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The performance of heat pump integrated with chilled water wall for air conditioning and domestic hot water

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Abstract. Chilled water walls (CWWs) have been developed as a means of air cooling, dehumidifying, and air cleaning. Their operating performance is superior to that of a radiant cooling ceiling, which does not clean the air and reduce the dew water temperature. The CWW is connected to a compressor that chills the water, and the setup thus consumes much energy when operated all day. When integrated with a heat pump, the CWW can chill water on one side and heat water on the other side. Because the water temperature of the CWW is 10°C–14°C, the heat pump can simultaneously generate chilled water at 7°C–10°C and hot water at 50°C. Additionally, indoor air pollutants are steadily removed by the thermal flow and flushed into the water tank by the water to clean the air. The dirty water can be cleaned using a filter and ultraviolet light. The heat pump integrated with a CWW supplies not only chilled water for air conditioning but also a domestic hot water supply, resulting in high energy efficiency due to multifunctionality.

Keywords: indoor environment quality, chilled water wall, climate zone.

1. Introduction

Surface-cooling systems that cool indoor air have been developed for a few years and include chilled-ceiling systems. The systems cool an indoor air environment evenly, but water can easily condense and drip from the ceiling when the cooled air temperature is lower than the dew point in the hot and humid climate zone. To prevent conditions from being favorable for mold growth, the surface humidity must always be kept below 80% relative humidity.¹ The surface temperature of a chilled ceiling must be higher than the dew point of the indoor air temperature. This causes the cooling efficiency to be low, and the air-conditioning performance of chilled ceilings is thus limited in the hot and humid climate zone.

A new type of air-conditioning system called the chilled water wall (CWW) has been developed for air cooling, dehumidifying, and air cleaning. The system operates at temperatures below the indoor air dew point, and moisture in the air is condensed into a water film that is discharged into a water basin. The water temperature is controlled by a cooling unit placed outside the air-conditioned zone. The CWW cools the convective air flow while simultaneously forming a heat sink for absorbing the



long-wave radiation emitted by people and objects in the room. Mitterer provided climate-specific design principles for optimizing the energy efficiency and occupant comfort of buildings.² Surface-cooling elements such as cooling walls noticeably reduced the amount of noise and uncomfortable draughts and had an additional benefit by providing radiative heat exchange. Unlike with a chilled ceiling, the advantage of a CWW is that the air flowing over the water film is not only cooled but also simultaneously dehumidified because the water has a temperature below the dew point of the indoor air.

CWWs are designed to chill water, dehumidify, and clean the air. Moreover, they are connected to a heat pump that chills and heats water on both sides simultaneously, which reduces the energy consumption for these dual functions, as illustrated in Fig. 1. The heat pump integrated with a CWW supplies not only chilled water for air conditioning but also domestic hot water, improving energy efficiency through its multifunctionality. The chilled water temperature, dew point for dehumidifying indoor air, water falling speed, and water quality are the factors that should be considered and optimized for different climate zones.

Research on the indoor environment quality (IEQ) of CWWs has focused on temperate climates, with less results and discussion related to the hot and humid climate zone. Numerous thermal comfort standards have been published in the past years, especially International Organization for Standardization 7730³ and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55-1992,⁴ but the ASHRAE standard is only applicable to the North American climate. Lee et al.⁵ discovered that the thermal comfort area in a hot and humid zone is different from that specified in the ASHRAE standard. Givoni⁶ suggested that the thermal comfort temperate range had to be modified to 29°C and the humidity to 80% for hot and humid tropical regions.

CWW research has been conducted at the Fraunhofer Institute for Building Physics. However, the research results have indicated that no empirical values are available regarding how the existing model performs for a relative humidity higher than 80% or an air temperature above 26°C, conditions common in Taiwan, which in most areas has a yearly average relative humidity of higher than 75% and has monthly average relative humidity above 70%.⁷ Therefore, because the existing model was developed using empirical data, a more detailed theoretical model must be constructed for conducting research with all conceivable boundary conditions. Measurements made in subtropical and tropical climate zones must be verified to evaluate the performance of CWWs.

