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Multi-objective optimization of a building free cooling system, based on weather prediction

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ABSTRACT

The renewed Energy Performance of Building Directive and European regulations for buildings energy efficiency are becoming increasingly restrictive and moving towards near zero energy buildings. To achieve this goal, amongst others measures, a building utility system has to be carefully designed and optimized to perform efficiently and to utilize renewable energy source to greater extent. This paper is focused on the multi-objective performance optimization of buildings free cooling systems. The optimization was twofold: firstly, the energy consumption and available free cooling potential were estimated using weather forecasts, and secondly, the free cooling system operation regime was optimized to meet the required energy consumption using variable air distribution and flow control. The results of the optimization show the significant influence of such system operation control on system performance indicators.

1. Introduction

In current practices of building service systems control, system operation depends solely on the instantaneous parameters of the ambient and indoor constraints. The efficiency of the building service system can be further improved with the prediction of future building energy requirements and the optimization of system operation using intelligent system control. In the case of a free cooling system, the building energy requirements can be predicted using weather forecast, and operation can be optimized using variable air flow control. In this paper, the development and case study of such a strategy of free cooling systems is presented. The optimization is based on weather prediction of the future energy potential of ambient air. Such an operation increases the efficiency of the systems and, in the case of the free cooling system, increases the utilization of renewable energy sources.

Several studies investigated the building free cooling efficiency. Waqas and Kumar [1] investigated the performance of latent heat storage for free cooling at constant air flow rate (4 and 5 m^3/h/kg of PCM). Santamouris et al. [2] analysed the data of 214 residential buildings using night ventilation techniques. The cooling energy of night ventilation was calculated and verified with a Trnsys simulation for various amounts of constant flow rate (2, 5, 10, 20 and 30 h^{-1}). It was found that the relation between the energy contribution of night ventilation and the air flow rate is almost linear. Pfafferott et al. [3] evaluated the design of mechanical night ventilation, experimentally and numerically; the efficiency of night cooling was evaluated based on different solar and internal gains and different constant air exchange rates. Shaviv et al. [4] calculated the influence of thermal mass and night ventilation on indoor temperatures for different locations using an energy simulation model; four different constant air exchange rates (2, 5, 20 and 30 h^{-1}) were selected and simulated using weather data for four different locations with different weather. The reduction of maximum indoor temperature compared with maximum outside temperature was determined. The results show that a 3–6 °C reduction can be achieved in a heavily constructed building.

Those studies of free cooling ventilation systems were largely focused on the characteristics of system operation under various influence parameters. The studies were performed mainly experimentally and at constant parameters of system operation. A significant effect of weather constraints on cooling load reduction was shown. To further improve free cooling system operation, it is therefore mandatory to optimize the operation of system according to the building demands, also taking into account weather forecasts. A large number of published studies on the possibility of using weather prediction in building services system control can be found.

Dovrtel and Medved [5] investigated the predictive control of building free cooling system under variable regimes of operation. Gruber et al. [6] developed a predictive control algorithm that utilizes numerical optimization techniques for a linear dynamic model. The algorithm computes the set point of the flow temperature control loop of a hot water heating system in such a way

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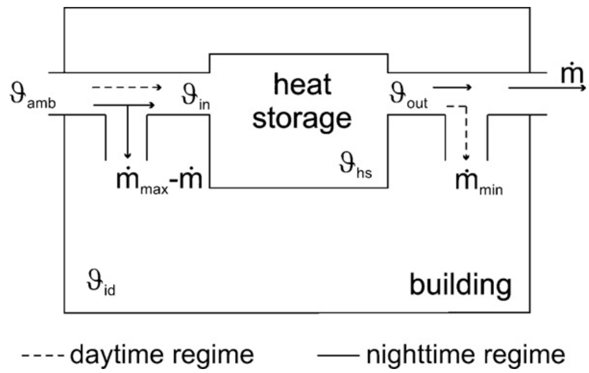

Fig. 1. Schematic of free cooling system analysed in the research.

