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Development and application of the load responsive control of the evaporating temperature in a VRF system for cooling energy savings

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ABSTRACT

The variable refrigerant flow system has received much attention due to its energy saving potential and design flexibility. A load responsive control of the evaporating control in the VRF system, which aims to reduce the cooling energy consumption of the VRF system, has been developed. This newly developed control consists of two algorithms. It starts with the load determinant algorithm, which evaluates the levels of internal cooling loads of individual indoor units. The second algorithm determines the target evaporating temperature based on the outcome of the first algorithm. A series of experiments in a multicalorimeter, which is composed of one outdoor unit chamber and two indoor unit chambers, indicates that increasing the evaporating temperature can reduce the electricity consumption of the VRF system by up to 35% without impairing the energy efficiency of the VRF system. The annual energy consumption of a typical office building with a VRF system has been simulated with whole-building energy simulation (EnergyPlus), and the EnergyPlus runtime language is used to make a code to model the performance variation of the VRF system as a function of the evaporating temperature. Our simulation results demonstrate that the annual cooling energy consumption is lowered by 14%.

1. Introduction

The building sector is one of the largest contributors to energy consumption worldwide, representing 32% of the total energy consumption in the world [1] and accounting for 60% of the world's electricity [2]. Thus, it is a significant source of greenhouse gas emissions. Without significant efforts to reduce energy consumption in buildings, the energy demanded by the building sector is expected to double by mid-century due to increases in wealth, lifestyle changes, and urbanization [3].

However, the building sector has the largest cost-effective potential for reducing energy use as compared to other sectors [4]. According to the International Energy Agency (IEA), the global energy efficiency investment in buildings has been gradually increasing and is estimated to reach 125 billion USD by 2020 [5]. As a result of efforts made to introduce energy efficiency measures into the building sector, the electricity used in OECD countries has plateaued since 2010 [5].

Warming climates have become a major driver for the increased adoption of air-conditioning units in buildings [6]. The world air-conditioning market continuously grew from 86.8 billion USD in 2012 to 97.9 billion USD in 2014 [7]. This increase was mainly attributed to the Asia–Pacific region, which is the largest global air-conditioning market. For example, the adoption of air-conditioners in urban Chinese households rose from 1% in 1990 to 62% in 2003; 50 million air-conditioners were sold in 2010 alone [8]. In particular, the variable refrigerant flow (VRF) system market showed rapid growth in the Asia–Pacific region, which includes China, Japan, and South Korea, and has an expected annual increase of 11% [7]. In addition, the VRF system shares 24% of the global commercial air-conditioning market [9]. Therefore, it is vital to improve the energy efficiency of VRF systems in order to reduce greenhouse gas emissions from the widespread use of VRF systems.

The VRF system utilizes a technology built on a direct expansion heat pump platform, which delivers heat between one outdoor condensing unit and multiple indoor units with variable refrigerant flow rates; this is done by controlling inverter-driven variable speed compressors and the electronic expansion values (EEV) positioned in individual indoor units to respond to changes in the zone's space cooling or heating loads [10,11]. Key features of the VRF system include individualized comfort control, which is regulated by controlling the amount of refrigerant flow to each indoor unit, and the provision of simultaneous heating and cooling in different zones on a single refrigerant circuit by using heat recovery units or

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mode change units [9,12,13]. These features enable VRF systems to be applied in various applications where individual zone controls and simultaneous heating and cooling operations are required.

One challenge encountered while designing VRF systems is the installation of additional ventilation systems to provide fresh outdoor air to indoor spaces; this is necessary because VRF systems do not have ventilation capabilities. A field experiment that investigated the effect of the heat recovery ventilation unit on the operation of the VRF system in a building indicated that installing a ventilation unit increased the energy use of the VRF system by 28% [14]. In order to reduce the energy consumption due to the ventilation load, several studies [15–18] have developed VRF systems with heat pumps coated by solid desiccant materials. Researchers have experimentally verified that integrated VRF systems with solid desiccant heat pumps can reduce the heat and cooling energy consumption while maintaining comfortable indoor conditions.

Water-cooled VRF systems have also been investigated in attempts to improve the energy performance of VRF systems. Water-cooled VRF systems have plate-type outdoor unit heat exchangers connected to a cooling tower. The energy consumption of the compressor in a water-cooled VRF system was lowered compared to the amount of energy used in an air-cooled VRF system, but the total energy consumption of the water-cooled VRF system was highly dependent on the energy consumption of the cooling tower fan [19,20].

The capacity modulation by the inverter-driven variable speed compressors is a key feature of the VRF system because the performance at various part load conditions determines the energy consumption of the VRF system during the operation stage. Two factors that determine the part load efficiency of the VRF system are the EEV opening of each indoor unit and the compressor speeds [21–25]. The opening of the EEV is modulated to meet the zone's load, while the superheat temperatures are controlled by the compressor speed.