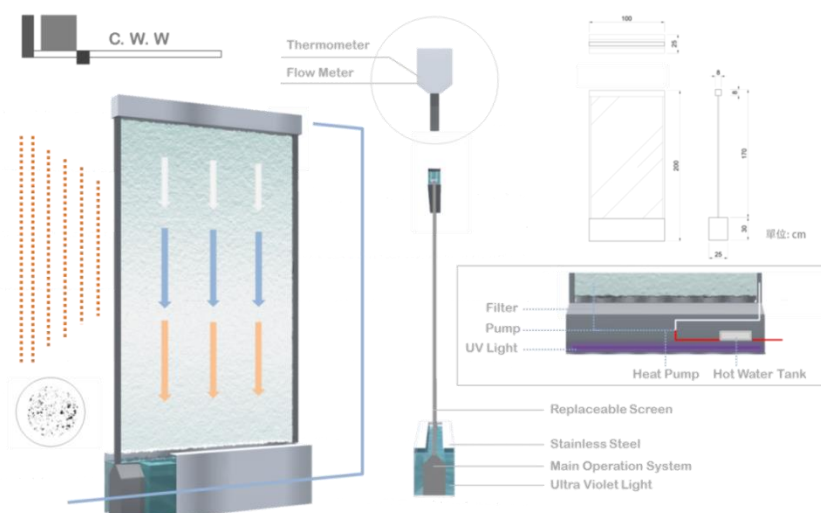


FIG. 1. Scheme of using a CWW with a heat pump for air conditioning, air cleaning, and water heating.

2. Methodology

According to the second law of thermodynamics (heat always flows spontaneously from a high-temperature heat source to a low-temperature heat source), the temperature of chilled water affects the radiative cooling efficiency at a given distance, as illustrated in Fig. 2. According to WUFI® simulation of a $5\text{ m} \times 5\text{ m}$ space at 26°C , the effective radiant cooling distance is approximately 2.5 m from a CWW when its chilled water temperature is 2°C , as shown in Fig. 3.⁸

A validation experiment was conducted in a full-size climate room to verify the parameters and boundary conditions for WUFI simulation. This study referred to the simulation results to design an experiment for determining the efficiency of a CWW in a hot and humid climate.

Two rooms of the same size were set up to compare climate conditions. The temperature of the CWW and air were measured, as well as the relative humidity of the air at various distances from the CWW, as illustrated in Fig. 4. A prototype CWW was placed in room A, as were the sensors used to measure the temperature, flow rate, and pressure of the chilled water in the prototype.

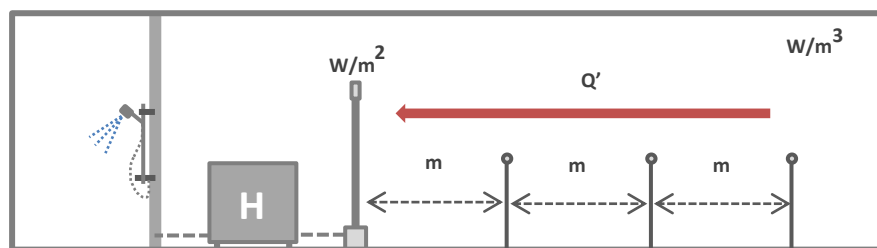


FIG. 2. Temperature of the chilled water affects the radiative cooling efficiency at a given distance.

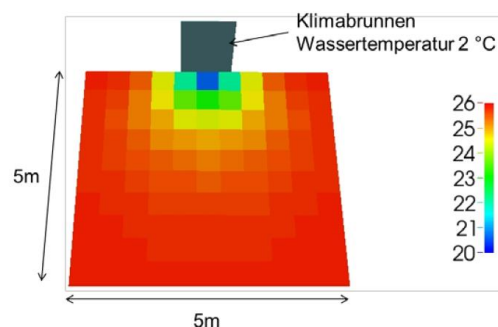


FIG. 3. Effective cooling distance simulation performed using WUFI.⁸

To evaluate the performance of the CWW, the chilled water temperatures in the water supply pipe (T_{CW}) and basin (T_W) of the water film were measured. The chilled and heated water temperatures (T_{CW} and T_{HW}), water velocities (V_{CW} and V_{HW}), and water pressures (P_{CW} and P_{HW}) were measured by sensors connected to a data logger (CR1000: Micro logger®).

To validate the simulation and real-site results, sensors measuring the air temperature (T_{ai}) and relative humidity (RHa_i) were set up at points 0 to 3 ($i = 0 \sim 3$) corresponding to distances from the CWW of 0~3 m (selected on the basis of the WUFI simulation result). A thermometer was also placed in the middle of room B and acted as point of a comparison. In addition to monitoring data of water temperature and flow during the water cycle, water quality was maintained using ultraviolet light and a filter for ensuring the CWW with heat pump was operating favorably, as indicated in Fig. 5. A water storage bucket wrapped with insulation material was employed to maintain the temperature of the chilled water from the heat pump that was used in the next CWW water cycle.

