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A simplified model to study the location impact of latent thermal energy storage in building cooling heating and power system

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ABSTRACT

Introducing the thermal energy storage (TES) equipment into the building cooling heating and power (BCHP) system proves to be an effective way to improve the part load performance of the whole system and save the primary energy consumption. The location of TES in BCHP has a great impact on the thermal performance of the whole system. In this paper, a simplified model of TES-BCHP system composed of a gas turbine, an absorption chiller/an absorption heat pump, and TES equipment with phase change materials (PCM) is presented. In order to minimize the primary energy consumption, the performances of BCHP systems with different PCM-TES locations (upstream and downstream) are analyzed and compared, for a typical hotel and an office building respectively. Moreover, the influence of the thermal performance of PCM-TES equipment on the energy saving effect of the whole system is investigated. The results confirm that PCM-TES can improve the energy efficiency and reduce the installed capacities of energy supply equipment, and that the optimal TES location in BCHP highly depends on the thermal performance of the TES equipment and the user load characteristics. It also indicates that: 1) the primary energy saving ratio of PCM-TES-BCHP increases with increasing NTU of TES; 2) for the studied cases, downstream TES location becomes more preferable when user loads fluctuate greatly; 3) only downstream TES can reduce the installed capacities of absorption chiller/absorption heat pump. This work can provide guidance for PCM-TES-BCHP system design.

1. Introduction

With the rapid modernization and industrialization, energy saving and environment protection have been becoming increasingly important global issues during recent years [1]. Buildings account for 20–40% of the total energy consumption, and greenhouse gas emissions [2,3]. Meanwhile, increasing demand for cooling and heating power in buildings calls for resurveying traditional energy production [4]. Building cooling heating and power (BCHP) is a novel kind of building energy supply system which can meet users' different load demands simultaneously with a single primary energy [5,6]. Compared to traditional separated generation system, BCHP systems show high energy efficiency, low pollution emission and good economic benefit [7–9]. In recent years, its application drew a growing attention. However, the energy supply units in a BCHP system show poor thermal performance under part load working conditions, due to the non-synchronized and fluctuating thermal and electrical demands [10]. Thus accurate feasibility evaluation and rational match between energy supply and demands are necessary for the realization of advantages of BCHP system [11]. Thermal energy storage (TES) transfers heat to storage media during the charging period, and releases it at a later stage during the discharging step [12]. It can be usefully applied in solar energy projects [13], industrial processes [14], heating ventilation and air conditioning (HVAC) systems [15]. Introducing TES equipment into BCHP systems proves to be an effective way to improve the part load performance of the whole system and saving the primary energy consumption [16].

Sensible and latent heat storage are two typical forms of TES, which rely on temperature and phase change respectively [17]. Sensible heat storage is well-documented and widely used in co-generation or tri-generation systems [18]. Khan [19] combined the storage of chilled water with a CHP system and fund it could offer a better economic benefit for co-generation. Bogdan [20] proposed a similar study and concluded that the introduction of the district sensible heat accumulator might substantially improve

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Nomenclature

c_p	specific heat (kJ kg^{-1} K^{-1})
C	cooling power (kW)
E	electrical power (kW)
H	heating power (kW)
Q	heat energy capacity (kW)
m	mass flow rate (kg s^{-1})
T/t	temperature (K/°C)
τ	time (s)
η	electricity generation efficiency

Subscripts

a	ambient
c	charge
con	condensation
d	discharge
e	exhaust air
eva	evaporation
gen	generation
$grid$	power grid
i	inlet
m	phase change material
o	outlet
r	rated condition
w	water

Abbreviations

AC	absorption chiller
AHP	absorption heat pump
BCHP	building cooling heating and power
COP	coefficient of performance
FEL	following electrical load
FTL	following thermal load
GT	gas turbine
IC	installed capacity
ICRR	installed capacity reduction ratio
NG	natural gas
NTU	number of transfer units
PCM	phase change material
PEC	primary energy consumption
PESR	primary energy saving ratio
TES	thermal energy storage

economic performance of the co-generation plant when electricity prices were governed by the dual-time tariff system, with significant differences between day and night time tariffs. Campos [21] proposed three approaches for hot water storage tank modeling in co-generation system and found that the technology and its modeling had a great influence on the simulation results. Bailey [22] used a water tank in the co-generation system and obtained the optimal installed capacity of equipment under complete mixing assumption for the sensible TES. Katulic [23] proposed a novel method to find the optimal daily heat storage tank capacity for a co-generation power plant. Fu [24] built the dynamic model for stratified water storage and investigated its energy saving effect on tri-generation system through experiment.

Compared to sensible heat storage, latent heat storage with phase change materials (PCMs) was of relatively high energy storage density, which makes them increasingly attractive for applications [25]. Pitié [26] presented the potential usage of PCM particales for high temperature energy capture and storage in industry fields through a circulating fluidized bed. Zhang [27] briefly reviewed the TES development, with special emphasis on the important applications of PCMs in both solar energy projects and waste heat recovery from industrial processes. Zeng [28] and Pomianowski [29] integrated PCMs with envelopes and optimized the thermophysical properties, in order to improve the indoor thermal comfort and reduce the energy consumption for passive buildings. Moreno [30] and Real [31] applied PCM-TES to HVAC systems and found that the PCM tank can effectively shift the cooling load and increase the overall efficiency of a heat pump system for space cooling.

However, even though PCM-TES application in BCHP system has a great potential for energy saving, relevant researches are not enough [16]. Zhang [32] proposed a new method to pre-estimate the feasibility of TES-BCHP system before design of practical systems, under ideal assumption that there is no irreversible loss during the heat transfer processes for the TES equipment. Chen [33] and Xiong [34] obtained the theoretically optimal phase change temperatures of PCM-TES-BCHP system for specific cases. Nevertheless, few researchers studied the system arrangement design of PCM-TES-BCHP, especially the PCM-TES equipment location in a BCHP system, even though the PCM-TES location had a great influence on the performance of the whole system. Furthermore, compared to traditional separated generation system, the energy saving effect of PCM-TES-BCHP system highly depends on the thermal performance of the PCM-TES equipment.

Therefore, for the system design, how to determine the optimal PCM-TES location in a BCHP system, and how the heat transfer performance of PCM-TES equipment can impact the energy consumption of the whole system, since there is no ideal TES equipment in practical applications [32], are important but unsolved problems. In this paper, considering the practical hourly fluctuating user loads, a simplified model of PCM-TES-BCHP system is established to investigate the influence of different TES locations (upstream and downstream) on the primary energy consumption of the whole system. Moreover, the impact of NTU of the PCM-TES equipment is analyzed for a typical hotel and an office building respectively. This work can provide guidance for PCM-TES-BCHP system design.

2. System model

A typical BCHP system consists of five basic elements: the prime mover, electricity generator, heat recovery system, thermally activated equipment and the management and control system [7]. The typical BCHP system is shown in Fig. 1. The gas turbine is driven by natural gas and the mechanical energy is further changed into electricity power. At the same time, the absorption chiller or absorption heat pump utilize the exhaust gas to produce cool or hot water, in summer and winter respectively. To improve the part load performance of the whole system, TES equipment is added and it can be placed to the absorption chiller/absorption heat pump uptream or downstream. For the operation strategy, some researches showed that following thermal load (FTL) was more energy-saving than following electrical load (FEL) for TES-BCHP systems [35,36]. Hence, the system gives priority to meet cooling or heating demand, and electricity can be bought from the power grid to compensate for the insufficient electrical load.