2018

Dynamic Optimal Control of a CO2 Heat Pump Coupled with Hot and Cold Thermal Storages

Fang Liu
Shanghai University of Electric Power, China, People's Republic of, fangliu_shiep@163.com

Jiaxin Deng
Shanghai University of Electric Power, China, People's Republic of, 2787076383@qq.com

Eckhard A. Groll
Purdue University - Main Campus, groll@purdue.edu

Dynamic Optimal Control of a CO_2 Heat Pump Coupled with Hot and Cold Thermal Storages

Fang LIU[1]*, Jiaxin DENG[1], Eckhard A. GROLL[2]

[1] College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai, 200090, PR China
Tel: +86 21 35303902, Fax: +86 21 35303902, E-mail: fangliu@shiep.edu.cn

[2] School of Mechanical Engineering, Ray W. Herrick Laboratories, Purdue University, 177 S. Russel Street, West Lafayette, IN 47907, USA
Tel: +1 765 496 2201, Fax: +1 765 494 0787, E-mail: groll@purdue.edu

* Corresponding Author

ABSTRACT

This study presents a model-based dynamic optimization strategy for a dual-mode CO_2 ejector expansion 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. The dynamic model of the coupled system was developed by Modelica. 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. To optimize the overall performances during energy process, the transient performances are optimized by genetic algorithm based on Modelica-based modeling of dynamic system. Single-objective and multi-objective dynamic optimal control strategies were developed and implemented into the simulation system. Modeling results show that these two developed model-based dynamic optimal control strategies are able to search the optimal transient performances and optimize the overall performances of such coupled systems during energy charging. Compared with the strategy with constant control parameters, these two dynamic optimal control strategies can be helpful in the coordinative optimization of multiple control parameters, and multi-objective dynamic optimal control strategy is superior to the single-objective one.

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. ‘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 (Blarke et al. 2012), which can minimize operational cost and CO_2 emissions (Calabrese et al. 2015). ‘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. (2013) 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. (2014) 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. (2017a) 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. 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 charging, which means the transient total COPs can be optimized by adjusting the control parameters during energy charging, and there are dynamically optimal setting points for these four control parameters at transient outlet water temperatures of thermal storage tanks. Thus Liu et al. proposed a novel experiment-based optimization approach for charging of dual-model energy storage systems (2017b) and developed a Modelica-based dynamic optimal strategy for a dual-mode CO2 heat pump coupled with hot and cold storage tanks (Liu et al. 2018).
Liu et al. (2012a) investigated CO_2 transcritical air conditioner experimentally and found that the cooling COP of a CO_2 air conditioning system can be enhanced significantly by using an ejector expansion device to replace a conventional expansion valve. Liu et al. (2016) also carried out an experimental study to examine the simultaneous cooling and heating performances of an ejector expansion CO_2 transcritical system with an adjustable ejector and a variable speed compressor under different operating conditions in detail. However, the model-based optimization of ejector expansion heat pump systems coupled with simultaneous hot and cold thermal storage is very delicate. It is essential to develop a model-based dynamic optimal control strategy for simultaneously charging of hot and cold thermal storage systems by ejector expansion heat pump in order to optimize the overall COP of such coupled system during energy charging process.
Therefore, this study is to develop a model-based dynamic optimal strategy for an ejector expansion dual-mode CO_2 heat pump coupled with hot and cold storage tanks; Genetic algorithm, an approach to solve global optimization problems, is an effective method to solve large scale optimization problem and was adopted to search the optimal setting points.

2. DYNAMIC MODELING OF EJECTOR EXPANSION COUPLED SYSTEM

Figure 1 shows a schematic of the ejector expansion CO_2 heat pump coupled with hot and cold thermal storages, which consists of a CO_2 compressor, an ejector, a evaporator, a gas cooler, an internal heat exchanger, a cold water thermal storage tank with a water circulation pump, and a hot water thermal storage tank with a water circulation pump.