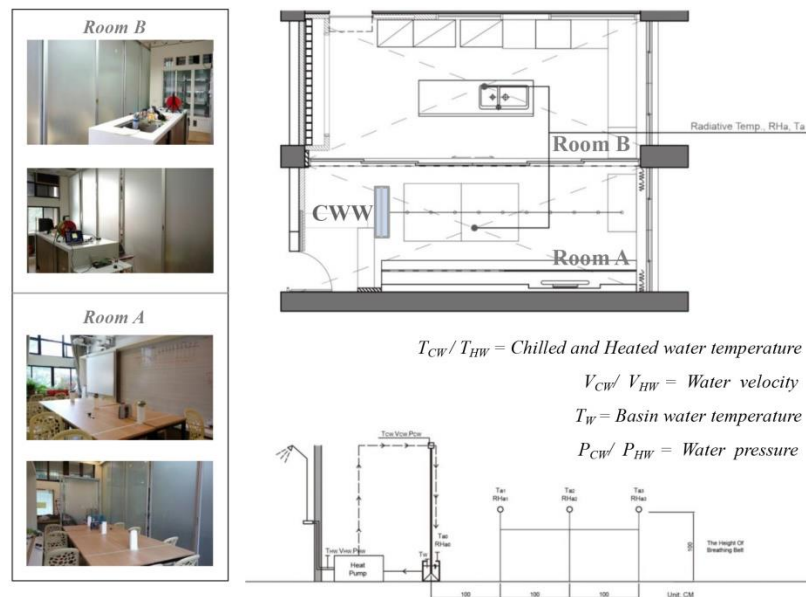


FIG. 4. Validation experiment and sensor setup in the two test rooms.

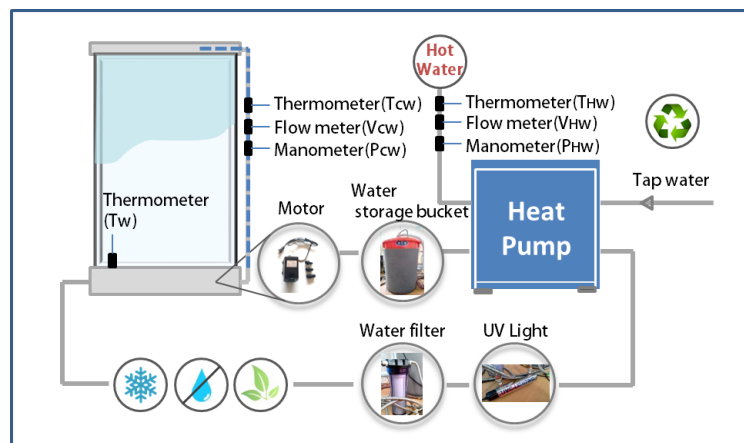


FIG. 5. Schematic of the chilled and heated water measurement points and cycle process of the CWW with heat pump.

Invited two occupants to enter the room A to do the questionnaire each time. To ensure that the metabolic equivalent of task of the occupants of room A was between 0.8 and 1.2, occupants sat quietly in room B for 5–10 min before they entered room A. The occupant then sat at point 0 (0.5 m from the CWW) to point 2 (2.5 m; selected on the basis of the effective cooling distance discovered in WUFI simulation), as illustrated in Fig. 6. The wind speed and noise from the CWW were recorded at each occupant position by using an anemometer and decibel meter, respectively. For each point, the occupant rated the IEQ [thermal comfort, air quality, visual comfort, and aural comfort] through a questionnaire.

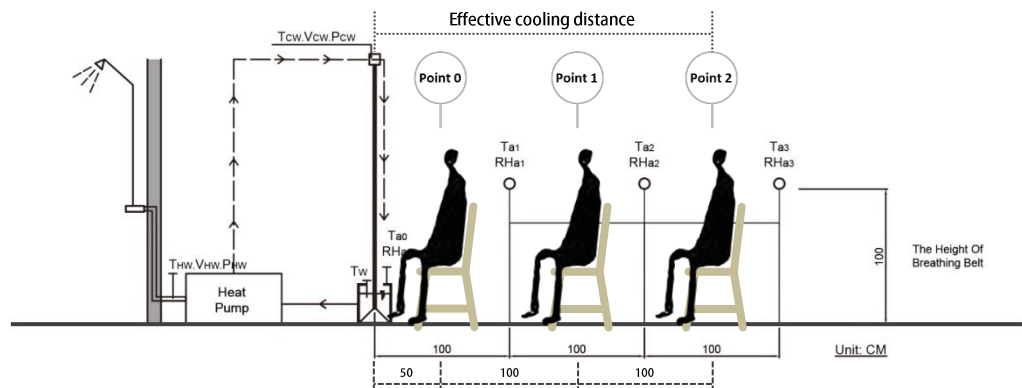


FIG. 6. Distance of occupant from the CWW: point 0 (0.5 m) to point 2 (2.5 m) in room A.

