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Evaluating and adapting low exergy systems with decentralized ventilation for tropical climates

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ABSTRACT

The use of low exergy high temperature radiant cooling in the tropics is only possible with adequate dehumidification. We analyze the adaption of a decentralized ventilation system to supply dehumidified air using models and experimental prototypes. The decentralized air supply prototype was developed and initially tested at the ETH Zurich, then installed in a building laboratory that was shipped to Singapore-ETH Centre, and it was modeled and evaluated in collaboration with the National University of Singapore. We present the findings on its performance and ability to mitigate the risk of condensation for high performance radiant cooling surfaces for buildings in the tropics from models and experiments. We show that adequate dehumidification can be achieved in the decentralized supply unit by our expanded cooling coil. Our model shows that when the supply air has a humidity ratio of 13 g/kg then sufficient mitigation of condensation on the chilled panels is achieved. Experiments in the laboratory showed supply air down to 11 g/kg, which should be sufficient, but also showed the potentially large impact of infiltration of humid outdoor air in the tropics because humidity in the space remained higher than expected, and was also very sensitive to infiltration in our models.

1. Introduction

We have embarked on collaboration between researchers based at the Swiss Federal Institute of Technology (ETH) in Zurich and the National University of Singapore. We are adapting decentralized ventilation units to support low exergy radiant cooling panels for the tropical climate using a novel building laboratory built for the Singapore-ETH Centre Future Cities Laboratory. The systems are based on the principle of low exergy design, which we have applied in projects described in the Swiss press [1–4], and in theory evaluated in the literature [5–7]. Low exergy implies an additional consideration for performance characteristics relevant to changes in entropy from the 2nd law of thermodynamics. In general, it means a better matching of temperatures across various building systems, independent of energy flows, leading to a higher overall efficiency.

The concept of exergy was invented by Rant [8] in the 1950s and was subsequently used to optimize the performance of power plants. We are interested in the application of the concept of exergy to building systems. Researchers have considered the use of the concepts of exergy, or 2nd law analysis, since the 1980s [9], but the focus on low exergy building systems began in the 1990s [10,11], which culminated in the IEA ECBCS Annex 37: Low Exergy Systems for Heating and Cooling Buildings that ran from 1999 to 2003 and produced publications detailing the use of exergy for building systems [12,13]. This was followed by the Annex 49: Low Exergy Systems for High Performance Buildings and Community Systems, which ran from 2007 to 2010 and resulted in the development of new tools for exergy analysis of buildings described in guidebook [14].

We aim to increase the understanding of the potential of low exergy building cooling systems for the hot and humid tropical climate. The system we have implemented uses a decentralized air supply system developed and studied in Zurich [15–18], which is being adapted to remove humidity for the tropics. The humidity removal is essential to eliminate the risk of condensation during the operation of the high-temperature radiant cooling panels, which is at the center of our low exergy system.

There has been some previous work on low exergy systems for cooling applications, but the majority of the work has been in the heating context. Jansen and Woudstra investigated the proper implementation of exergy equations for cold exergy applications, but the evaluation of buildings focused the final cooling demand and properly valuing its exergy content [19]. Alpuche et al. looked

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at another cooling application and did explicit exergy analysis for the system side, but this was looking at desiccant systems alone [20]. There has been a study specifically on the condensation risk of radiant panels in a system with separate ventilation [21], and it gives insight into the operation of these systems in the humid environment, but the study only looks at a model of the system considering the startup timing. It does not consider the operation of the ventilation units or experimental data. There have also been several ASHRAE publications considering humidity and the operation of radiant panels with dedicated outdoor air systems (DOAS) [22–25], which are very relevant to our system evaluation, but they do not consider the tropical context or the concept of decentralized DOAS units, which we are adapting. Finally, there is no significant work done studying decentralized ventilation units and dehumidification capacity. There are some studies looking at their performance [26,27], but these are in the Scandinavian climate and thus not relevant to our adaptation for the tropics.

We present the analysis of a new heat exchanger implementation in our decentralized air supply unit and its performance in humidity removal from the supply air along with the development and implementation in a low exergy building system laboratory in the tropics. There were bench tests of individual supply units and experimental tests of four units installed in a laboratory. Models of the dehumidified air supply were created to evaluate the risk of condensation on the radiant ceiling panels for a wide range of operating scenarios and to validate experimental results.

