An improved integrated comfort control algorithm with cooling and ventilation systems to maintain indoor relative humidity

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Abstract. This study evaluates an improved Integrated Comfort Control (ICC) algorithm with an air conditioner and ventilator system that considers the outdoor environment to ensure appropriate indoor thermal comfort for occupants. In this investigation, the ICC algorithm has been improved to maintain acceptable indoor humidity levels within a comfortable range using a ventilation system. To evaluate this algorithm, we performed experiments and simulations in a virtual testbed. In Case 1 (mild and humid outdoor air) and Case 2 (hot and humid outdoor air), the comfort ratios increased from 0% to 52.1% and from 0% to 45.0%, respectively, with the improved ICC algorithm. The evaluation results show that the improved ICC algorithm can help indoor conditions to reach a defined comfort range quickly and maintain these conditions well.

1. Introduction

Thermal comfort is affected by temperature, humidity, air velocity, and personal factors, among others. Thus, these factors should be within appropriate ranges to maintain thermal comfort [1]. To maintain an indoor temperature within an appropriate range, many people use air conditioning systems, such as variable refrigerant flow (VRF) systems. However, VRF systems cannot achieve full thermal comfort, because they cannot satisfy comfortable humidity conditions, as they dehumidify indoor air during cooling cycles [2]. Dry indoor conditions can have negative effects on occupants, such as influenza viruses, respiratory disorders, and skin disease [3][4]. Thus, it is crucial to maintain appropriate indoor humidity as well as temperature. Earlier research has described Integrated Comfort Control (ICC) algorithms with an air conditioner, humidifier, ventilator, and other auxiliary systems to maintain appropriate indoor comfort ranges [5][6]. These studies showed that the ICC algorithm can contribute to improved thermal comfort and energy efficiency. However, the ICC algorithm has a limited ability to reach the comfort range without a humidifier in low indoor humidity levels. To resolve this problem, in this study, a ventilation system that is a mandatory installation in apartment units in large complex town is utilized to maintain indoor relative humidity as an extension of the ICC algorithm. To evaluate the improved ICC algorithm, we demonstrated the effectiveness of ventilation to increase indoor humidity in a testbed. A virtual testbed modeled by a building energy simulation program was used to examine the operation of the improved ICC algorithm in various cases.

2. Methods

We investigate the improved ICC algorithm to maintain relative humidity within a defined comfort range by using ventilation considering outdoor environmental conditions. The comfort range in the cooling season is set to a dry-bulb temperature of 24.4–26.5 °C and relative humidity of 40–55%. Details of the comfort range are described in an earlier paper [2]. To reach this relative humidity range, we use a ventilation system that compares the absolute humidity of indoor and outdoor air. The major difference of the proposed improved ICC algorithm relative to that developed earlier is a ventilation
system that operates when a humidifier-free room has low relative humidity. In the previous study with the earlier ICC algorithm, a humidifier was used to increase the room’s relative humidity. In the improved ICC algorithm, however, the relative humidity of the room is increased by the exchange of indoor dry air for outdoor humid air through the ventilation system.

As shown in Figure 1, the operation status of the ventilation system for enthalpy control is determined in the first stage. This stage induces indoor air to reach the comfort zone by comparing the indoor and outdoor air enthalpies. Previous papers provide more detailed explanations of this operation scheme [5][6]. After the ventilation effectiveness is evaluated, the indoor air status is determined for each operation scheme based on its initial state. The indoor air state is divided into four regions of Comfort, Cooling, Cooling and humidifying, and Humidifying. In the Comfort region, the indoor temperature is between 24.4°C and 26.5°C and the indoor relative humidity is between 40% and 55%. In the Cooling region, the indoor temperature is higher than 26.5°C and the indoor relative humidity is higher than 40%. In the Cooling and humidifying region, the indoor temperature is higher than 26.5°C and the indoor relative humidity is lower than 40%. Finally, in the Humidifying region, the indoor temperature is between 24.4°C and 26.5°C and the indoor relative humidity is lower than 40%. The description of these regions is explained more detail in [7]. In the Comfort region, all systems are turned off because the room is already comfortable. In Cooling region, an air conditioner is turned on to maintain the indoor temperature within the appropriate range; ventilation and humidification are not used because the indoor humidity is within the comfort region. In the Cooling and humidifying region, an air conditioner is turned on to maintain an indoor temperature in the appropriate range; a humidification or ventilation system is operated to maintain the indoor relative humidity within comfort region. In this region, humidification can be performed using a ventilation system when the absolute humidity is
higher than those of indoor air. However, if the absolute humidity is lower than those of indoor air, the ventilation system does not work because ventilation cannot achieve a humidification effect. In the humidifying zone, the indoor temperature is already comfortable, thus the air conditioner does not operate. Humidification using a humidifier or ventilation system is operated in the same way as it is in the cooling and humidifying zone.