3. Results&Discussion

The test was conducted in the summer, when the indoor ambient temperature was approximately 32°C and the relative humidity was approximately 58.5%. The area of each room was approximately 20 m². Data were obtained every 5 min for 8 hours by using the automatic sampling method.

According to Fig. 7, the temperatures at the sensors located from the CWW (distance of 0 m) to 3 m away were 27°C, 30°C, and 32°C, respectively, when the chilled water temperature was 8°C to 9°C and the indoor ambient temperature was approximately 32°C. Comparing the charts of indoor air temperature, relative humidity, and absolute humidity, which are displayed in Figs. 7 and 8, the absolute humidity can be observed to be affected by the distance from the CWW. This verified that the CWW exerts a dehumidifying effect under these climate conditions. (The absolute humidity in room B was the highest absolute humidity measured in this test.) The relative humidity at point 0 (RH0) and point 1 (RH1) were always higher than that in room B because of the lower temperature in room A. The temperatures at point 2 (T2) and point 3 (T3) were similar to the indoor ambient temperature (approximately 32°C), and the difference in relative humidity between point 2 (RH2) and point 3 (RH3) indicates that the dehumidifying effect was stronger at point 2 than point 3, which was further from the CWW.

This result verifies the performance of the CWW at air cooling and dehumidifying, but some additional points are worth discussing regarding the dehumidifying and air-cooling effect of distance from the CWW. When the average water temperature is lower than the dew point temperature of indoor air, moisture in the air condenses more easily onto the water film, which must be reflected by a drop in the relative humidity. This study speculated that if the chilled water temperature was lower than or equal to 6°C for a long time, the cooling effect at each temperature point in room A would be stronger.

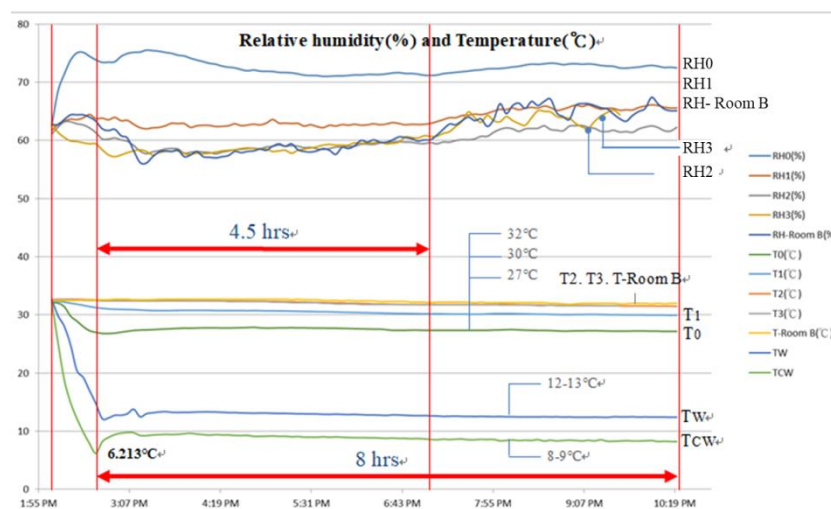


FIG. 7. The chart of temperature (°C) and relative humidity (%)