The analysis focuses on the hygrothermal performance of the air supply system, but it is a necessary part of the low exergy building paradigm for the tropics. The objective is to supply as much of the cooling as possible at as high of a temperature as possible, because due to properties of exergy, the higher the temperature we supply the cooling, the less exergy it takes to generate that cooling [28]. Our low exergy building system paradigm does not require an explicit exergy metric for evaluation. When designing systems with heat pumps, or even more common in the cooling case, chillers, the performance metric for the system is governed by the same basic relationship as exergy: performance is equal to the ratio of the temperature heat is transferred at to the difference between source and sink temperatures. More simply, the closer the source and sink temperatures are for a heat pump or a chiller, the higher the performance. The difference between where heat or cold is supplied to and where it is removed to defines the theoretical limit of the system coefficient of performance (COP), and also defines its minimum exergy input per unit heat supplied or removed. In this sense, we define low exergy systems as any building system that minimizes temperature-lift across the building chiller or heat pump, and using the term low exergy we do not imply a separate exergy analysis, but rather that the delivered exergy to the system, usually electricity, is minimized by facilitating the use of systems that minimize temperature-lift.

Decentralized air supply in buildings is an approach that is not widely used. Regular ventilation systems rely on centralized air handling units to condition outside air and distribute it in the building. The appeal of decentralized supply is its directness. Outside air is brought into the building through the façade over short transport distances. This implies low-pressure losses not only because of short transportation distance, but also because the total amount of air supplied is distributed among several supply units working in parallel. In centralized supply structures that follow a tree topology, throttling is required to evenly distribute the air supplied to the different terminals leading to significant pressure losses. In a decentralized system, high efficiency DC fans can be employed and fan speed can be modulated to for efficiently control supply. Splitting up one big central device in decentralized units also has spatial advantages because less ducting is required and an integration of technology in the building structure becomes possible.

There is great potential if the decentralized air supply can be successfully implemented in the tropical context. The biggest limitation to the performance of the low exergy system is the need to dehumidify the fresh air supply at a low temperature. The decentralized supply allows for a further optimization of the fresh air delivery. Not only is it separated from the cooling demand, but it can be steered to supply the ideal amount of fresh air when combined with occupancy monitoring or CO_2 control, as shown by research at ETH [15]. It also provides a direct supply of pure fresh air that can work well with new personalized ventilation systems that have been developed at NUS [29,30]. By studying the performance and characteristics of decentralized ventilation combined with radiant cooling panels we can steer toward a minimal exergy input for cooling supply, while also adding flexibility in the delivery of fresh air and good indoor air quality. Contributions of our study are performance analysis of the newly developed decentralized air supply units with multiple heat exchangers for cooling and dehumidification of air with the large latent heat load present in the tropics and investigation of the condensation risk on the cooling ceiling panel surface.

2. Materials and methods

2.1. Integrated laboratory design for Singapore

The challenge faced in Singapore is a new set of climate conditions and a radically different demand for creating a comfortable indoor climate. The objective is to adapt low exergy building systems, specifically the decentralized ventilation, for high performance in the humid tropical climate. Therefore we must consider how our systems can operate to provide cooling, and more importantly dehumidification. Our method is to evaluate the performance of low exergy systems in the tropics by first designing a laboratory to test systems, second adapting the decentralized air supply system for dehumidification, and finally creating a model to check for adequate humidity removal radiant cooling panel operation.

The laboratory design revolves around the testing of the decentralized air system and the radiant cooling. In conjunction with these systems, other building technologies can be integrated into the low exergy design as well. Central to the laboratory is the control and monitoring of the components. The decentralized air supply units must remove enough humidity to allow operation of the high-temperature radiant panels without condensation. The high levels of humidity in the tropics will cause condensation on the surface. The dew point in Singapore, the location of the design, is $25 \pm 1\,^{\circ}$C all year round, typical of the tropics and above radiant panel surface temperatures. This creates the risk of condensation, and is why the system must monitor the humidity in the space as well as potential sources of infiltration from humid outside air, such as from doors and windows. One solution is to limit operation of windows and doors, but we will also evaluate the adaptability and controllability of the system. Therefore management of the interaction between the radiant cooling and air supply will be much more crucial in the tropics. The laboratory is designed to be able to measure all aspects of system performance, including these critical fluxes of humidity in the air as well as the overall energy and exergy performance.

2.2. Decentralized air supply adaption and experimentation for the tropics

The current design of the decentralized supply unit designed for moderate climates of Mid-Europe features a single heat exchanger with sufficient heating capacity to heat up outside air from −10 to 20 °C. Standard cooling capacity is designed for conditioning air from 45 °C outside to a 24 °C supply with a water supply