To evaluate the suggested improved ICC algorithm, we set up an experiment in a testbed to verify the effectiveness of indoor humidification through Energy Recovery Ventilation (ERV) system operation. Based on the experimental results, the improved ICC algorithm is evaluated against a virtual testbed by using the Energy Plus building energy simulation program and Building Controls Virtual Test Bed (BCVTB). The testbed is an enclosed chamber that consists of a VRF system, an ERV system, a humidifier, a dehumidifier, a floor heating system, a dimming system, an automatic blind, and a building energy and environmental monitoring system. The testbed was constructed in the inside of a building to set outdoor environmental conditions such as temperature and humidity by using air conditioning systems, humidifiers, and dehumidifiers in the building.

3. Results

3.1 The effect of the ventilation system for indoor humidity
The suggested improved ICC algorithm utilizes a ventilation system to maintain indoor relative humidity within an appropriate range when the outdoor absolute humidity is higher than the indoor absolute humidity. To verify this idea, an experiment was conducted in the testbed under the specific conditions shown in Table 1. The experimental initial conditions were as follows: the indoor air temperature and relative humidity were 25.5°C and 33.0%, respectively; the outdoor temperature and relative humidity were 26.0°C and 59.1%. The indoor and outdoor absolute humidity values were calculated as 0.007 kg/kg and 0.012 kg/kg, respectively. The total experimental time was one hour. As the ERV system was operating, the indoor relative humidity was increased from 33.0% to 40.6% while the outdoor relative humidity was increased from 59.1% to 66.9%. However, the increase in outdoor relative humidity was caused by decreases in the outdoor temperature, not by increases in the absolute humidity. As shown in Figure 2, the outdoor absolute humidity is maintained at 0.012 kg/kg. The outdoor absolute humidity could be maintained by operating the humidifier for the building in which the testbed was installed. During ERV system operation, the indoor absolute humidity increased from 0.007 kg/kg to 0.009 kg/kg. These results showed that the indoor humidity could be maintained in an appropriate range using the ventilation system.

![Figure 2](image)

*Figure 2. Change of indoor and outdoor environmental conditions during ventilation system operation ((a): Temperature, (b): Relative humidity, (c): Absolute humidity)*

| Temperature (°C) | Relative humidity (%) | Absolute humidity (kg/kg) |
|------------------|----------------------|---------------------------|
| Start | End | Start | End | Start | End |
| Indoor air condition | 26.0 | 26.3 | 33.0 | 40.7 | 0.007 | 0.009 |
| Outdoor air condition | 25.5 | 23.8 | 59.1 | 66.9 | 0.012 | 0.012 |
Evaluation of the improved ICC algorithm

In this study, the Energy Plus building energy simulation program and BCVTB were used to model a building with both VRF and ERV systems. We selected two simulation cases considering the conditions of indoor and outdoor air. Information on the temperature and relative humidity for the two cases are shown in Table 2. In Case 1, we simulate mild and humid outdoor conditions and hot and dry indoor conditions. In Case 2, we simulate hot and humid outdoor conditions and hot and dry indoor conditions. These cases were used to examine the effect of humidification using the ventilation system.

Table 2. Selected simulation cases

| Outdoor air condition | Indoor air condition |
|-----------------------|----------------------|
| Temperature (°C)      | Relative Humidity (%)| Temperature (°C) | Relative Humidity (%) |
| Case 1                | 25                   | 60                | 32                   | 35 |
| Case 2                | 32                   | 45                |                      |    |

- Case 1 (Outdoor air: mild and humid, Indoor air: hot and dry)