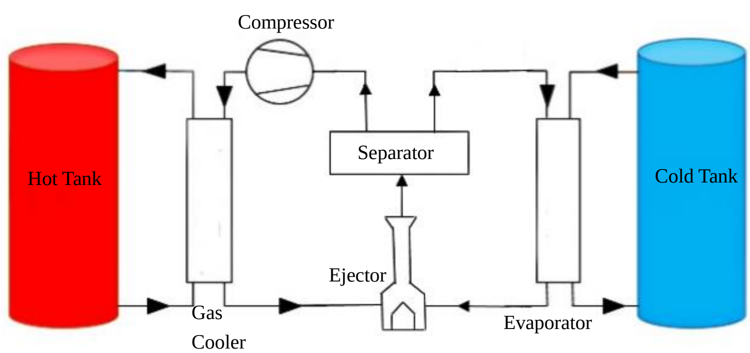

Figure 1: Schematic of ejector expansion heat pump system coupled with hot and cold thermal storages

2.1 Dynamic model

In this study, the dynamic simulation model of the heat pump system coupled with hot and cold thermal storage is developed using Dymola and TIL library. The Dymola layout for such coupled system is shown in Figure 2. The ejector model follows component *TIL.VLEFluidComponents.Valves.OrificeValve* in the TIL Library (2017). The readers are referred to (Liu et al. 2018) for the sub-models of compressor, gas cooler, evaporator, thermal storage tanks and other components, as well as the related validation.
The water-side transient cooling and heating capacities and the transient total power consumption were calculated using Eqs. (1) to (3), respectively.

Cooling capacity: $$\dot{Q}_{clg} = \rho \cdot \dot{V}_{w,c} \cdot C_p \cdot (t_{c,o} - t_{c,i}) \quad (1)$$
Heating capacity: $$\dot{Q}_{htg} = \rho \cdot \dot{V}_{w,h} \cdot C_p \cdot (t_{h,o} - t_{h,i}) \quad (2)$$

Total power: $\dot{W}_{tot} = \dot{W}_{comp} + \dot{W}_{pump,c} + \dot{W}_{pump,h}$ (3)

Where C_p is 4186.8 J/(kg· K) , ρ is 1000kg/m^3, $t_{c,i}$ and $t_{c,o}$ are the transient inlet and outlet water temperatures of cold thermal storage tank respectively, $t_{h,i}$ and $t_{h,o}$ are the transient inlet and outlet water temperatures of hot thermal storage tank respectively.

The water-side transient cooling COP, heating COP and total COP of such system were calculated using Eqs. (4) to (6), respectively.

Cooling COP: $$COP_{clg} = \frac{\dot{Q}_{clg}}{\dot{W}_{tot}} \quad (4)$$

Heating COP: $$COP_{htg} = \frac{\dot{Q}_{htg}}{\dot{W}_{tot}} \quad (5)$$

Total COP: $$COP_{tot,t} = \frac{\dot{Q}_{clg}+\dot{Q}_{htg}}{\dot{W}_{tot}} \quad (6)$$

The initial water temperature in both thermal storage tanks is set as 27°C. The thermal energy storage tanks were being charged until the average water temperature in hot tank increases up to 60ºC. Assuming that the transient system performances remain unchanged during 5 seconds, the data to evaluate the overall system performances during energy charging were recorded every 5 seconds. Thus the water-side overall system performances were calculated using Eqs. (7) to (10).

Overall cooling capacity： $$Q_{clg} = \sum_{i=0}^{n} \dot{Q}_{clg,i} \quad (7)$$

Overall heating capacity： $$Q_{htg} = \sum_{i=0}^{n} \dot{Q}_{htg,i} \quad (8)$$

Overall power： $$W = \sum_{i=0}^{n} \dot{W}_{tot,i} \quad (9)$$

Overall COP： $$COP_{ov} = \frac{\sum_{i=0}^{n}(\dot{Q}_{clg,i}+\dot{Q}_{htg,i})}{\sum_{i=0}^{n}(\dot{W}_{tot,i})} \quad (10)$$

Where *i* is the recorded number during energy charging.

2.2 Dynamic model validation

An experimental study on the performances of this coupled system during energy charging was carried out, with compressor frequency *f* set at 45 Hz, ejector throat area A set at 2.5 mm^2, hot-side and cold-side circulating water flow rates, $\dot{V}_{w,h}$ and $\dot{V}_{w,c}$ were set at 0.15 m^3/h and 0.20 m^3/h, respectively. The initial water temperature in both thermal storage tanks is set as 27°C. The thermal energy storage tanks were being charged until the average water temperature in hot tank increases up to 60ºC. The measured transient data for pressures, temperatures, flow rates and power consumptions were recorded every 5 seconds. Figures 2 present comparisons of the transient COPs between test and simulation, respectively. It can be found that the deviation of the transient COPs between test and simulation is within 5.59%; the dynamic model can predict the dynamic performances of this coupled system well in general as shown in Figure 2. As shown in Fig. 2, the dynamic model is not capable of simulating the start-up COP of the coupled system, because the start-up performances of the simulation system are stable while those of the experimental system are unstable.

