Effects of humidification process on the thermal behavior of floor heating systems

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Abstract. Since the outbreak of the Covid-19 pandemic, working from home has become the norm for millions of workers in the world. Indoor humidification and heating are essential for health and comfort in a dry and cold climate. In order to investigate the interaction between humidification process using a cool mist humidifier and the heating process using a floor heating system, a total of 4 experimental tests were carried out, which included three experimental groups with humidification process in the conditions of three relative humidity setpoints (45%, 55%, 65%), and one control group without humidification process. In the process of experiments, indoor relative humidity of the control group basically maintained around 30%. Therefore, the heated room would be dehumidified to about 30% before each experiment started. The indoor temperature was maintained at 25 ℃ by the floor heating system. Obtained results showed the floor heating system was stimulated to reheat the room due to the cooling effect of the humidifier and a new balance was established in the process of competition between the evaporative cooling and floor heating. When humidifying air to over 45%, it would lead to floor overheating. Furthermore, the humidification process improves the non uniformity of air temperature distribution, but at the same time brings more uneven RH distribution. Besides, the energy consumption increases following with the rising of setpoints of RH, and the growth rate is 60%, 87% and 100% respectively for RH 45%, 55% and 65%. In conclusion, the optimal setpoint of the humidifier is RH 45% based on a comprehensive consideration of health, thermal comfort and energy consumption.

Keywords. Humidification, Floor heating system, Thermal comfort, Energy consumption, Experiments
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1. Introduction

Since the beginning of its history, man has been preoccupied with protecting oneself against environment assaults and always tries to create a safe and comfortable indoor environment. Currently, people spend most of their time indoors especially since the outbreak of the Covid-19 pandemic and working from home becomes the norm for millions of workers in the world. In this case, a safe, clean and comfortable indoor environment is particularly important.

Indoor temperature and humidity are two important parameters that could affect thermal comfort in buildings. The effects of humidity on the thermal sensation is rather limited compared to air temperature based on the ISO 7730 [1], while low relative humidity probably causes dryness of the eyes and skin, and even exacerbates symptoms in the upper and lower airways [2,3]. Jin et al [4] carried out a field study and found that a minimum humidity of 41% could be predicted to avoid dry skin for elderly people in care homes, if the room temperature is maintained at 21 ℃. Cold and dry environments also facilitate the survival and spread of viral diseases, and some studies observed air humidity negatively correlated with Covid-19 morbidity and mortality [5,6].

Some studies on the indoor environment of buildings located in Greenland [7], Beijing [8] and New York [9] cities have shown that the heating systems of residential buildings in winter generate dry indoor environments where the indoor humidity remains below 30%. However, it remains to be noted that the recommended humidity comfort range is 40-70% based on CIBSE Guide A [10]. Clearly, it's quite necessary to increase indoor humidity in the heating season of these regions.

Portable humidifiers humidifying air directly may induce greater impacts than humidification systems installed in ventilation ducts with heat recovery on indoor thermal and humid environment. Feng et al [11] studied the impact of the humidification process on the indoor environment in a reference chamber using a portable ultrasonic humidifier generating steam and water droplets. The results showed that the evaporation of water droplets as a "constant enthalpy process" led to an increase in humidity and a decrease in temperature.

Portable humidifiers generally fall into three categories: ultrasonic, cool mist, and warm mist [12]. Of them, the cool mist humidifier has a 50% of high market penetration [12]. In a cool mist humidifier, air is forced through a water-saturated filter by an in-built ventilator and absorbs the evaporated moisture. The total enthalpy of the air flow is considered as constant in this process [13,14].

Therefore, when a cool mist humidifier, subjected to constant enthalpy humidification, is used in a heated room, in which air temperature is controlled around a comfort setpoint by heating systems, the reduction of air temperature in this humidification process may induce the room to be reheated. In this situation, when it happens in a building with a floor heating system (FHS) of high thermal inertia [15], the regulation system would have a time lag in response to the sudden change in indoor temperature, further leading to a larger deviation of air temperature from setpoint, which will cause FHS to deliver more hot water to the pipes embedded in the floor. Besides, since the constant enthalpy humidification enhanced indoor air cooling process, hot water supply would be also more frequent. Therefore, the competition between the humidification and the heating process probably leads to the overheating of the floor surface and have an influence on the indoor thermal comfort and on the energy consumption of the FHS as well.

