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Numerical analysis and model-based control of energy recovery ventilator in HVAC system

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Abstract — In recent years, the energy conservation demand attracted much attention due to the depletion of energy resource and environmental impact by increasing energy consumption. In particular, heating, ventilation, and air-conditioning (HVAC) systems in buildings is responsible for significant portion of global energy demand. Heat or energy recovery is one of the key energy-efficient technologies, which reveals to overcome the increase of energy consumption in building without reducing the indoor air quality. However, in the conventional heat recovery system, only the sensible heat was recovered, but the latent heat was ignored. In this work, the energy recovery ventilation (ERV) model is developed with semi-permeable membrane, and the performance of sensible and latent energy subject to tropical climate conditions is investigated by both numerical and experimental methods. The 3D ERV model is comprehensively studied first by CFD simulation for analysis of several important parameters, such as the velocity, temperature, humidity of supply, and exhaust air flow. The building energy simulation is then carried out for a conventional HVAC system coupled with an ERV to study the effects of ERV on annual energy consumption. The CFD simulation results show that the sensible and latent effectiveness could be gained at 75% and 65% respectively. Some preliminary experiment is also carried out to validate the simulation results for the impacts of ERV on energy consumption. The dynamic model of HVAC is then constructed and developed in Simulink. The model predictive control strategy for the control of temperature, humidity and CO₂ level will be implemented in this model for optimization of ERV control integrated into the whole HVAC system to achieve much more energy saving.

Keywords-energy recovery ventilator; heat exchanger; indoor air quality; HVAC system; control

I. INTRODUCTION

Recently the global energy consumption steadily increases with a high rate as a consequence of economic development and population explosion [1]. This situation raises concerns about the depletion of energy resource and environmental issues. For tropical weather such as that in Singapore, the electricity consumption in HVAC system is a major energy part, accounting for 50% of the energy use in the building sector in Singapore [2]. In addition, to improve the indoor air quality (IAQ) in environment, the ventilation rate should be increased which significantly consumes the energy to condition the new fresh air. In particular, in hot and very humid climate, the energy for traditional cooling and dehumidifying fresh air

accounts for 20~40% of total HVAC energy consumption, in which dehumidification process plays a major part [3] and causes the high energy loading on the energy system.

In order to address the problems of high energy requirement and the associated environmental concern, heat and energy recovery system is one of the sustainable technologies to decrease energy demand for HVAC system and to improve the indoor air quality significantly. In the conventional recovery technology for building applications, the sensible energy was recovered through heat transfer but the latent energy was ignored. Lately, with the development of membrane technology, Zhang *et al.* [4] proposed the membrane-based energy recovery ventilator (ERV), which has capability to exchange both sensible and latent heat from the exhaust air to pre-condition the outdoor fresh air through the heat transfer and moisture diffusion with high effectiveness. Zhang and Niu [5] conducted the simulation in the humid weather of Hong Kong and showed that the ERV achieved greater impact on energy saving than traditional heat recovery. Nasif *et al.* [6] conducted an experimental study to investigate the performance of an Z-shaped energy heat exchanger in term of both sensible and latent effectiveness. They found that the air conditioning system with this ERV saved energy of 4% and 8% respectively, compared with traditional air conditioning system in moderate climate and humid climate. Mardiana and Riffat [7] developed an energy recovery system, which utilized cellulose paper as the material for transferable core. The experimental investigation indicated that the efficiency of 66% and 59% was possible for sensible and latent effectiveness respectively. The recovered energy was obtained up to 167W at 3.0m/s air velocity.

Moreover, various control techniques and optimization strategies were implemented in building automation and control system. Due to various inherent advantages, the model predictive control (MPC) has emerged in building control system in recent years as a promising approach, which can deal with variety of disturbances to select an optimal set of actions. MPC control utilizes a system model with predictable action and the ability to handle constraints. The cost function of MPC control is designed to achieve multiple objectives [8].

The energy recovery technique is a sustainable solution to solve the problems in increasing energy consumption and indoor air quality. The MPC control algorithm is highlighted because of its advantages in dynamic model control. However,

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it was recognized that few studies were carried out for the recovery system in tropics climate. In addition, few researchers paid attention to control aspect, which is potential for considerable improvement in energy recovery device efficiency. As such, the objectives of this study are to investigate the performance of ERV in hot and humid tropical climates, and to develop an optimal control strategy for ERV, which is integrated into the whole building control system, in order to reduce the energy consumption and maximize the thermal comfort.

II. MATHEMATICAL MODELING OF HEAT EXCHANGER

Firstly, the performance of sensible and latent energy subject to tropical climate conditions is investigated by numerical methods. The 3D ERV model with semi-permeable membrane is comprehensively studied by Computational Fluid Dynamic (CFD) simulation to conduct the analysis of several important parameters, including the velocity, temperature, humidity of supply, and exhaust air flow, as shown in Fig. 1.

Fig. 1. Description of mathematic model.

The heat equilibrium equation for conduction/convection and the mass balance equation for convection/diffusion in the ERV membrane are solved by finite volume method [9]. The ERV performance is estimated below by the capability to transfer sensible and latent energy of a recovery system [3]

$$\varepsilon_s = \frac{(T_{si} - T_{so})}{(T_{si} - T_{ei})} \quad \varepsilon_L = \frac{W_{si} - W_{so}}{W_{si} - W_{ei}} \quad \varepsilon_s = \frac{H_{si} - H_{so}}{H_{si} - H_{ei}} \quad (1)$$

III. EXPERIMENTAL APPROACH

The experiment of ERV with counter-cross flow configuration is carried out. Temperature and humidity sensors are set up at 4 sides of the device. LabVIEW by National Instruments is used as a platform to collect, display and record data transmitted from the sensors employed in the experiment. Various outdoor conditions are simulated by employing a heater and humidifier to alter the temperature and humidity level of the outdoor environment. Physical parameters, such as the mass flow rates and efficiencies (sensible/latent /enthalpy), are evaluated, as illustrated in Fig. 2.

Fig. 2. Effect of outdoor air temperature on sensible efficiency and the effect of humidity ratio difference on latent efficiency.

IV. CONCLUSIONS

Energy recovery is one of the key energy-efficient technologies, which reveals to overcome the increase of energy consumption in building, without reducing the indoor air quality. The CFD simulation results demonstrate that the sensible and latent effectiveness could be gained at 75% and 65% respectively. The preliminary experimental data show that the sensible and latent efficiencies are primarily dependent on the outdoor temperature and humidity ratio respectively. With the tropical climate, ERV has a great potential for significantly saving total energy consumption in building.

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