Energy and Buildings 49 (2012) 226–234

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Cost-optimal design of an ice-storage cooling system using mixed-integer linear programming techniques under various electricity tariff schemes

Jan Vetterli, Michael Benz*

ETH Zurich, Department of Mechanical Engineering, Sonneggstrasse 3, 8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 25 October 2011
Accepted 7 February 2012

Keywords:
Commercial building
Vapor compression system
Ice storage
Optimal control
MILP
Optimal design
Variable electricity rates
Ancillary services
Control reserve power

ABSTRACT

The increasing costs of energy encourage the development of cost-efficient building cooling systems. Based on a thermal model of a commercial building and its cooling system, the cost-optimal design of a vapor compression system and an incorporated ice storage is determined. Special emphasis is placed on the refrigeration machine and its interaction with the thermal capacity of the building. The implementation as a mixed integer linear programming problem allows the evaluation of the optimal system operation for an entire year in approximately 50 s on a desktop computer. Based on these results, the design of the optimal systems is determined for various electricity tariff schemes. Therefore, a model for variable electricity rates is introduced including costs for control reserve power. Compared to the cooling system without storage, the system including an optimally designed ice storage achieves lifetime cost reductions of approximately 8% by reducing the operational costs and the investment costs for the downsized refrigeration machine.

1. Introduction

The growing number of power plants based on renewable energy with their intermittent production asks for new control policies of the future smart power grid. Demand-side management using financial incentives is a promising solution to reduce the usage of expensive control reserve power and to prevent an overload of the power grid.

Buildings in general, and particularly their cooling systems, are responsible for high peak loads. Their associated costs of operation account for a considerable share of the total lifetime costs. As a consequence, their operating costs are highly sensitive to increasing energy prices. The integration of thermal energy storages, such as ice storage systems, is a promising solution to reduce the operating costs and the peak power consumption.

Several previous studies have already made important contributions to the optimal design and control of cooling systems with ice storage. In [1], Kintner-Meyer and Emery presented an optimal design for a cooling system including cold storage facilities. Their model-based operating strategy includes a precooling of the building structure. The optimal control is based on a nonlinear model. In [2], MacPhee and Dincer provide a good introduction to the topic of thermal energy storage. Their focus lies on the performance assessment of different ice storage systems in terms of energy efficiency. In [3], Ma et al. present a model predictive control approach for a university cooling system and estimate the resulting electricity cost reductions at 24.5%. In [4], Henze et al. compare four different control strategies using optimal control strategies as a benchmark. In [5], Lee et al. focus on the optimal design of an ice storage system using particle swarm algorithms. Their objective is to determine the optimal system configuration while minimizing the life cycle costs and CO_2 emissions. In [6], Stuhlenmiller and Koenigsdorff showed the optimal design for providing the grid with control reserve power.

In this study special attention is paid to the thermal modeling of the building, the ice storage system and the refrigeration machine. Fig. 1 shows the system configuration investigated. Due to the linear modeling approach of the total cooling system including the thermal capacity of the building structure, the optimal design and control problem can be solved for an entire year. The costs are then extrapolated to the lifetime of the cooling system.

The paper is structured as follows. First, the thermal model of the building are presented, including all of the important heat gains, the vapor compression system (VCS), and the ice storage system (ISS). The simplifications introduced to linearize the model are shown next. Finally, the model is used to derive optimal designs under various electric tariff schemes.

* Corresponding author. Tel.: +41 632 59 26; fax: +41 44 632 11 39.
E-mail address: mbenz@alumni.ethz.ch (M. Benz).

0378-7788/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2012.02.012

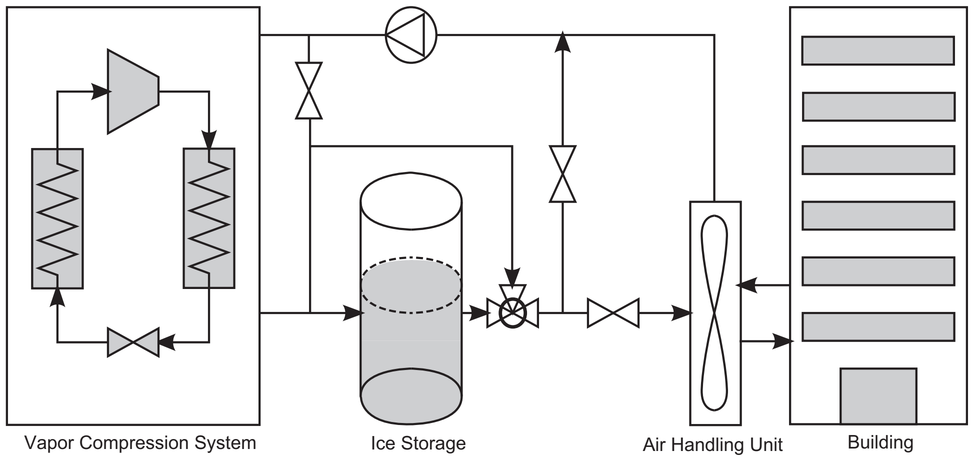

Fig. 1. Cooling system schematics.