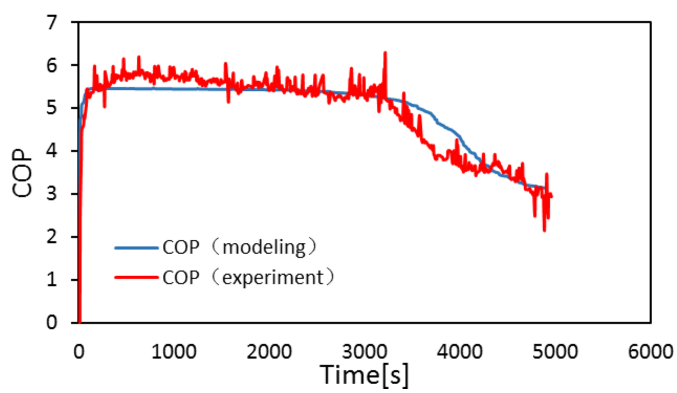

Figure 2: Model validation of system performances during energy charging at constant control parameters

3. DYNAMIC OPTIMIZATION METHOD

The optimization process in this study searches the setting points for the optimal operating strategy to maximize the overall performances of charging of hot and cold storages using a dual-mode heat pump. Dynamic remaining maximum of the transient total performances during the whole energy charging process would be beneficial for the overall performance optimization as indicated in (Liu et al. 2017a). Therefore, the model-based dynamic optimization for the transient total performances is focused in this study. The outlet water temperatures of hot and cold storage tanks were affected by the performances of heat pump and thermal tanks significantly (Liu et al. 2017a), and are considered as two uncontrollable parameters. The optimization problem is formed through the objective function and the constraints. Genetic algorithm in *ModelOptimization* of Dymola was used to determine dynamic optimal setting points for the control parameters. The optimal control strategy was developed and implemented into the experimental setup for practical operation and validation.

3.1 Objective function

The objective of global optimization for charging of hot and cold storages using a dual-mode heat pump is to maximize the transient performances ($COP_{tot,t}$, $\dot{Q}_{clg}$, $\dot{Q}_{htg}$) during energy charging. The objective function is established as the transient performances and determined by the four control parameters (compressor frequency, ejector throat area, circulating hot and cold water flow rates), and varies with the transient outlet water temperatures of hot and cold tanks (Liu et al. 2017a). Therefore, the optimization model for maximizing the transient performances during energy charging can be expressed as Eq. (11), and obtained from dynamic system modeling. The model inputs are uncontrolled variables and controlled variables, while the model output is the transient performance.

$$Performance_t = f\left(f, A_{th}, \dot{V}_{w,c}, \dot{V}_{w,h}, t_{h,o}, t_{c,o}\right) \qquad (11)$$

All the variables related with this optimization problem, according to their properties, can be classified into three types, namely:

Uncontrolled variables ($t_{h,o}$,$t_{c,o}$): these two variables are determined by the performances of heat pump and the temperature stratification in thermal storage tanks. Both of them continuously change, normally $t_{h,o}$ increases and $t_{c,o}$ decreases, during energy charging.

Controlled variables (f,A_{th}, $\dot{V}_{w,h}$, $\dot{V}_{w,c}$): compressor frequency, ejector throat area, circulating hot and cold water flow rates can be controlled by the inverter, the electric current through a solenoid, the variable-speed pumps for hot and cold water circulation, respectively. These four variables affect the performances of heat pump and thermal stratification in thermal storage tanks, and they are considered as the setting points. The four variables can be selected to meet all the constraints and the optimization algorithm will search the optimal setting points for the maximal transient performances.

Dependent variables ($COP_{tot,t}$,$\dot{Q}_{clg}$, $\dot{Q}_{htg}$): The dependent variables can be determined by the uncontrollable and controllable variables through the properties, the interactions and the constraints between the components. Then the dependent variables will be used to evaluate the overall system performances during energy charging.

3.2 Constraints

In order to ensure the feasibility of the solution for this optimization problem, some constraints are imposed so that the solution falls within the physical feasible operational region. During energy charging, two types of constraints, physical limitations of the components and interactions between the components, are involved.