Up to now, for the best knowledge in comportment or regulation of this combined systems, there is no available studies combining a cool mist humidifier with a floor heating system to investigate their interactions. In this paper we present a study on a full-scale experiment in order to be able to provide some measurement-based answers to the following questions: (1) how does the underfloor heating system behave when a humidification process is used? (2) In this situation, how does the thermal comfort is impacted? (3) What is the impact on the energy consumption of such heating systems when combined to the humidification process?

2. Research methods

The experiments were performed in a full-scale test cell with an available space of 11 m² of area and 2.1 m of height, located at EPF School of Engineering in City of Troyes (France) as shown in Fig. 1. The test cell is composed of two adjacent well-insulated rooms. The first one is equipped with a floor heating system as the heated room, and the other one is as a cold room with an air conditioner to simulate outdoor conditions in winter. In this study, the cold room was fixed at 5 ℃ as the outdoor condition of the heated room, which was relatively close to the average temperature in winter season in City of Troyes.

The FHS is a hydronic system that circulates hot water in a spiral layout of crosslinked polyethylene tube to provide heat to the room through the floor surface. The tube is embedded in the bottom of a 5 cm thick of anhydrite screed slab and the top of a 6 cm thick of insulation layer. The length of tube is 51m and the inner and outer diameters are 13 mm and 16 mm, respectively. Hot water is supplied by an air source heat pump. In this study, the inlet water temperature was set to 35 ℃. The volume flow rate of supply water is controlled by means of a thermostatic valve to keep the indoor air temperature within a setpoint value.

The time-dependent air temperature, relative humidity, floor surface temperature, inlet and outlet water temperature in the tube, and water flow rate values were measured in the experimental tests. Figure 2 presents the position of the humidifier and the arrangement of measuring points. The humidifier was placed below the sensor at control point 1 (1.78 m in height along Z axis) that connected the control system and provided measured air temperature and relative humidity to be compared with the setpoint. Besides, the sensors located at points 2 and 3 were 1.1 m and 0.1 m above the floor respectively and were also used to measure the air temperature and relative humidity. According to their locations, the temperature and relative humidity gradients in vertical direction would be acquired. All measurements would be collected to process and analyze the changes occurred on the indoor environment. The characteristics of measuring instruments are given in Tab. 1.

Figure 3(a) shows the schematic diagram of the humidifier (P=18W) used in this study, which is a cool mist humidifier. Indoor air is forced through water-saturated anti-bacterial filter cartridges by an in-built ventilator. In this process, water absorbs heat from air and releases vapor to humidify the air. It is considered as an approximate constant enthalpy humidification process as shown in Fig. 3(b). The humidifier used tap water in each experiment. The tap water temperature varied from 10 ℃ to 20 ℃. A total of 4 experimental tests were carried out in the heated room, which included three experimental groups with humidification process in the conditions of three relative humidity setpoints (45%, 55%, 65%), and one control group without humidification process. Each experiment was repeated three times. The indoor temperature was maintained at 25℃ by the FHS. The setpoints of RH were selected according to CIBSE Guide A [15] and the recommended humidity comfort range is 40%-70%. When air temperature of the heated room reached the setpoint and followed an equilibrium state, the humidifier was started to humidify air and keep the relative humidity at 45%, 55% and 65%, respectively. In the process of experiments, indoor relative humidity of the control group basically maintained around 30%. Therefore, the heated room would be dehumidified to about 30% before each experiment started.

