [11], where better performance in meeting the air conditioner requirements was obtained from the hybrid grid photovoltaic (PV) wind system. A solar electric-vapor compression refrigeration system and investigated its performance for different evaporating temperature [12], but the system required a large photovoltaic panel area when decreasing evaporative temperature. To balance the inconsistency between solar radiation and cooling load, a solar-powered absorption refrigeration system was presented in [13], using the mass energy transformation and storage technology to obtain a system COP of 0.7525 for the air-cooled condenser, and 0.7555 for the water-cooled condenser. The performance of a condenser heat recovery with a PV/T air heating collector to regenerate desiccant for reducing energy use of an air conditioning room was investigated by [14], who indicated via experimental test and dynamic simulation that electricity of about 6% of the daily total solar radiation can be gained from the PV/T collector. The proposed system was able to save about 18% of the total energy use of the air conditioner. A dynamic model for investigating the performance of a solar-driven ejector refrigeration plant was presented in [15] for an office building, wherein a conservation of more than 75% of electricity was shown in comparison to a traditional compressor based air conditioner. A solar driven two-stage rotary desiccant cooling plant was combined with a vapor compression air conditioning system in [16], where experimental investigations showed that the solar driven desiccant cooling system can handle about 33% of the cooling load which means a 34% reduction in power consumption compared with a vapor compression system. Solar-assisted heat pump drying systems have also been shown as capable of improving coefficient of performance (COP) and thermal efficiency while reducing energy consumption to enhance the quality of agricultural and marine products where low temperature and well-controlled drying conditions are required [17].

To date, not much research has been devoted to the influence of solar vacuum collectors installed after the compressor on the energy performance of vapor compression air conditioning systems. In existing solar-assisted air conditioner, the compressor is sized solely on the discharge pressure requirement, with additional heat input to the refrigerant being provided by solar collectors and their associated hot water storage tank. In this paper, in line with the modeling and control framework of achieving higher performance of solar air-conditioners via closed-loop control [18], the system has been configured to increase the sub-cooling process at partial loads by regulating the mass flow rate of the refrigerant in the hot water tank as well as the air flow rate at the condenser outlet as control variables. Because building cooling load varies with the time of the day, an HVAC system could be equipped with an effective controller to reduce the energy consumption by keeping the process variables to their optimal set-point required. This has motivated the work presented in this paper, to reconfigure the system developed in [19] with a refined model validated from experiments, and to design and implement an optimal regulator for its closed-loop multivariable control. The new hybrid solar-assisted system features a discharge bypass line, an inline controlled solenoid valve, a condenser fan with variable speed drive, and a programmable logic controller for closed-loop control of two outputs, namely the temperatures of the refrigerant leaving the condenser and leaving the compressor, respectively. Thus, the contribution of this paper rests with (i) a new configuration of the solar-assisted DX air-conditioner with controllable flow rates of the refrigerant passing through the hot water tank and of the air from the condenser outlet by varying its speed, (ii) a comprehensive model of the reconfigured system, and (iii) a multi-input multi-output control scheme based on the linear quadratic regulator (LQR) technique for optimal control of the system dynamics.

The objective of this study is thus to describe the new configuration of the hybrid solar-assisted air conditioning system, to derive its dynamical model and develop an optimal controller, and to report on its system performance with regard to the ultimate goal of reduction of the energy consumption. In our system, as the solar collector is installed after the compressor to reduce the compressor work, it increases the refrigerant temperature leaving the condenser because of the additional heat added before the condenser especially in partial load conditions. This results in some reduction of the system's COP. Therefore, a proper control strategy should lower the refrigerant temperature leaving the condenser and, in turn, increase the overall COP [20]. To achieve this, a novel configuration including a by-pass line together with a current-controlled three-way proportional valve has been inserted in the discharge line after the compressor in order to control the refrigerant temperature [21]. Furthermore, a variable speed drive (VSD) is also connected to the condenser fan to adjust the condenser fan speed in accordance to the closing and opening of the by-pass valve. Our aims include the regulation of the refrigerant flow rate in order to enhance the sub-cool temperature for various cooling loads and ambient conditions and also the control of the air flow from the condenser fan so as to reduce the refrigerant temperature entering the evaporator, with the ultimate goal to enhance the system refrigeration effect overall and thereby its coefficient of performance. Mathematical models and experimental data are implemented on a transient simulation tool, TRNSYS 16 [22], to predict performance of the system. Results show that the new implemented mechanical design together with its proposed control system can yield to higher sub-cool temperature after the condenser which can increase further the overall coefficient of performance up to 9%.

This paper is organized as follows. After the introduction, the proposed configuration of the system is described in Section 2. A dynamic model of the system is derived in Section 3, followed by Section 4 on its optimal control design. The results and discussion are included in Section 5. Finally a conclusion is drawn in Section 6.

2. Proposed configuration

2.1. System description

A single stage vapor compression solar air-conditioner consists of six major components: a compressor, a condenser, an expansion device, an evaporator, a solar vacuum collector and a solar storage tank. The schematic diagram of the arrangement is shown in Fig. 1. The cycle starts with a mixture of liquid and vapor refrigerant entering the evaporator (point 1). The heat from the warm air is absorbed by an evaporator coil. During this process, the state of the refrigerant is changed from liquid to gas and becomes superheated at the evaporator exit. The superheat vapor enters the compressor (point 2), where the increasing pressure causes to raise the refrigerant temperature. A vacuum solar panel installed after the compressor uses the sun radiation to heat up the water. An insulated water storage tank is connected to the vacuum solar collector to maintain the water temperature. The refrigerant from the compressor goes through the copper coil inside the tank and undertakes a heat exchange (point 3). The vacuum solar collector reheats the refrigerant to reach the necessary superheat temperature. At this point, the high pressure superheated gas travels to the condenser for heat rejection to the ambient air (point 4). A further reduction in temperature happens in the condenser and causes it to de-superheat, and thus, the refrigerant liquid is sub-cooled as it enters the capillary tube.

Since a rotary scroll compressor is used in this plant, when the desired temperature inside the building is reached, the compressor will be turned off and block the return of the refrigerant back to the suction line via an inline two-way valve, installed at the condenser inlet after the storage tank. In this case, the condenser inlet valve is closed and thus the temperature and pressure of the refrigerant inside the heat