that comfortable temperatures in the room are maintained; the objective function of optimization is used to minimize energy consumption. Henze et al. [7] investigated the cooling load shifting in commercial buildings using two different systems: pre-cooling of building structure or by using an active heat storage system utilizing ice storage; the objective function was the cost of system operation. The study showed that in commercial buildings cooling load shifting can drastically reduce the costs and peak electrical power and thus justified the use of a predictive controller. Kummert et al. [8] studied the optimal heating control of a passive commercial building. The objective function combines the comfort level and the energy consumption; the auxiliary heating system operation was optimized. It was shown that energy can be saved whilst improving the comfort level. Argiriou et al. [9] investigated a building optimal heating control using artificial neural networks. The controller included a meteorological module forecasting ambient temperature and solar radiation. The performance criterion was chosen as a trade-off between thermal comfort and energy consumption. The expected energy savings were evaluated at 15% compared to conventional controllers and peak power was also reduced. Gouda [10] investigated and tested quasi-adaptive fuzzy heating control of solar building; a neural network controller is used to control the auxiliary heating. Gwerder et al. [11] studied the control of thermally activated building systems. They integrated the building thermal response model into the energy management strategy. The building was modelled using an RC model and controlled in a way that sufficient comfort criteria were met. Oldewurtel et al. [12] developed and analysed a stochastic model of a predictive control strategy for a building climate control. The goal of the model was to select the system operation, depending on future weather constraints in order to fulfil the comfort requirements and minimize the energy costs.

Despite the number of papers studying free cooling system energy performance, there is a lack of research in the weather-predicted variable operation of such low exergy systems. Therefore, this paper will focus on this perspective of free cooling system operation and the energy performance of such systems.

2. Problem description

The free cooling system performance optimization was analysed in the case of a simple free cooling system consisting of heat storage, air ducts and a fan with variable flow rate control, shown in Fig. 1. During the summer, the system operates in two ways: night-time and day-time regime. In the night-time regime (Fig. 1 – solid line), the system intakes the ambient air and divides it into two streams: one for free cooling of the building and the other for cooling the heat storage. After cooling the heat storage, this stream is drained back to the environment. In the day-time regime, the total amount of fresh air flows through heat storage and enters the building as pre-cooled fresh air (Fig. 1 – dashed line).

Prior to the optimization of free cooling system operation, the following steps were needed:

- the daily weather forecast from local weather information centre must be acquired and corrected for the specific location using a Kalman filter. The building indoor temperature was predicted using the corrected weather forecast data and the Trnsys building thermal response numerical simulation program;
- the heat storage model was developed, including the heat transfer within the heat storage and heat losses to the surrounding;
- the free cooling process was divided into three time intervals that were analysed sequentially. The sum of intervals equals approximately 24 h.

The free cooling system performance optimization was then carried out using the variable air flow distribution to the building or to the heat storage and variable air flow rate control. The analysis and system performance was done based on a multi-objective criteria analysis.

3. Prediction of ambient and indoor air temperature

The ambient air temperature can be predicted using weather forecasts, which can be obtained from local weather information centres, in our case from the Environmental Agency of the Republic of Slovenia [13]. The weather forecast is based on ALADIN/SI model that simulates the weather in a smaller local area, using boundary and initial constraints from the IFS/APRAGE global weather model. The horizontal grid spacing of the ALADIN/SI model is 9.5 km × 9.5 km. The model calculates hourly values of air temperature, rainfall, solar radiation, relative humidity, wind speed, wind direction and cloudiness twice a day for the following 72-h period.

The weather parameters on the specific location within the forecast grid space area can significantly differ from the real value of parameters due to the forecast error and small scale effects (topography or water areas), which are important to local weather, but are not necessarily included in weather forecast model [14]. The comparison of the forecast ambient air temperature, which is the most influential parameter on the free cooling system operation, and the observed temperature shows a significant error in weather forecast accuracy (Fig. 2). One of the options to improve the weather forecast accuracy for a specific location is the use of a Kalman filter, which utilizes previous known differences between the observations and forecast.

3.1. Kalman filter

The Kalman filter theory [15,16] provides a tool for the estimation of the unknown process and correction of its systematic error by using the observation and forecast data. The discreet Kalman filter is presented in the following paragraph.

Let x_k be the vector describing the internal state of the process that describes the systematic error between observation and forecast at time k. The internal state of the process is related to the previous internal state by the system equation:

$$x_k = A_k x_{k-1} + w_k \quad (1)$$

where A_k is internal state transition matrix at time k and w_k the random noise, which has a multivariate Gaussian distribution $\mathcal{N}(\mu, \sigma^2) = \mathcal{N}_w(0, Q)$ with mean value of 0 and covariance matrix Q, affecting the system. The internal state vector x_k is related to the measurement vector z_k with the observation equation:

$$z_k = H_k x_k + v_k \quad (2)$$