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Experimental and numerical investigations of the energy efficiency of conventional air conditioning systems in cooling mode and comfort assurance in office buildings

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ABSTRACT

This paper provides a comparative study of the energy efficiency of a conventional ventilating and air conditioning (VAC) system with three configurations. This system was used to cool an experimental room in an office building in more control scenarios realised by adopting different cooled water temperatures and chiller cooling systems. In this purpose, an air–water mist cooled system for an air-cooled chiller is proposed. Depending on the components, the analysed VAC system has the following configurations: (1) air handling unit (AHU) and fan-coil units (FCUs); (2) air handling unit (AHU); and (3) heat recovery unit (HRU) and fan-coil units (FCUs). The electricity consumption weight of the equipment of each VAC system, the total energy consumption and the influence of control parameters on this consumption are analysed. The results of the experiments indicate that the optimal efficiency VAC system in office buildings includes an AHU and FCUs with an air–water mist cooled chiller and a cooled water temperature of 8 °C. For this system, a mathematical model is developed to minimise the electricity consumption by optimal control, where the consumption depends only on non-controlled parameters (solar radiation intensity and outdoor air temperature). This model is verified with actual measurements to confirm its accuracy, and a good agreement between the prediction and measurement is achieved. Additionally, the assessment of thermal comfort in the experimental office is performed based on the PMV-PPD model using the ASHRAE Thermal Comfort programme. The obtained results demonstrate that the AHU&FCUs system assures an increase in thermal comfort. Finally, a TRNSYS simulation model of energy consumption and PMV-PPD indices for the AHU&FCUs system is developed and experimentally validated.

1. Introduction

Energy is vital for the progress and development of a nation's economy. In Europe, the ownership and electricity consumption of ventilation and air conditioning in buildings has been increasing for several decades. On the other hand, people's concerns about thermal comfort and indoor environment quality (IEQ) are increasing. The main purpose of most buildings and installed ventilating and air conditioning (VAC) systems is to provide an acceptable environment that does not impair the health and performance of the occupants.

Ventilation has long been known to have a major impact on a building's indoor air quality (IAQ) and comfort [1]. Ventilation also has a very significant influence on the energy use in buildings, which represents approximately 40% of the total primary energy use in developed countries [2]. It is estimated that in those countries the energy use for ventilating and cooling residential and tertiary buildings often represents more than half of the total primary energy use and that air exchange with the outdoor environment, either by air infiltration or by proper ventilation, is one of the main aspects driving that use [3–5]. The relationship between ventilation of buildings and their energy use, however, is no simple matter, as it is dependent on a large number of variables. The influence of many of these variables has been explored individually in previous studies, such as air-flow control [6–8], heat recovery [9,10], building air tightness [11] and humidity control [12].

Recent studies have demonstrated that air conditioning (AC) systems represent between 10% and 60% of the total energy consumption of office buildings [2]. An ongoing effort to simultaneously reduce the level of energy consumption and increase the leak-proofing of buildings is strictly connected to an increasing demand for cooling during the summertime. The higher demand for cooling is caused by the need to deliver fresh air to reduce the carbon dioxide (CO_2) concentration and to lower the temperature

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and humidity to permissible levels inside buildings as determined by the quality norms for the interior environment [13,14].

Conventional AC systems, such as variable air volume (VAV), constant air volume (CAV) and fan-coil units (FCUs) air conditioning systems, supply cool air to spaces to remove thermal loads. A VAV system satisfies the health criterion and IAQ by supplying a minimum amount of fresh air based on national regulations and standards. The theory for the optimal supply air temperature in a VAV system is presented in [15]. There are three categories of AC systems that are used for comfort cooling: moveable units, fixed room air conditioners, and central systems. All three types of systems are used in both residential and public buildings, albeit to different degrees. In Europe, central systems are overwhelmingly found on non-residential buildings while most moveable units are used in dwellings. Fixed room air conditioners are used in both market sectors.

Conventional AC systems need a refrigeration plant (chiller) to produce cold water and a complex pipe network to distribute the cold water to the air conditioned spaces. Air-cooled chiller systems are commonly used in office buildings because of their flexibility. The operation of chillers usually takes up the highest proportion of the total electricity consumption of buildings [16]. The coefficient of performance (COP) of the chiller directly influences the performance of the AC system. Compared to water-cooled chillers, air-cooled chillers are regarded as energy inefficient. This is due to the head pressure control (HPC) under which the compression ratio of the condensing pressure to the evaporating pressure is kept high. The temperature of the air-cooled chiller is directly dependent on the ambient air temperature. This is of particular concern in areas with very hot weather in the summer.