2. Model development

2.1. Building model

The building analyzed in this paper is a twelve-floor office building. Table 1 shows its dimensions and relevant parameters. The dynamic behavior of the building is modeled by a lumped parameter approach. The energy balance of the building represented by a reference zone with temperature T_b is given by

$$C_b \cdot \dot{T}_b = \frac{1}{R_{b2a}} \cdot (T_a - T_b) + \dot{Q}_{tot} \quad (1)$$

where T_a is the ambient temperature, C_b the thermal capacity, and R_{b2a} the thermal resistance between the reference zone and the ambient node. The heat gains introduced by solar radiation $\dot{Q}_{sol}$, occupants $\dot{Q}_{occ}$, and electrical equipment including lighting $\dot{Q}_{eq}$ act as disturbances to the building system. The cooling power $\dot{Q}_c$ and the air ventilation $\dot{Q}_v$ are additional controllable heat or cooling gains, respectively. The total heat gain to the building $\dot{Q}_{tot}$ is then calculated as the sum of these heat gains

$$\dot{Q}_{tot} = \dot{Q}_{sol} + \dot{Q}_{occ} + \dot{Q}_{eq} + \dot{Q}_v - \dot{Q}_c \quad (2)$$

The solar radiation on each glazing surface is calculated using the sky model proposed by [7].

The occupancy heat gain is derived by the multiplication of the sensible heat per person $\dot{q}_{occ}$, the nominal number of persons in the building $n_{p,nom}$ and the so-called simultaneity factor f_{occ}

$$\dot{Q}_{occ} = \dot{q}_{occ} \cdot n_{p,nom} \cdot f_{occ}. \quad (3)$$

The simultaneity factor is a function of time which relates the nominal number of people in the building to the number of people actually present in the building. The heat gain or heat loss due to ventilation is calculated according to the following equation as

$$\dot{Q}_v = \dot{V}_v \cdot \rho_{air} \cdot c_{p,air} \cdot (1 - \eta_v) \cdot (T_a - T_b) \quad (4)$$

where $\dot{V}_v$ is the ventilation volume flow, ρ_{air} the air density and $c_{p,air}$ the specific enthalpy of air. Since the building is equipped with a heat recuperation system with an efficiency η_v, the ventilation heat gain can be reduced by 90%. The air flow is specified to be 30 m^3 of fresh air per person per hour. The ventilation air flow is derived as

$$\dot{V}_v = 30\,m^3/h \cdot n_{p,nom} \cdot f_{occ}. \quad (5)$$

Furthermore, for hygienic reasons the minimal air change rate is set to 0.3 per hour. The heat gain of the office equipment such as computers and printers is calculated by multiplying the building floor area A_b with the specific equipment heat gain $\dot{q}_{eq}$ and the simultaneity factor of equipment f_{eq}

$$\dot{Q}_{eq} = A_b \cdot \dot{q}_{eq} \cdot f_{eq}. \quad (6)$$

The cooling power is the sum of the cooling power from the VCS provided directly to the building $\dot{Q}_{b,vcs}$ and the cooling power from the ISS to the building $\dot{Q}_{b,iss}$.

$$\dot{Q}_c = \dot{Q}_{b,vcs} + \dot{Q}_{b,iss} \quad (7)$$

Fig. 2 shows the various heat gains during the first week of July for the reference building used. The simultaneity factors are taken from the building design guidelines of the Swiss architects association [8].

2.2. Ice storage system

The ISS is modeled as a receiver consisting of water and ice in thermal equilibrium. A loss-free transfer of cooling energy from the

Table 1
Reference building data.

Element	Value
Building width	16 m
Building length	50 m
Number of floors	12
Number of offices per floor	34
Nominal number of occupants	907
Outside wall area	1931 m^2
Building volume	22,080 m^3
Total window area	2346 m^2
Energy transmittance window	0.35
Total heat capacity	1.75 GJ/K
Heat transfer coefficient of wall	0.5 W/K m^2
Heat conductivity of windows	2.6 kW/K

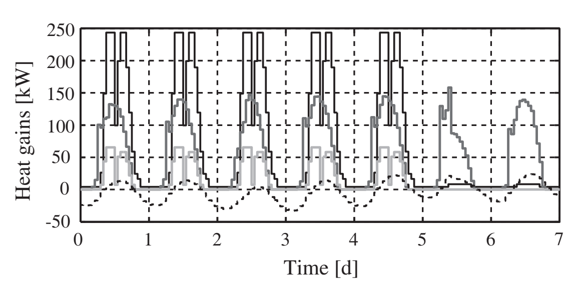

Fig. 2. The various heat gains of the reference building during the first week of July: equipment (black), solar (dark gray), occupants (light gray), and heat loss through building envelope (dotted).