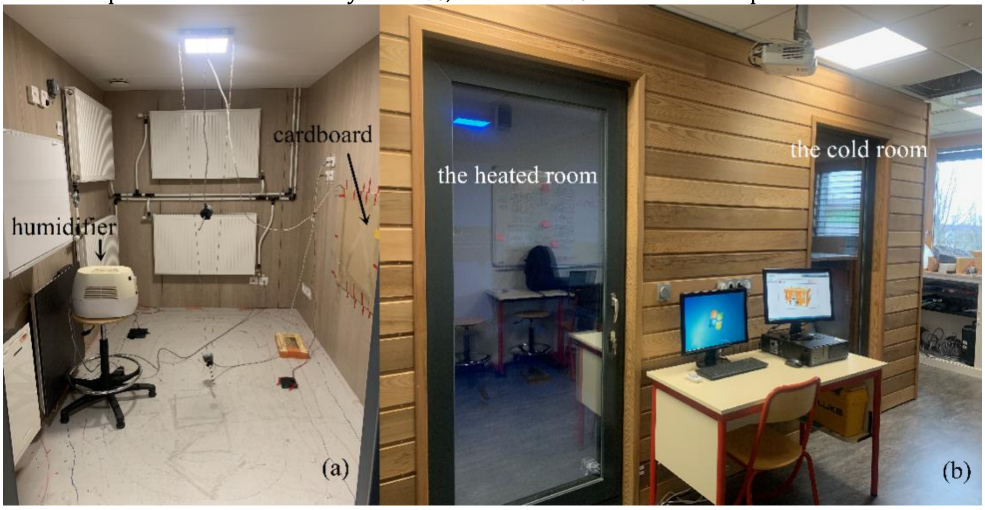

Fig. 1 - Full-scale test cell (a) Inside view of the heated room. (b) Outside view.

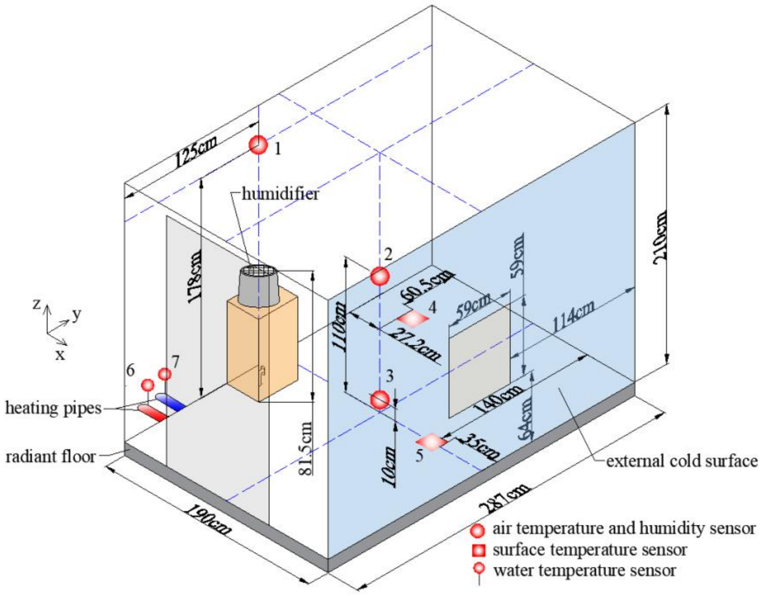

Fig. 2 - Arrangement of the measuring points in the heated room.

Tab. 1 - Measuring instruments characteristics.

Instrument	Number	Measuring points	Measuring range	Accuracy
Air RH and temperature sensor (KLH 100)	1	1	[-50, 50]°C [0, 100]%	±0.5°C at 25°C ±2% at 25°C
Air RH and temperature sensor (KLK100)	2	2, 3	[-50, 50]°C [0, 100]%	±0.5°C at 25°C ±3% at 25°C
Temperature sensor (PT 1000)	2	4, 5	[-20, 100]°C	±0.3°C at 0°C
Surface temperature sensor (TEPK PT1000)	2	6, 7	[-20, 80]°C	±0.3°C at 0°C