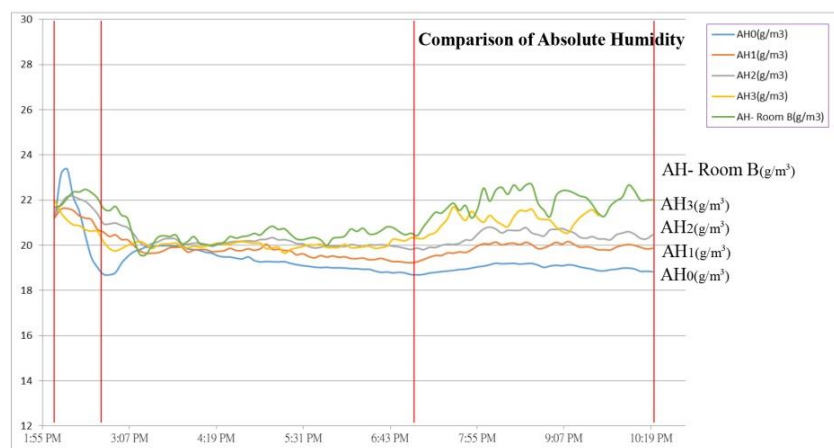


FIG. 8. The comparison of absolute humidity from each point

In this experiment, the average chilled and heated temperatures of water in the heat pump were approximately 9°C and 37°C, respectively, and the average chilled water flow was 2.8 L/min. The variation in the chilled and heated water temperature in this experiment is displayed in Fig. 9. The coefficient of performance of the heat pump was calculated to verify the energy efficiency, which is integrated with CWW.

To research all conceivable boundary conditions in subtropical and tropical climate zones, future studies must verify the performance of the CWW at air cooling and dehumidifying for various parameters of the CWW to reflect different climate zones (constant water temperature with constant water flow, constant water temperature with variable water flow, variable water temperature with constant water flow, and variable water temperature with variable water flow).

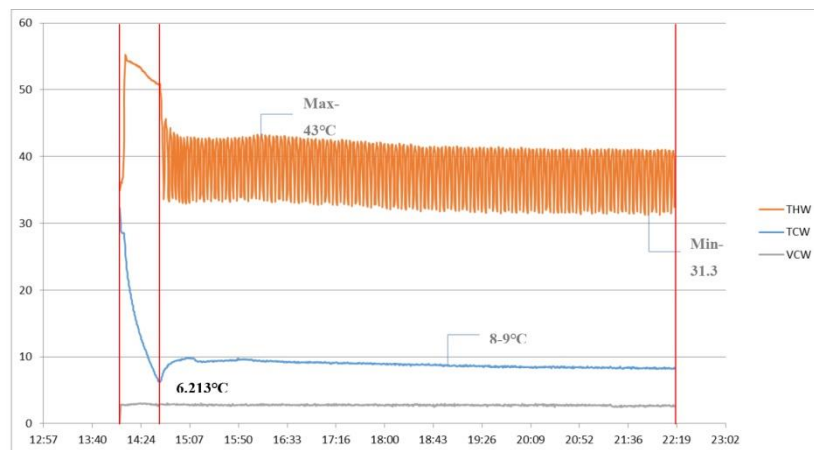
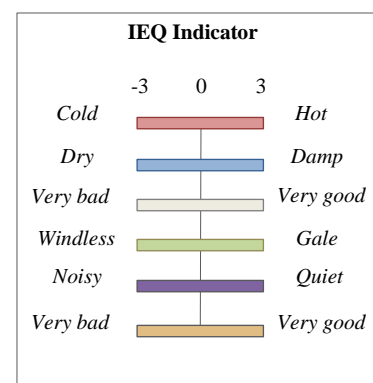
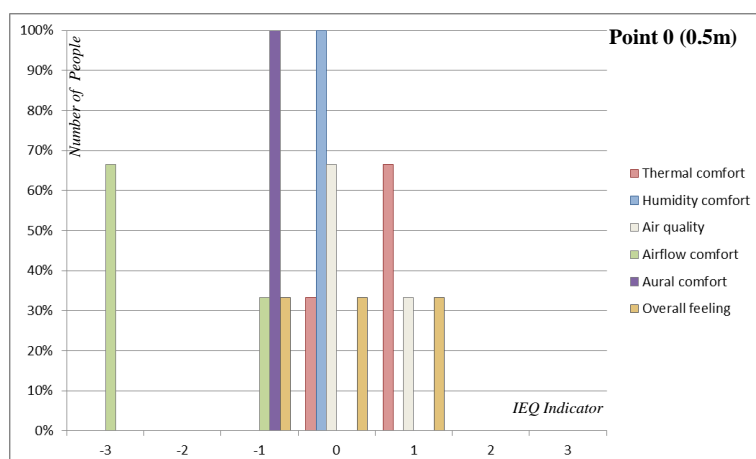


FIG. 9. Temperature of chilled and heated water in the heat pump.

The IEQ was scored by an occupant of the CWW-cooled room under hot and humid conditions. The occupant sat at point 0 (0.5 m from the CWW) to point 2 (2.5 m away) and completed the IEQ questionnaire, the results of which are illustrated in Fig. 10.