In Case 1, the outdoor air temperature and relative humidity were 25°C and 60%, while the indoor room air temperature and relative humidity were 32°C and 35%. With these initial conditions, two ICC methods were tested without (earlier) and with (improved) ventilation for increasing humidity. In Table 3, the ventilation for enthalpy control operated for 10 min because the indoor air enthalpy was higher than the outdoor air enthalpy. This is because the cooling load could be reduced by introducing low-enthalpy outdoor air. Previous research papers provide more detailed explanation of the earlier ICC algorithm [3][4]. After ventilation for enthalpy control, as shown in Figure 3(b) and Table 3, with the improved ICC algorithm, the cooling system and ventilation for humidification control began to maintain indoor air conditions within the comfort range. However, as shown in Figure 3(a) and Table 3, with the earlier ICC algorithm, only the cooling system control could maintain indoor air conditions in the comfort range after ventilation for enthalpy control. As shown in Table 3, the improved ICC algorithmic method reached the comfort zone in 55 minutes. On the contrary, the earlier ICC algorithm without a humidifier could not reach the comfort zone because the relative humidity did not reach 40%. In terms of the comfort ratio, the improved and earlier ICC algorithms showed the comfort ratios of 52.1% and 0%, respectively. This suggests that the improved ICC algorithmic method is more favorable in terms of maintaining thermal comfort. However, it was disadvantageous in terms of overall energy consumption. This is because the improved ICC algorithm operated the ERV system more often to increase the indoor humidity. In addition, the VRF system consumed more electric power because the total cooling load was increased by bringing humid outside air into the indoor environment through the ERV system. The changes of the indoor air conditions are depicted in the psychometric charts shown in Figure 3.

- Case 2 (Outdoor air: hot and humid, Indoor air: hot and dry)

In Case 2, the outdoor air temperature and relative humidity were 32°C and 45%, respectively, while the indoor room air temperature and relative humidity were 32°C and 35%. Unlike Case 1, the VRF system and ventilation for humidification control started immediately; ventilation for enthalpy control did not operate, because the indoor enthalpy was lower than the outdoor enthalpy. As shown in Table 3, the improved ICC algorithm reached the comfort zone in 99 minutes. On the contrary, the earlier ICC algorithm without a humidifier could not reach the comfort zone because the relative humidity did not reach 40% (Figure 4(c)). The improved ICC algorithm had the comfort ratio of 45.0%. However, as shown in Table 3, it was disadvantageous in terms of overall energy consumption for the same reason as Case 1. The changes to indoor air conditions are shown in the psychometric chart in Figure 4(c),(d).
Table 3. Results of Case 1 and Case 2

| Thermal comfort | Case 1 | Case 2 |
|-----------------|--------|--------|
| Reaching time to comfort range (min) | N/A | 55 | N/A | 99 |
| Comfort ratio (%) | 0 | 52.1 | 0 | 45.0 |

| Operation time (min) | Case 1 | Case 2 |
|----------------------|--------|--------|
| VRF system | 184 | 182 | 216 | 228 |
| Ventilation for enthalpy control | 10 | 10 | 0 | 0 |
| Ventilation for humidification control | 0 | 64 | 0 | 66 |

| Energy consumption for 4h (Wh) | Case 1 | Case 2 |
|-------------------------------|--------|--------|
| VRF system | 899.8 | 963.2 | 1259.2 | 1445.6 |
| Ventilation | 9.83 | 72.8 | 0 | 64.9 |
| Total | 909.6 | 1036.0 | 1259.2 | 1510.5 |

Figure 3. Indoor air status profiles using (a) earlier ICC and (b) improved ICC algorithms for Case 1

Figure 4. Indoor air status profiles using (c) earlier ICC and (d) improved ICC algorithms for Case 2
4. Discussion and conclusions

In this study, we suggested an improved ICC algorithm to maintain indoor relative humidity within an appropriate range by using a ventilation system for specific outdoor conditions. To evaluate this algorithm, we conducted a testbed experiment to verify the effectiveness of ventilation to increase indoor humidity. After this experiment, a building energy simulation study was performed to evaluate the improved ICC algorithm in terms of the time necessary to reach the comfort range, comfort ratio, system operation time, and energy consumptions. Simulation results showed that the improved ICC algorithm is favorable in terms of thermal comfort by introducing humid outside air to the dry indoor air. In Case 1 (mild and humid outdoor air) and Case 2 (hot and humid outdoor air), the comfort ratios increased from 0% to 52.1% and from 0% to 45.0%, respectively, with the improved ICC algorithm. This showed that the improved ICC algorithm could be used to maintain the indoor environment comfortably with a ventilation system in a room without a humidifier under favorable outdoor conditions. However, the algorithm was disadvantageous in terms of the overall energy consumption because of the increased usage rate of the cooling and ventilation systems. In Case 1 and Case 2, the improved ICC algorithm consumed 126.5 Wh and 251.3 Wh more than the earlier operation scheme, respectively. To minimize energy consumption, it is necessary to optimize the operations of the environmental control systems and building systems (e.g., windows) together.

In future research, we will conduct experiments on a real climate situation for further evaluation of the improved ICC algorithm. We will also extend the applicability of this algorithm to various situations. For example, the ICC algorithm of a floor heating system for the heating season is under investigation. In addition, we are studying the operation of a shading device together with the suggested algorithm for the visual comfort of occupants.

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