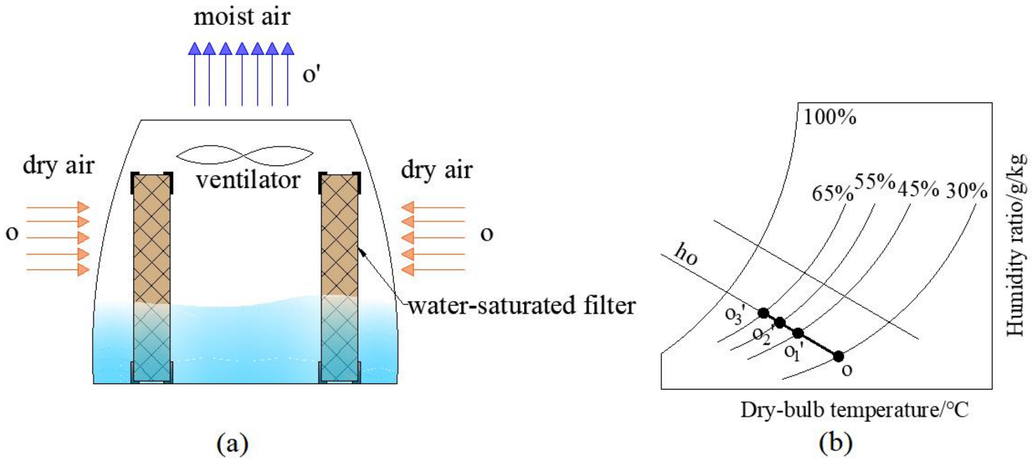

Fig. 3 - (a) Schematic diagram of the humidifier. (b) Change of state points in psychrometric chart.

3. Results and discussion

3.1 Impact of humidification process on the thermal performance of the FHS

Figure 4 illustrates the changes of average floor surface temperature, hot water volume flow rate, air temperature and RH at the control point with different setpoints of RH during the humidification process. For the control group of RH 30%, indoor thermal environment is in a dynamic equilibrium under the regulation of FHS. When the air temperature is below the setpoint, the hot water is supplied to heat the floor and the floor then transfers heat to the air through thermal convection and radiation. In this process, the volume flow rate of hot water is constant approximately around 1.8L/min. Then, when the air temperature reaches the setpoint, the inlet valve is closed. Due to the high thermal mass of the floor, there is a time delay to get the thermal response of the floor surface after hot water supplied. Therefore, the air and floor surface temperature continue to increase after the valve closed. Finally, the variations of indoor temperatures form stable fluctuating curves.

For the experimental groups, the humidification process disrupts the equilibrium described above. At the beginning, when the humidifier is turned on, the air temperature drops firstly due to the evaporative cooling effect of the humidifier and at the same time, the floor heating system is reactivated to reheat the room with a volume flow rate of more than 2L/min.

The higher is the design value of RH, the longer the cooling duration and so the air temperature is harder to return the setpoint and further more, the system feeds more hot water to heat the floor. Consequently, the maximum floor surface temperatures have exceeded 30℃ obviously, which are over the maximum limit value of 29 ℃ recommended by ASHRAE [16] in occupied-spaces for comfort reasons in terms of overheating. Ultimately, a new balance is established in the process of competition between the evaporative cooling and floor heating. The cool mist humidifier enhances the cooling of indoor environment, and therefore it could be found that in the steady state, the FHS works more frequently by supplying more hot water in the experimental groups compared to that in the control group. The floor surface temperature is obviously higher than that before humidifying. After indoor RH reaching 45% and 55%, the humidifier operates intermittently to keep the RH within a gap of ±1%. However, RH 65% is difficult to attain due to the appearance of water condensation, as a result, the humidifier is kept working.

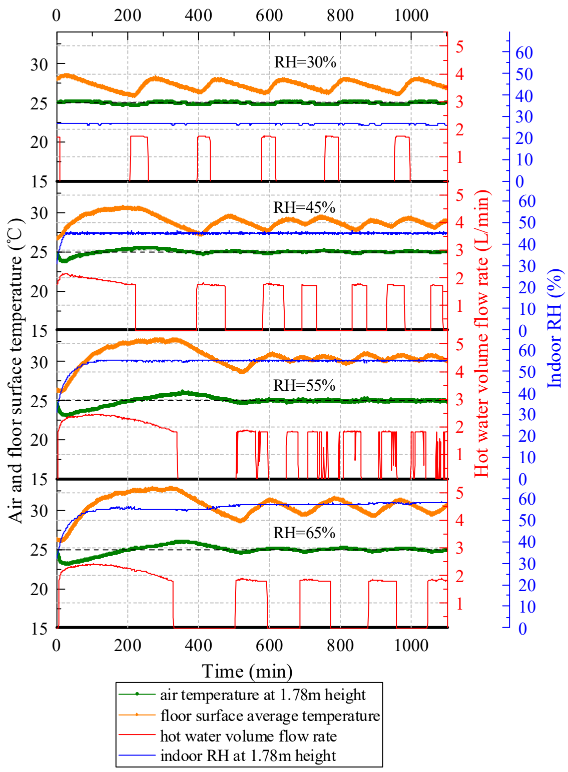

Fig. 4 - Changes of indoor environment parameters with time during the humidification process at different setpoints of RH.