The occupant rated the thermal comfort as increasingly hot the further they sat from the CWW. The humidity comfort was rated around 0 (neither dry nor damp) at all points. Figure 7 shows that relative humidity maintained at below 80% is acceptable to people. Air quality and overall feeling were rated higher at point 3 than the other points. Aural comfort in this experiment was rated as noisy, probably because of the noise of heat pump operation.

In future research, more questionnaires will be collected and the predicted mean vote and predicted percentage dissatisfied calculated to determine satisfaction with the environment in greater detail. The IEQ results will be integrated, and the modified CWW parameters will be compared with the original CWW parameters for a different climate zone to verify the favorable performance of the CWW. In the next experiment, some impact factors may be needed to be controlled, such as the effective radiant cooling effect and dehumidifying distance from the CWW in different climate zones, chilled water temperature, water falling speed (pumped speed), and water quality for flushing air pollutants into water (using ultraviolet light and a filter).



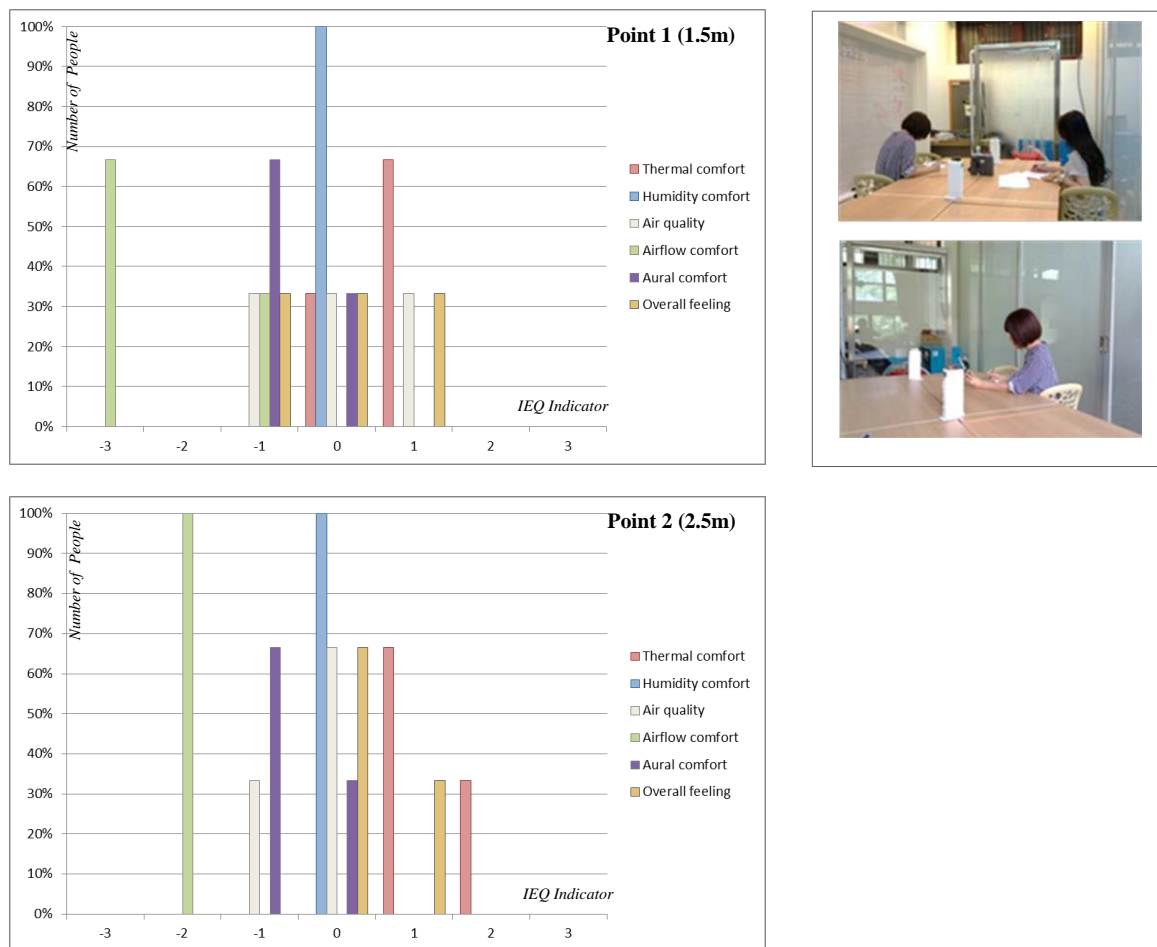


FIG. 10. Analysis of IEQ questionnaire results.

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