To increase the performance of an air-cooled chiller, one of the best solutions is to decrease the condensation temperature. Thus, variable condensing temperature control (CTC) has been proposed as an alternative to HPC to lower the condensing temperature in air-cooled chillers [16,17]. To reduce the condensing temperature, one of the easiest ways is the application of a direct evaporative cooler in front of the condenser to cool down the outdoor air temperature before it passes over the condenser. This approach results in a decrease in the compressor power of air-cooled chillers and the COP of the system could improve by 0.034–0.067 for each degree Celsius of pre-cooling provided [18]. Zhang et al. [19] investigated an evaporative cooler filled with corrugated holed aluminium foil and presented correlations to predict the performance, pressure drop and temperature outlet of the cooler. He reported that the application of evaporative pre-coolers improves the COP of air-cooled chillers by 14.7% under the climatic conditions of Tianjin. Yu and Chan [20] simulated an air-cooled chiller equipped with a direct evaporative cooler and showed up to a 14.4% reduction in power consumption and up to a 4.6% increase in the refrigeration effect. The application of a direct evaporative cooler by injecting water on the media pad installed in front of the condenser of a window air conditioner unit was reported [21], and the COP could be improved by approximately 50% in regions with very hot weather conditions (approximately 50 °C).

Variable speed control is another approach to decreasing compressor power because the motor efficiency can be improved at lower speeds when the chiller compressor is operating under a partial load [22,23]. When a variable speed control is applied to the condenser fans, each fan can be operated at a lower speed with a large reduction in power while the condensing temperature remains at its set point.

A possibility for improving the energy performance of a VAC system is the reduction of consumed electrical energy by adequate choices of the system configuration and control parameters. Among these parameters, the cooling mode of the cooled water chiller is very important. The VAC system must be complemented with an efficient control scheme to maintain comfort under any load conditions. Efficient control will also reduce energy use by keeping the process variables (temperature, pressure, etc.) at their set points.

One the main innovative contribution of this study consists in the achievement and implementation of an air–water mist cooled system for the air-cooled chillers of different VAC systems that has significant effect on the energy performance improvement of these systems. The experimental measurements are used to develop a mathematical model to minimise the power consumption by optimal control, depending only on non-controlled parameters (solar radiation intensity and outdoor air temperature) and to validate a TRNSYS (Transient System Simulation) simulation model for energy consumption of a VAC system.

This paper provides a comparative study of the energy efficiency of a VAC system with three configurations used to cool an experimental room in an office building in control scenarios involving different cooled water temperatures and compression chiller cooling systems. For this application, an air–water mist cooled system for the air-cooled chiller is proposed. Depending on the components, the analysed VAC systems have the following configurations: (1) air handling unit (AHU) and fan-coil units (FCUs); (2) air handling unit (AHU); and (3) heat recovery unit (HRU) and fan-coil units (FCUs). During the experimental programme, the set point indoor air temperature was 25 °C, according to Standard EN 15251 [24], and the outdoor air temperature, solar radiation intensity, cooling thermal energy and electrical energy consumed by the equipment of each VAC system were measured. The electricity consumption weight on the equipment of each VAC system, the total energy consumption and the influence of control parameters on this consumption were analysed. The results of the experiments showed that the most efficient VAC system for office buildings consists of an AHU and FCUs with an air–water mist cooled chiller and a cooled water temperature of 8 °C. For this system, a mathematical model is developed to minimise the electricity consumption by optimal control, depending only on non-controlled parameters. This model is verified with actual measurements to confirm its accuracy and a good agreement between the prediction and measurement is achieved. Additionally, the assessment of thermal comfort in the experimental office is performed based on the PMV (predicted mean vote)-PPD (predicted percent dissatisfied) model using the ASHRAE Thermal Comfort programme. The obtained results demonstrated that the system with an AHU and FCUs assures an increase in thermal comfort. Finally, a simulation model in a TRNSYS programme for energy consumption and PMV–PPD indices for the AHU&FCUs system is developed and experimentally validated.

2. Description of the experimental office room

The building under consideration is an eight story office building located in Timisoara, Romania. It contains a total air conditioned floor area of 8260 m^2. The city has a continental temperate climate with four different seasons and the demand for cooling is observed between 1 May and 30 September. The cooling load was calculated for four construction solutions:

(A) Building with an upper glass quality surface (quality window coefficient $c_1 = 0.27$) with exterior shading elements (shielded window coefficient $c_2 = 0.2$).
(B) Building with an upper glass quality surface ($c_1 = 0.27$) without exterior shading elements ($c_2 = 1.0$).
(C) Building with a glass area made by a double leaf window with thick windows ($c_1 = 0.8$) and exterior shading elements ($c_2 = 0.2$).