3.2.1 Physical limitations of the components

Compressor frequency *f*:

$$f_{min} \le f \le f_{max} \qquad (12)$$

Where f_{min} and f_{max} are the lower bound and upper limit of the compressor frequency, respectively.

Ejector throat area A_{th}:

$$A_{t,min} \le A_{th} \le A_{t,max} \qquad (13)$$

Where $A_{th,min}$ and $A_{th,max}$ are the lower limit and the upper bound of expansion valve opening pulse number, respectively.

3.2.2 Interactions between the components

Besides the physical limitations of the variables, the interactions between some components should also be addressed as the constraints for this optimization problem so that the transient performances can be maximized correspondingly.

The COPs of heat pump cycle and the thermal stratification in thermal storage tanks are affected by the circulating hot and cold water flow rates as well as the outlet water temperatures of thermal storage tanks significantly (Liu et al. 2017a). Therefore, the circulating hot and cold water flow rates are restricted by

$$\dot{V}_{w,h,min} \leq \dot{V}_{w,h} \leq \dot{V}_{w,h,max} \quad (14)$$
$$\dot{V}_{w,c,min} \leq \dot{V}_{w,c} \leq \dot{V}_{w,c,max} \quad (15)$$

Where $\dot{V}_{w,h,min}$ and $\dot{V}_{w,h,max}$ are the lower and upper bounds of the circulating hot water flow rates, respectively; $\dot{V}_{w,c,min}$ and $\dot{V}_{w,c,max}$ are the lower and upper bounds of the circulating cold water flow rates, respectively. The water will be turned into ice when passing through the evaporator if the circulating cold water flow rate smaller than $\dot{V}_{w,c,min}$. The compressor discharge pressure will increase beyond the upper limit if the circulating hot water flow rate smaller than $\dot{V}_{w,h,min}$. The thermal stratification in a thermal storage tank will be destroyed if the circulating hot or cold water flow rate larger than upper bounds of circulating hot or cold water flow rates.

The outlet water temperatures of thermal storage tanks should meet the requirements for the heating and cooling supply, which can be described as follows:

$$t_{h,ini} \leq t_{h,o} \leq t_{h,req} \quad (16)$$
$$t_{c,ini} \leq t_{c,o} \leq t_{c,req} \quad (17)$$

Where $t_{h,ini}$ and $t_{c,ini}$ are the initial water temperatures in tanks, $t_{h,req}$ and $t_{c,req}$ are the required water temperature for heating and cooling supply.

Consequently, for single-objective dynamic optimization, the objective is to maximize the transient total COP of the coupled thermal storage systems as follows.

$$\text{Max} \quad COP_{tot,t} = f\left(f, A_{th}, \dot{V}_{w,c}, \dot{V}_{w,h}, \mathrm{t_{h,o}}, \mathrm{t_{c,o}}\right) \quad (18)$$

For multi-objective dynamic optimization, the three objectives are to maximize the transient total COP, transient cooling capacity $\dot{Q}_{clg}$ and transient heating capacity $\dot{Q}_{htg}$ as follows.

$$\begin{aligned} &\text{Max } COP_{tot,t} = f\left(f, A_{th}, \dot{V}_{w,c}, \dot{V}_{w,h}, \mathrm{t_{h,o}}, \mathrm{t_{c,o}}\right) \\ &\text{Max } \dot{Q}_{clg} = f\left(f, A_{th}, \dot{V}_{w,c}, \dot{V}_{w,h}, \mathrm{t_{h,o}}, \mathrm{t_{c,o}}\right) \\ &\text{Max } \dot{Q}_{htg} = f\left(f, A_{th}, \dot{V}_{w,c}, \dot{V}_{w,h}, \mathrm{t_{h,o}}, \mathrm{t_{c,o}}\right) \end{aligned} \quad (19)$$

They are all subject to:

$$\begin{aligned} f_{min} &< f < f_{max} \\ d_{th,min} &< d_{th} < d_{th,max} \\ \dot{V}_{w,h,min} &< \dot{V}_{w,h} < \dot{V}_{w,h,max} \\ \dot{V}_{w,c,min} &< \dot{V}_{w,c} < \dot{V}_{w,c,max} \\ t_{h,ini} &\leq t_{h,o} \leq t_{h,req} \\ t_{c,ini} &\leq t_{c,o} \leq t_{c,req} \end{aligned}$$

