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Research Paper

Model-based dynamic optimal control of a CO_2 heat pump coupled with hot and cold thermal storages

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HIGHLIGHTS

- Model-based dynamic optimization strategy for charging of hot and cold storages.
- Modelica based modeling of a dual-mode heat pump coupled with thermal storages.
- Coordinative optimization of multiple optimal control parameters by GA.
- Outlet water temperatures of thermal tanks as indicators for optimal control.
- Experimental performance enhancement by dynamic optimal control strategy.

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ABSTRACT

This study presents a model-based dynamic optimization strategy for a dual-mode CO_2 heat pump coupled with hot and cold thermal storages, which was proposed as a high-efficiency smart grid enabling option in heating and cooling services for buildings or industry. Dynamic optimal control for simultaneously charging of hot and cold thermal storages is very delicate. The optimal control of compressor discharge pressure were commonly used for optimal control of heat pump systems. In this study, the outlet water temperatures of hot and cold tanks are used as indicators in the dynamic optimal strategy for charging of hot and cold storages using a dual-mode heat pump. The Modelica based dynamic model of the coupled system was developed and validated. To optimize the overall coefficient of performance (COP) during energy process, the transient total COP is optimized by genetic algorithm based on Modelica-based modeling of dynamic system. A dynamic optimal control strategy was developed and implemented into an experimental system. Test results show that this developed model-based dynamic optimal control strategy is able to search the optimal transient total COP and optimize the overall COP of such coupled systems during energy charging; and the optimal results is better than those obtained using another two experiment-based methods.

1. Introduction

CO_2 is being advocated as one of the natural refrigerants to replace CFCs and HCFCs in vapor compression systems due to its environmentally friendly characteristics. Many experimental and modeling studies have been conducted on CO_2 heat pumps in cooling or heating *single-mode* and their control methods in the past year. The coefficient of performance (COP) of CO_2 heat pump systems is affected by several operational variables, such as ambient temperatures, water outlet temperature, and discharge pressure [1–4]. Many experimental and theoretical studies have resulted in a number of correlations on optimal discharge pressure for transcritical CO_2 heat pumps for optimizing COPs of heat pump systems [3,5]. Minetto [6] developed a control method for the upper cycle pressure to maximize the COP of the CO_2 heat pump combined with a thermal storage tank for domestic hot water. Baek et al. [7] investigated the control methods of the gas-cooler pressure by varying the electric expansion valve opening, compressor frequency, and outdoor fan speed at various outdoor temperatures in the cooling mode. Hu et al. [3] proposed a self-optimizing control scheme to maximize the COP in real time by using the extremum seeking control strategy (ESC) for the air-source

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Nomenclature

COP	coefficient of performance (–)
Cp	specific heat at constant pressure (J/kg/K)
f	compressor frequency (Hz)
$\dot{m}$	mass flow rate (kg/s)
n	pulse number (pulse)
P	pressure (MPa)
$\dot{Q}$	transient capacity (W)
Q	overall capacity (MJ)
T	temperature (°C)
$\dot{V}$	volumetric flow rate (m^3/h)
$\dot{W}$	power (W)
W	overall power (MJ)

Subscripts

c	cold, cold tank
clg	cooling
comp	compressor
evap	evaporator
h	hot, hot tank
htg	heating
i	inlet
o	outlet
ov	overall
tot	total
w	water

transcritical CO_2 heat-pump water heater, and the discharge pressure setpoint is taken as the input to the ESC controller [3].

Most of these existing methods for control and optimization of energy system operation are based on models [8–10]. There are a few researches on model-based optimal control of energy system under dynamic operating conditions. Zhao et al. [8] developed a model-based optimization strategy for vapor compression refrigeration cycle by a modified genetic algorithm to search the optimal settings for air source heat pump based on the hybrid models, and regrouped the measured temperatures according to the temperature range in order to analyze the energy consumptions at different temperature conditions [8]. Wang et al. [9] proposed a model-based optimization strategy using genetic algorithm to obtain the optimal set-points for desiccant solution temperature and flow rate in order to minimize the energy usage in the dehumidifier; parameters of the models would be updated every period of time by the operating data collected in the real process of the liquid desiccant dehumidifier [9].