3.2 Thermal comfort evaluation

This study aims to evaluate the indoor thermal comfort and energy consumption during a daytime and/or a nighttime over the humidification process in a cold and dry climate. The data for the first 12 hours was selected for analysis.

Figure 5 shows the average value of floor surface temperatures during 12 hours for different setpoints of RH. It could be found that the floor surface temperature increases following with increasing the setpoint of RH. The higher the design value of RH, the longer the cooling duration and so the system inputs more hot water to heat the floor in order to keep air temperature around the setpoint. When humidifying air to over 45%, it would lead to floor overheating based on ASHRAE [16], which gives a limit value of 29℃ marked with a black dash dot line. Therefore, floor overheating problem should be taken into account while meeting humidification needs at air temperatures of 25℃ or higher.

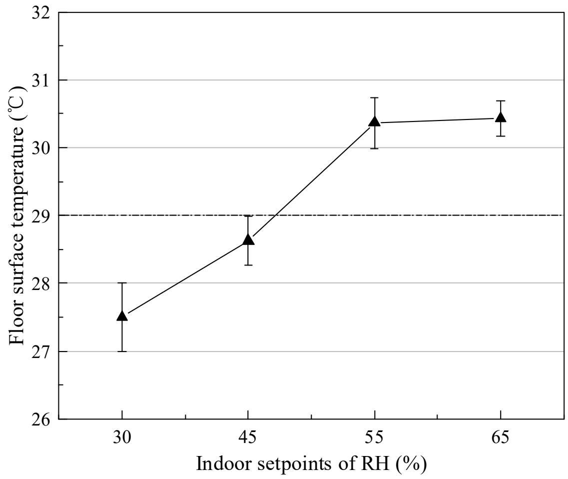

Fig. 5 - Average floor surface temperature varying with different setpoints of RH.

In this study, air temperatures and RH were measured at three different heights of 1.78m, 1.1m and 0.1m from the floor surface respectively. The average values of air temperatures and RH at the three heights were used to evaluate overall indoor temperature and RH. The non uniformities of indoor air temperature and RH distribution are amounted with the standard deviation (SD) [17] defined by equation (1). The larger SD value, the worse the uniformity of indoor air temperature or RH, and vice versa.

$$SD = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}{n}} \qquad (1)$$

Where y_i is the air temperature or RH at the measuring point, $\overline{y}$ is the average air temperature or RH, n is the number of measuring points.

Figure 6(a) displays the average indoor air temperature and its non uniformity varying with different setpoints of RH. The results show that the average air temperature slightly increases with the RH increasing. The FHS regulates the air temperature based on the control point namely the measuring point at 1.78m, and thus the air temperatures at other locations away from the humidifier would be mainly influenced by the floor surface temperature. As a result, the overall indoor air temperature rises with the floor surface temperature under the influence of humidification. It ' s worth noting that the non uniformity of air temperature has significantly reduced in the experimental groups and slightly decreases with the RH set value. During the humidification process, the humidifier sucks dry air and injects the humid air into the room, which facilitates air flow and avoids air stratification so as to make air temperature distribution more uniform. Figure 6(b) shows the average indoor RH and its non uniformity varying with different setpoints of RH. The non uniformities of RH distributions for the experimental groups are larger than that of the control group and slightly increases with the RH set value. The uniformity of RH in the room during humidification process is limited by the spatial position of the humidifier. As a result, the humidification process improves the non uniformity of air temperature distribution, but at the same time brings more uneven RH distribution.