3.3 Dynamic optimization strategy

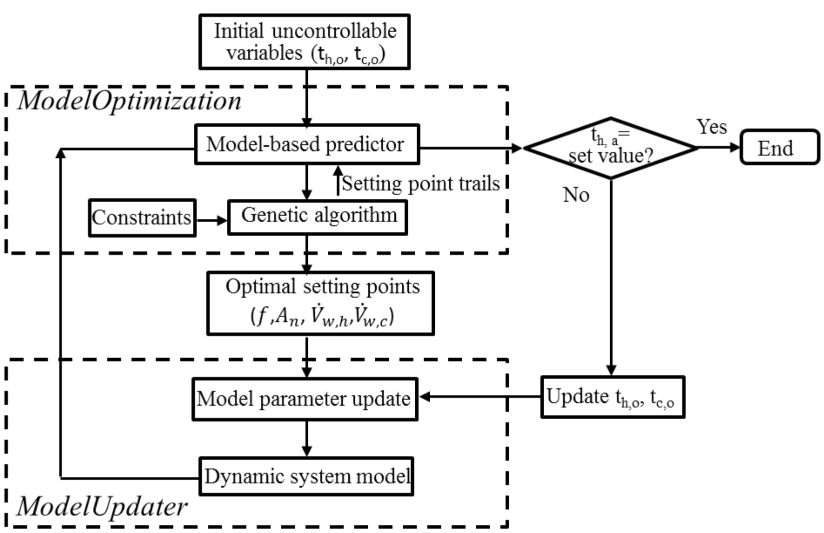

Figure 3: Flow chart of dynamic optimization strategy for energy charging

In order to solve the optimization problem of energy charging, a model-based optimization strategy by GA (Genetic algorithm) was developed. The strategy mainly consists of two modules: *ModelUpdater* and *ModelOptimization* as illustrated in Figure 3. In the *ModelUpdater* module, parameters of the system model was updated every period of time by the transient data of the uncontrolled variables and the optimal setting points, which were determined by *ModelOptimization* module. In the *ModelOptimization* module, the updated model from *ModelUpdater* is applied to predict the transient performances of the coupled system within the constraints. Genetic algorithm is employed to optimize the transient total COP by adjusting the solution f, d_{th}, $\dot{V}_{w,h}$ and $\dot{V}_{w,c}$ setting points within the feasible range. After a number of trails, the optimal setting point, f, d_{th}, $\dot{V}_{w,h}$ and $\dot{V}_{w,c}$, can be determined and configured as the control setting points in the next updating period, and then the transient uncontrollable variables could be updated, until the average water temperature, $t_{h,a}$, in hot tank reaches the set value and the energy charging process ended.

4. RESULTS AND DISCUSSIONS

4.1 Optimal Control Strategy for Energy Charging

Using the proposed model-based optimization strategy, a dynamic optimal control strategy was developed for energy charging of such coupled system. Table 1 and Table 2 illustrate the single-objective dynamic optimal control strategy and multi-objective dynamic optimal control strategy respectively, in which the optimal control parameters of f, A_{th}, $\dot{V}_{w,h}$ and $\dot{V}_{w,c}$ were determined by GA based on the outlet water temperatures of hot and cold storage tanks. It is found that the coordinative optimization of these four control parameters can be achieved by genetic algorithm based on Modelica-based modeling of dynamic system in the present study, and the four control parameters are variable during energy charging.

Table 1: Single-objective dynamic optimal control strategy for energy storage

Stage No.	Time period (s)	f (Hz)	A_{th} (mm)	$\dot{V}_{w,c}$ (m^3/h)	$\dot{V}_{w,h}$ (m^3/h)
1	0 - 2005	41	0.373	0.200	0.100
2	2005 – 3775	47	0.387	0.411	0.279
3	3775 - 5200	45	0.384	0.285	0.202

Table 2: Multi-objective dynamic optimal control strategy for energy storage

Stage No.	Time period (s)	f (Hz)	A_{th} (mm)	$\dot{V}_{w,c}$ (m^3/h)	$\dot{V}_{w,h}$ (m^3/h)
1	0 - 1695	40	0.397	0.350	0.400
2	1695 - 3390	40	0.385	0.347	0.408
3	3390 - 5200	40	0.403	0.348	0.359

4.2 Comparisons of System Performances during Energy Charging by Three Control Strategies

The developed model-based optimal control strategy was implemented into the experimental system for energy charging. Figure 5 presents the comparisons in the transient total COPs of the coupled system using these three control strategies. With the constant control parameters by the control strategy 1, the transient total COPs remained relatively lower through the energy charging process, and dropped quickly in the second half of charging process. It can be found that using the variable control parameters in dynamic optimal control strategy 3, the transient total COPs remained relatively high through the energy charging process, especially during the first stage of energy charging, which resulted in a short energy charging time and thus the relatively low overall energy consumption, as shown in Fig. 5. The control strategy 3 is clearly superior to the control strategies 1 and 2, because the transient COPs always stay optimal through during energy charging by dynamically adjusting the control parameters based on the multi-objective dynamic optimization strategy proposed in this study.

