Effective design and operation strategy of renewable cooling and heating system for building application in hot-humid climate

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Abstract

The utilization of renewable energy sources is commonly constrained by the building form and the site environment particularly in a densely-populated city which limits the space available to install the respective facilities. The hybrid use of solar and geothermal energy helps improve the situation as the roof and the ground can be fully utilized. A renewable cooling and heating system (RCHS) was therefore investigated based on this approach when applied to a three-storey office building in sub-tropical climate. Solar energy was used in absorption cooling and water heating while ground source was utilized by a high-temperature chiller for radiant cooling. Appropriate control and operation schemes were adopted for the ground-coupled radiant cooling system according to the ambient conditions in order to minimize the system energy demand. By performing dynamic system simulations using TRNSYS, the year-round performances of RCHS were thoroughly evaluated under different design factors including radiant panel type, ground thermal conductivity, borehole length and water heating demand. It was found that the RCHS was effective to tackle the high cooling demand for building in the hot-humid climate, with 44.4% annual primary energy saving against the conventional system.

1. Introduction

Renewable energy becomes an essential player for climate change mitigation (IPCC, 2011). In a modern city, buildings contribute to the majority of the energy demand. In particular the heating, ventilation and air-conditioning (HVAC) as well as the water heating systems account for over half of the building energy use. Hence, the adoption of renewable cooling and heating in buildings is essential to relieve the climate change. To achieve this, solar thermal energy has been advocated for heating and cooling in the recent decade in regions with mild summer and cold winter. The various solar cooling and heating technologies for use in buildings were outlined (Eicker, 2003, 2009; Henning, 2004). A novel building-integrated solar cooling and heating system was investigated for use in Tianjin with the average cooling capacity reaching 87 W/m² in summer (Cui et al., 2015). Analysis was made on solar cooling systems installed in different climatic conditions (Eicker et al., 2015). It was found that the primary energy saving was between 30 to 79%, and to achieve a payback period of 10 years the investment cost had to be reduced by 30 to 70%. A multi-objective design optimization methodology was proposed and applied to an integrated solar absorption cooling and heating system for use in an office building in various cities of USA in terms of the economic, energy and environmental merits. Meanwhile, the use of ground-source heat pump (GSHP) system has been popular for space cooling and heating in Europe and USA. Design and installation guidelines for the GSHP systems were proposed (CIBSE, 2013; Kavanaugh and Rafferty, 2014). The application of GSHP systems for cooling and heating in a district level of different European countries was investigated (De Carli et al., 2014) with the primary energy saving between 50 to 80%. A GSHP system with horizontal ground heat exchangers was tested and used to validate a simulation model in TRNSYS for system control optimization study (Safa et al., 2015) with an energy saving of 28.2% achieved.

In recent years, the European Technology Platform on Renewable Heating and Cooling aims at decarbonization of the energy sector through the effective deployment of renewable energy sources for heating and cooling (2020–2030 Common Vision for the Renewable Heating and Cooling Sector in Europe, 2011; Common Implementation Roadmap for Renewable Heating and Cooling Technologies, 2014). To achieve the goal, it is expected that the involvement of more than one renewable source is necessary in order to maximize the provision of renewable energy for generating the approach of “renewable heating and cooling”. In the urban areas, the combined use of solar energy and geothermal
energy is worth being promoted, particularly to the multi-storey buildings with severe space constraints in which usually only the roof and the ground are available to install the renewable energy systems. Indeed, from a previous study by the authors (Fong et al., 2010a), the use of the roof for installing the solar collectors could only manage to serve the cooling load for one office floor when applied to sub-tropical climate. Hence, full utilization of both the roof and the ground within the building site is important in this circumstance.