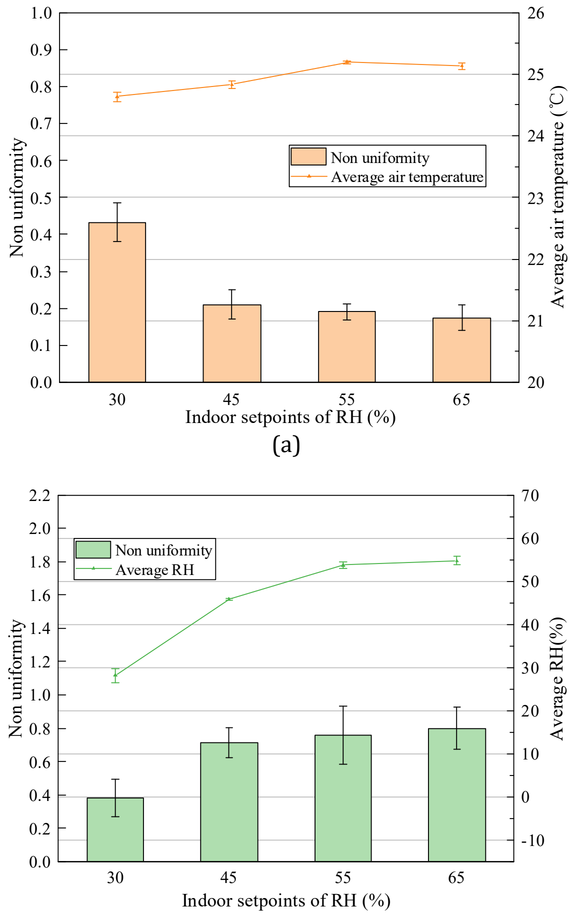

Fig. 6 - (a) Average indoor air temperature and its non uniformity varying with different setpoints of RH. (b)

Average indoor RH and its non uniformity varying with different setpoints of RH.

3.3 Energy consumption analysis

In humidification process, the energy consumption of floor heating system was evaluated by heat energy circulating hot water released. Based on the experimental data, the energy consumption was amounted by integration as shown in equations (2) and (3). The calculation range was the first 12 hours considering the daytime and/or the nighttime people used humidifiers.

$$Q = c\int_{\Delta t} \dot{m}\left(T_{inlet} - T_{outlet}\right)dt \qquad (2)$$

$$\dot{Q} = \frac{Q}{\Delta t} \qquad (3)$$

Where Q is the released heat energy (J) and $\dot{Q}$ is the power (W), c is the specific heat of water (4.18 kJ/kg·°C), $\dot{m}$ is the mass flow rate (kg/s), T_{inlet} is the inlet water temperature (°C), T_{outlet} is the outlet water temperature (°C), and Δt is the calculation range (s).

The obtained results are shown in Fig. 7. It can be seen that the energy consumption increases following with the rising of setpoints of RH. The power consumption of control group is 146W and the power consumption of the experimental groups are 234W, 273W and 292W respectively for RH 45%, 55% and 65%. The growth rate is 60%, 87% and 100% respectively for RH 45%, 55% and 65%. Due to the cooling effect of the humidifier, the heating load of the FHS is increased in the process of humidifying the room. This effect becomes greater as the RH setpoint increases.

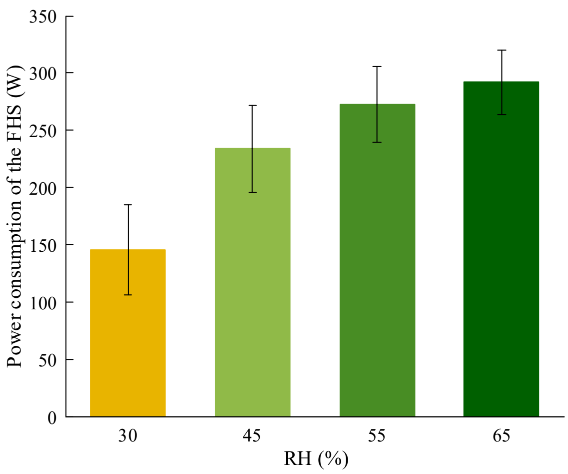

Fig. 7 - Power consumption of the floor heating system under different setpoints of RH.

4. Conclusions

This study mainly investigates the interaction between humidification process using a cool mist humidifier and the heating process using a floor heating system. The main findings are as follows:

1. The floor heating system is stimulated to reheat the room when the air temperature drops due to the evaporative cooling effect of the humidifier. The higher the design value of RH, the longer the cooling duration and so the system feeds more hot water to heat the floor. Eventually, a new balance is established in the process of competition between the evaporative cooling and floor heating.