By the three control strategies, the overall system performances (COP_{ov}, Q_{clg}, Q_{htg}, W) were calculated using Eqs. (7) to (10), and compared as shown in Figure 6. Using the model-based dynamic optimal control strategy 3, the overall system COP during energy charging can be increased by 35.4%, the energy consumptions can be saved by 18.5%, and the charging time is shorter, compared with Strategy 1 using constant control parameters. The overall cooling capacity obtained by strategy 3 is slightly higher than those obtained by strategy 2, while the total power input of system is lower than that by strategy 2 and the charging time by strategy 3 is shorter than that by strategy 2. Using control strategy 2 or control strategy 3, the overall COP of the coupled system is higher than that using control strategy 1, because the transient COPs can stay optimal through during energy charging by dynamically adjusting the control parameters.

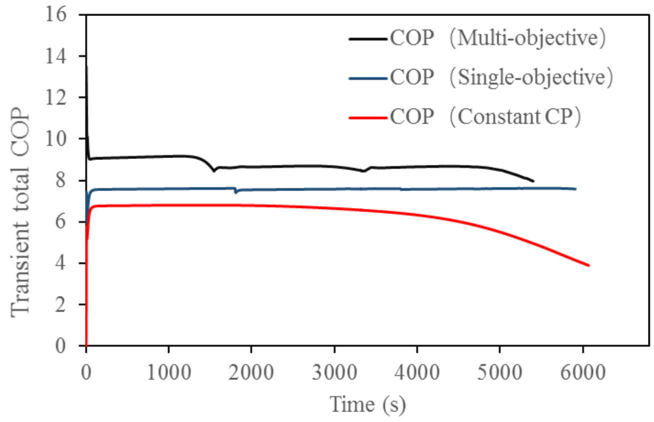

Figure 4: Comparison of the transient total COPs during energy charging process

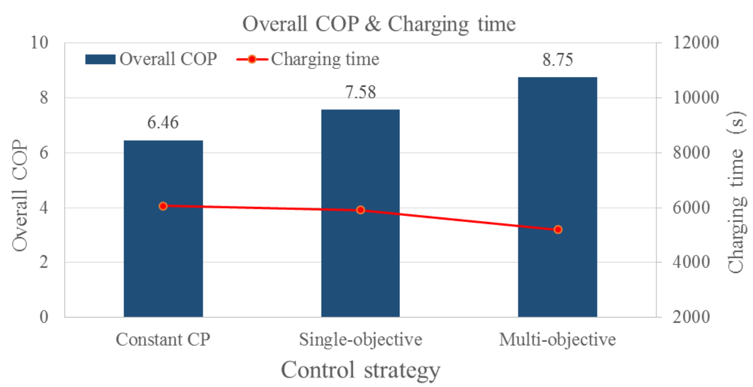

Figure 5: Comparison of overall COPs and charging time

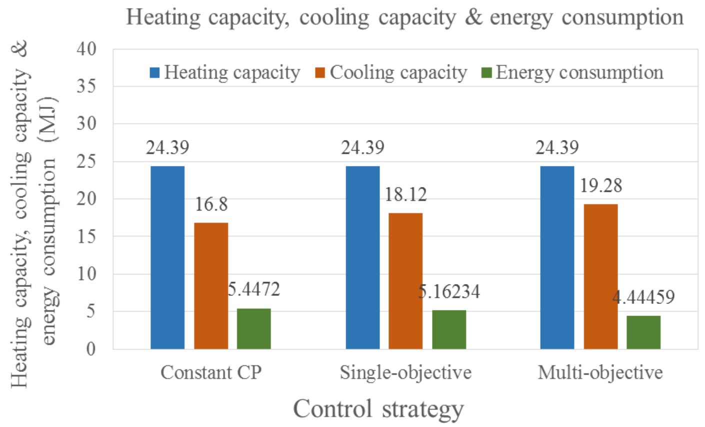

Figure 6: Comparison of overall cooling & heating capacities and power consumptions