The control strategy of the VRF system at part load conditions is a critical issue that has a great influence on the operational energy use and system stability. Wu et al. [26] proposed a strategy that controls the compressor speed and the opening of the EEV by changing the suction pressure and the room temperature, while the evaporating temperature remained constant in the cooling model. A control method by Lin and Yeh [25] regulates the evaporative pressure and superheat by varying the compressor speed and the EEV opening, respectively. Elliot and Rasmussen [27] developed the model predictive control (MPC) strategy for VRF systems; this controls the EEV opening and fan speed of individual indoor units with evaporator cooling and the pressure setpoints of each unit, which are determined by the MPC supervisor. In a novel capacity control algorithm established by Xiangguo et al. [28], the compressor speed was determined by the number of EEV openings and the corresponding cooling load. Recently, Zhao et al. [29] proposed a control method that regulates the evaporating temperature. This is an important step because the evaporating temperature is kept constant in most control strategies for VRF systems [30], but the part load performance of the VRF system improves as the evaporating temperatures increase [31]. However, controlling the evaporating temperature has a potential to cause an instability in compressor capacity controls. This is because the compressor capacity controller, in most cases, is programmed to maintain the evaporating temperature close to a constant target value according to the pressure detected in the outdoor unit, and the evaporator performance varies with a change in evaporating temperatures. Therefore, the careful selection of the type of evaporator and the programming of the compressor capacity controller in consideration of varying the target value of the evaporating temperature is required.

Based on previous studies that have investigated VRF systems, this study aims to develop a control model that modulates the evaporating temperature in VRF systems in response to the cooling load of a zone in order to reduce the cooling energy consumption. Additionally, we aim to evaluate the energy saving potential of the developed control system, which is applied to a VRF system installed in a normal office building. After explaining the load responsive control of the evaporating temperature in the VRF system, this paper describes the experimental method used to investigate the energy consumption of a compressor operated by the developed control method. We also explain the simulation method used to evaluate the energy performance under realistic conditions. Finally, this paper presents experimental and simulation results and discusses the outcomes of the study.

2. Load responsive evaporating temperature control for a VRF system

A typical VRF system regulates its refrigerant flow rates to match changes in the zone's cooling load with a fixed evaporating temperature. Alternatively, this study develops a control method that modulates the evaporating temperatures to closely match the cooling load of the indoor unit in an attempt to reduce the VRF system energy under part load conditions. A recent study showed that increasing the evaporating temperatures can reduce the operational energy by up to 50% [29].

Load responsive control of the evaporating temperature in a VRF system consists of two main algorithms. It starts with an algorithm that determines the levels of internal cooling loads of individual indoor units (Fig. 1). The load determinant algorithm calculates three indexes using the elements available in the VRF system. The load determinant algorithm first calculates the difference between the current room temperature and the setpoint temperature of the current indoor unit with Eq. (1):

$$\Delta T_{\mathrm{rs}} = T_{\mathrm{room}} - T_{\mathrm{setpoint}} \tag{1}$$

here, T_{room} is the temperature of the room and T_{setpoint} is the setpoint temperature. If this difference (ΔT_{rs}) is equal to or greater than 3 K, the load coefficient of the current indoor unit ($\mathrm{Ld0}_{(n)}$) is 1.0. T_{rs} is used to determine whether the room condition is significantly away from the desired indoor temperature. In normal indoor conditions, a change in an air temperature of 3 K is roughly equivalent to a change of the Predicted Mean Vote (PMV) by 0.5. We assume that the full capacity of compressor is required when the difference in the PMV value is over 0.5. When the difference (ΔT_{rs}) is less than 3 K, the algorithm assumes this is the low level of the cooling loads and moves to the next step. In the next step, the algorithm calculates the two load coefficients of the current indoor unit: Ld1 and Ld2. Ld1 is a value based on the change in the temperature of the room over the past five minutes (ΔT_{rm}) and the room temperature change criterion (T_{rc}), which can be determined from Table 1. The reference values for a change in indoor temperature over the past five minutes are dependent on a difference between air and refrigerating temperatures [32]. Ld2 is the ratio of the current indoor unit operated over the past thirty minutes:

$$\mathrm{Ld2} = \frac{\sum T_{\mathrm{on}}}{\sum T_{\mathrm{on}} + \sum T_{\mathrm{off}}} \tag{2}$$

here, ΣT_{on} is the sum of the time that the current indoor unit is on and ΣT_{off} is the sum of the time that the current indoor unit is off. In this way the algorithm calculates the runtime fraction of the indoor unit. The higher value indicates that the indoor unit needs to be run to meet the cooling load over the past thirty minutes. Once Ld1 and Ld2 are determined, the load coefficient of the current indoor unit ($\mathrm{Ld0}_{(n)}$) takes the smallest values of Ld1 and Ld2. This is because the algorithm is conservative to apply the evaporating temperature modulation, so that they the VRF system can maintain its stability