2. The floor surface temperature increases following with the increase of RH setpoint. When indoor air temperature is 25 °C, humidifying air to over 45% would lead to floor overheating. Therefore, floor overheating problem should be underlined while meeting humidification needs at air temperatures of 25 °C or higher. The non uniformity of air temperature decreases with the rising of RH setpoint, but at the same time the non uniformity of RH rises accordingly.

3. The energy consumption increases with the rising of RH setpoint. The growth rate is 60%, 87% and 100% respectively for RH 45%, 55% and 65%.

In summary, when working with a FHS at 25 °C air temperature setpoint, the optimal setpoint of the humidifier is RH 45%, which observably improves the non uniformity of air temperature distribution and there is no much difference even compared with 55% and 65%. Meanwhile, the non uniformity of RH and energy consumption are also lowest.

5. Acknowledgement

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6. References

[1] ISO 7730:2005(E) [Internet]. Switzerland: ISO (the International Organization for Standardization); 2005. Annex F Humidity; [updated 2015; cited 2021]. Available from: https://www.iso.org/standard/39155.html.

[2] Sunwoo Y, Chou C, Takeshita J, et al. Physiological and subjective responses to low relative humidity in young and elderly men. J Physiol Anthropol. 2006 May;25(3):229-38.

[3] Lukcso D, Guidotti TL, Franklin DE, et al. Indoor environmental and air quality characteristics, building-related health symptoms, and worker productivity in a federal government building complex. Arch Environ Occup Health. 2016;71(2):85-101.

[4] Jin Y, Wang F, Carpenter M, et al. The effect of

indoor thermal and humidity condition on the oldest-old people's comfort and skin condition in winter. Build Environ. 2020 May;174:106790.

[5] Ma Y, Zhao Y, Liu J, et al. Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China. Sci Total Environ. 2020 Jul 1;724:138226.

[6] Biktasheva IV. Role of a habitat's air humidity in Covid-19 mortality. Sci Total Environ. 2020 Sep 20;736:138763.

[7] Kotol M, Rode C, Clausen G, et al. Indoor environment in bedrooms in 79 Greenlandic households. Build Environ. 2014 Nov;81:29–36.

[8] Fan G, Xie J, Liu J, Yoshino H. Investigation of indoor environmental quality in urban dwellings with schoolchildren in Beijing, China. Indoor Built Environ. 2017;26(5):694-716.

[9] Quinn A, Shaman J. Indoor temperature and humidity in New York City apartments during winter. Sci Total Environ. 2017 Apr 1;583:29-35.

[10] Guide A Environmental design [Internet]. London: CIBSE (the Chartered Institution of Building Services Engineers); 2015. Humidity; [updated 2019 May; cited 2021]. Available from: http://www.cibse.org/GuideA.

[11] Feng Z, Zhou X, Xu S, et al. Impacts of humidification process on indoor thermal comfort and air quality using portable ultrasonic humidifier. Build Environ. 2018 Apr;133:62–72.

[12] United States Environmental Protection Agency. ENERGY STAR Market & Industry Scoping Report Residential Humidifiers. Washington: EPA; 2012 Oct. 21 p.

[13] Ghazikhani M, Khazaee I, Vahidifar S. Exergy analysis of two humidification process methods in air-conditioning systems. Energy Build.. 2016 Jul 15;124:129-140.

[14] Trane air conditioning manual. 75th ed. La Crosse, Wisconsin: Trane Company; 2007.

[15] Rhee K-N, Olesen BW, Kim KW. Ten questions about radiant heating and cooling systems. Build Environ. 2017;112:367-381.

[16] 2016 ASHRAE Handbook – HVAC Systems and Equipment. ASHRAE; 2016.

[17] Pu L, Li Y, Xiao F, et al. Effects of different inlet vent positions on the uniformity of humidity inside a building chamber. Energy Build.. 2014 Jan 1;76:565-571.

Data Statement

The datasets generated and analysed during the current study are not available because authors need the approval of the funders and faculty staff, but the authors will make every reasonable effort to publish them in near future.