5. SUMMARY

This paper proposed a model-based dynamic optimization strategy for energy charging of hot and cold storage using a dual-mode transcritical CO_2 heat pump. To maximize the overall performances of the coupled system during energy charging, the single-objective and multi-objective function was established. Model-based dynamic optimization strategy by genetic algorithm was proposed to obtain the optimal setting points, namely compressor frequency, ejector throat area, circulating hot and cold water flow rates, to maximize the transient total system performances during energy charging. Using the outlet water temperatures of thermal tanks as indicators, a dynamic optimal control strategy for energy charging of both hot and cold storages using a CO_2 heat pump was developed and implemented into an experimental system. The coordinative optimization of multiple control parameters can be achieved for optimizing charging of hot and cold storages by genetic algorithm based on Modelica-based modeling of dynamic system. The transient COPs and the overall performances of the coupled system using the three control strategy were compared. It can be found that by multi-objective dynamic optimal control strategy, the overall performances during the charging process can be increased, the energy consumptions and the charging time can be saved significantly

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

A	area	(mm^2)
COP	coefficient of performance	(-)
Cp	specific heat at constant pressure	(J/kg/K)
d	diameter	(mm)
f	compressor frequency	(Hz)
$\dot{m}$	mass flow rate	(kg/s)
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)

Subscript

c	cold, cold tank
clg	cooling
comp	compressor
evap	evaporator
h	hot, hot tank
htg	heating
I	inlet
O	outlet
ov	overall
th	throat
tot	total
w	water

REFERENCES

Blarke, M. B., Yazawa,K. , Shakouri, A., Carmo, C. (2012). Thermal battery with CO_2 compression heat pump: techno-economic optimization of a high-efficiency smart grid option for buildings, Energy and Buildings, 50:128-138

Calabrese,N., Mastrullo, R., Mauro, A. W., Rovella, P., Tammaro, M. (2015). Performance analysis of a rooftop, air-to-air heat pump working with CO2, Applied Thermal Engineering, 75:1046-1054

Jensen, L. H., Holten, A., Blarke, M. B., Groll, E. A., Shakouri, A., Yazawa, K. (2013). Dynamic analysis of a dual-mode CO_2 heat pump with both hot and cold thermal storage, Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition, San Diego, California, USA, IMECE2013-62894
Liu, F., Li, Y., Groll, E. A. (2012a). Performance enhancement of CO2 air conditioner with a controllable ejector, Int. J. of Refrigeration, 35(6) 1604-1616
Liu, F., Groll, E. A., Li, D. (2012b), Investigation on performance of variable geometry ejectors for CO2 refrigeration cycles, Energy, 45(1):829-839
Liu, F., Groll, E. A., Ren, J. (2016). Comprehensive experimental performance analyses of an ejector expansion transcritical CO_2 system, Applied Thermal Engineering, 98: 1061–1069
Liu, F., Zhu, W., Cai, Y., Groll, E. A., Ren, J. , Lei, Y. (2017a). Experimental performance study on a dual-mode CO_2 heat pump system with thermal storage, Applied Thermal Engineering, 115: 393–405
Liu, F., Zhu, W., Zhao, J., Ren, J. Groll, E. A., Cai, Y. (2017b). A new method for optimal control of a dual-mode CO_2 heat pump with thermal storage, Applied Thermal Engineering, 125: 1123-1132
Liu, F., Zhu, W., Zhao, J. (2018). Model-based dynamic optimal control of a CO2 heat pump coupled with hot and cold thermal storages, Applied Thermal Engineering 128:1116-1125
TLK-Thermo GmbH. TIL-model library for components of thermal system; 2017
Wang, T., Dharkar, S., Kurtulus, O., Groll, E. A., Yazawa, K. (2014). Experimental study of a CO2 thermal battery for simultaneous cooling and heating applications, Proceedings of 15th Int. Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, R2701

ACKNOWLEDGEMENT

The financial supports from the Natural Science Foundation of Shanghai in China (Grant No. 15ZR1417700), the Program for Professor of Special Appointment (Eastern Scholar) supported by Shanghai Institutions of Higher Learning (2013-66), and "Shuguang program" supported by Shanghai Education Development Foundation and Shanghai Municipal Education Commission in China (14SG50) are gratefully acknowledged.