The common design for the combined use of solar thermal energy and geothermal source employs solar heat to relieve the load deficit in the ground when applied to heating-dominated regions. This is directed to the development of solar-assisted ground source heat pump (SAGSHP) systems, which were found with tangible energy merit in space heating and water heating compared to the conventional provision. The performance of a SAGSHP system for use in a greenhouse in Turkey was experimentally investigated (Ozgener and Hepbasli, 2005). It was found that auxiliary heating source was required to maintain the greenhouse temperature in winter. The combined use of GSHP and SAGSHP systems in an office building in Tianjin was analyzed by dynamic simulation using TRNSYS (Wang et al., 2012). An energy saving of 32% could be achieved. A laboratory scale SAGSHP installed in Dalian was studied experimentally under different operating modes (Dai et al., 2015). It was found that the connection of the solar collectors in series with the ground heat exchangers performed better as reflected by a smaller soil temperature drop after 10 years of operation. Optimization of a SAGSHP system was also made by using two optimization methods (Verma and Murugesan, 2014). The optimum coefficient of performance was found to be 4.23. The application of SAGSHP systems in 19 European cities were investigated (Girard et al., 2015). The average system coefficient of performance ranged from 4.4 to 5.8 while it was between 4.3 and 5.1 for conventional GSHP systems. The payback periods varied from 8.5 to 23 years with better performance in southern Europe. Performance comparison of a SAGSHP system was also made by using R22 and R744 as refrigerants for the heat pump. It was found that the energy performance of the heat pump was 28.8% higher with the use of R22 and that the heating capacity of the heat pump with R22 was 10% higher than that based on R744. Meanwhile, the solar collector efficiency was 4.1% higher with the employment of R744.

Besides the common design of SAGSHP system as mentioned before, the ground heat exchangers can be coupled with the cooling tower in a solar cooling system to enhance the system efficiency. A case study was made in Spain in which cooled groundwater at around 22 °C from one ground well was drawn to assist the cooling tower in cooling the condenser water supplied to a solar-driven absorption chiller (Rosiek and Batlles, 2012). The warmed groundwater was discharged back to the ground through a solar-driven absorption chiller (Rosiek and Batlles, 2012). The warmed groundwater was discharged back to the ground through another ground well. It was found that 31% of the electric demand from the cooling tower could be saved and that the water consumption from the cooling tower reduced by 116 m³.

However, in a hot and humid city in which the annual air-conditioning load is cooling-dominated, such kind of common solar-assisted ground-source system design is considered inappropriate. In particular, air-conditioning is indispensable in office buildings throughout the year, whereas heating demand is comparatively minimal. Practical considerations like architectural geometry, site environment and space availability of the building also substantially affect the amount of renewable energy that can be harnessed. As a result, this study is to devise a more effective design and operation strategy for the renewable cooling and heating system (RCHS) utilizing both solar energy and ground source, with emphasis on serving multi-storey building under hot-humid climate.

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**Nomenclature**

- **CO**$_{\text{Ab}}$ coefficient of performance of the absorption chiller
- **CO**$_{\text{HTVCC}}$ coefficient of performance of the high-temperature vapor-compression chiller
- **E**$_{\text{pr,ac}}$ primary energy consumption of electricity demand (kWh)
- **E**$_{\text{pr,aux}}$ primary energy consumption of auxiliary heating demand (kWh)
- **R**$_{\text{Hzone}}$ zone relative humidity (%)
- **R**$_{\text{Hzone,avg}}$ year-round-averaged zone relative humidity (%)
- **S**$_{\text{f}}$ solar fraction
- **T$_{\text{bf,out,}}$max** maximum borefield fluid leaving temperature (°C)
- **T$_{\text{zone}}$** zone temperature (°C)
- **T$_{\text{zone,avg}}$** year-round-averaged zone temperature (°C)
- **te**$_{\text{pr}}$ total primary energy consumption of the entire system (kWh)

**Abbreviations**

- BWP borefield water pump
- CC chilled ceiling
- CWP cooling water pump
- EWP chilled water pump
- FCV free-cooling valve
- GSHP ground-source heat pump
- GHE ground heat exchanger borefield
- HVAC heating, ventilation and air-conditioning
- HHWP hot water pump
- PCR passive chilled beams
- RCHS renewable cooling and heating system
- RH relative humidity
- RPP radiant panel pump
- RPV radiant panel valve
- RWP regenerative water pump
- SAF supply air fan
- SAGSHP solar-assisted ground-source heat pump
- SAV supply air valve
- WCVCC water-cooled vapor-compression chiller
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