'Thermal Battery', i.e. the water source CO_2 heat pump system coupled with hot and cold thermal storages, converts electricity simultaneously to hot and cold reservoirs at useful temperature levels for buildings and industry using a high-pressure CO_2 compression heat pump [11] (Fig. 1), which can minimize operational cost and CO_2 emissions [1,12]. 'Thermal Battery' can enhance grid stability and will be the most cost-effective Smart Grid enabling option for supporting higher penetration levels of intermittent renewables in the energy system. Modeling and experimental studies have found that the dynamic COP (coefficient of performance) of 'Thermal Battery' with CO_2 compression heat pump depends on multiple parameters such as compression speed, expansion valve opening, water temperature and flow rates. Jensen et al. [13] developed a dynamic model for a heat pump system including hot and cold thermal storages for flexible and simultaneous supply of heating and cooling for buildings, and found that the performance of heat pump is highly sensitive to the temperature distribution in the storages. Wang et al. [14] investigated experimentally the dynamic COP of a thermal battery system as a function of different gas cooler pressures, water flow rates and expansion valve openings, and found that a 20% more efficient in terms of cooler capacity can be achieved by controlling the hot and cold water flow rates to maintain the thermal profile of the water tanks. Liu et al. [12] investigated experimentally the dynamic performances of a dual-mode transcritical CO_2 heat pump coupled with hot and cold thermal storages during energy charging process, and found that the COPs of such coupled system can be optimized through controlling compressor frequency, expansion valve opening and hot and cold water flow rates [12]. Thermal stratification in thermal storage tanks is one of the most important impact factors on the coupled system COPs [12,13]. The outlet water temperatures of thermal storage tanks vary with time during energy charging, and affect the COPs of heat pump cycle and the thermal stratifications in thermal storage tanks significantly [12]. This is different from those optimization methods through minimizing super-heating, optimizing sub-cooling or adjusting the setpoint to the pressure controller in [15,16]. At the same outlet water temperatures of hot and cold tanks, the transient total COPs are different at different constant compressor frequency, expansion valve opening and hot and cold water flow rates during energy

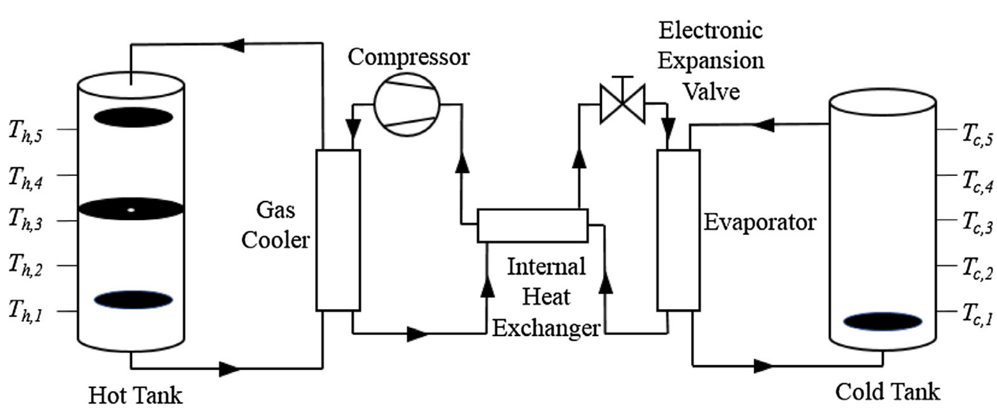

Fig. 1. Schematic of heat pump coupled with hot and cold thermal storages [12].