TEMPERATURE AND HUMIDITY DISTRIBUTIONS IN A MID-RISE RESIDENTIAL BUILDING SUITE

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ABSTRACT

It is essential to design and operate buildings with good indoor air quality as people spend most of their time indoor. Their productivity, comfort and health depend on the quality of the indoor air. In addition to other air quality parameters, indoor humidity and temperature need to be controlled and maintained to acceptable ranges. These conditions may not be uniform within the house/building due to local heat and moisture sources and absence of an effective indoor air mixing mechanism as in the case of in buildings with baseboard heating systems. Localized high humidity creates favourable conditions for localized mold growth, poor indoor air quality and building envelope damage. In this paper, the indoor humidity and temperature distributions within four suites (designated as Suite 'A', 'B', 'C' and 'D') in a six-storey multi-residential building are studied. A total of 22 rooms are monitored with indoor temperature and relative humidity data loggers, and the outdoor climatic conditions are measured with a weather station for over a year. The hygrothermal performances of exterior walls in the master bedrooms of the respective suites are assessed.

Analysis of the measured data suggests that the temperature variations between the rooms (bedrooms, living room, kitchen excluding bathroom) are relatively low during the summer period (mean temperature difference less than 1^{o}C) compared to the winter period where the variations between the rooms can be as high as 2^{o}C. The excess humidity differences between the rooms, excluding the kitchens, are in the range of 0.2 g/m^3 to 1.0 g/m^3 during both winter and summer periods, whereas the excess humidity fluctuations within the rooms are fairly the same and have standard deviation values between 0.8 g/m^3 and 1.0 g/m^3. Excess humidity is defined as the difference between the indoor and outdoor absolute humidities, quantities that are derived from the simultaneously measured temperature and relative humidity of the indoor and outdoor locations. Hygrothermal simulation results of exterior wall systems indicate that, in a mild coastal climate, the winter average indoor relative humidity shall be below 43% (for a seasonal average indoor temperature of 20^{o}C) to avoid building envelope moisture damage.

INTRODUCTION

The hygrothermal performance of building envelope components depends on the indoor and outdoor climatic conditions which they are exposed to. Based on outdoor climatic conditions building envelope designers choose appropriate materials and systems in their design process. For example in climatic region with a Moisture Index greater than one (MI >1) a rain screen wall system will be chosen to minimize moisture transfer from rain water absorbing claddings. To minimize condensation during winter seasons, the National Building Code (NBC 2010) puts a limit to the maximum indoor humidity that a house shall have, which is 35% in a cold climate and 60% in a mild climate. There are reports where these limits are exceeded in a room and/or house levels (Rousseau et al., 2007; Finch et al., 2006). The actual humidity condition in a room or house depends on occupant density and their activities associated with indoor heat and moisture generations in addition to the building's air exchange rate and level of moisture buffering material in the house/room (Tariku et al., 2011). In the current building envelope hygrothermal performance assessment practice, the indoor temperature and relative humidity are assumed to be uniformly distributed throughout indoor space, and defined as constant (Maref et al., 2009), or calculated as per the ASHRAE 160 Standard (2009) ‘Simple’ or ‘Intermediate’ models, or the European Standard EN ISO 13788 (2004), which is based on Sandberg (1995) work. The indoor air conditions generated with one of these models are later used in a deterministic building envelope hygrothermal performance analysis. The temperature and humidity distributions in a house or apartment suite can vary from room to room (Hens, 1992; Janssen and Vandepitte, 2006). The variation depends on the level of air mixing that occurs in the unit by the heating and/or ventilation system and outdoor climatic conditions. A forced-air heating system promotes mixing of air of different rooms and creates relatively uniform air conditions in comparison with an electrical heating system (CMHC, 2006). As the local moisture and heat gains in an electrically heated unit remains locally, in some cases significantly higher than the other rooms. It is useful to understand the temperature and humidity variations that are expected in such units to identify and effectively assess the hygrothermal performance of a critical building envelope section. In this paper, the temperature and humidity distributions in 22 rooms of four apartment suites that are electrically heated are investigated. The temperature and humidity variations within the apartment units and between the units are presented. In addition, the hygrothermal responses of the suites’ exterior walls, and more specifically, the moisture content profile of a critical layer in the corresponding exterior walls are reported.

STUDIED BUILDING

To assess the indoor temperature and humidity distributions in a multi-unit residential building in Vancouver, the temperature and humidity of 22 rooms in four suites of a six-storey residential building were monitored for 17 months. The four suites that are considered in this study are all on the fifth floor and represent different occupant density, floor area and physical orientations. They were chosen to be at the same height level to allow similar outdoor and corridor environmental exposures including stack and mechanical corridor pressures. Suite ‘A’ and Suite ‘D’ are end units and Suite ‘B’ is adjacent to a Lounge room in the east and a neighbour suite in the west. The corridors of the suites, except that of Suite ‘B’, are pressurized and conditioned. Two of the suites (Suite ‘B’ and ‘D’) have two bedrooms and the other two (Suite ‘A’ and ‘C’) have three bedrooms. Each suite has an open style kitchen (facing to a foyer and a living room), a bathroom and a living room with a balcony. The two bedroom suites have a floor area of 643 sq.ft. and 654 sq.ft., whereas the three bedrooms have a floor area of 892 sq.ft. each. The number of occupants in the suites varies from two to six. Table 1 shows the occupants in the tested suites and measured exhaust fan ventilation capacity.

	Suite ‘A’	**Suite ‘B’**	**Suite ‘C’**	**Suite ‘D’**
Floor area (sq.ft.)	892	643	892	654
Number of occupants	3	4	6	2
Measured exhaust fan ventilation capacity (CFM)	61	66	51	72

TABLE 1: TESTED SUITES’ OCCUPANT DENSITY AND MEASURED EXHAUST FAN VENTILATION CAPACITY

Mechanical ventilation is provided using the bathroom exhaust fans (Panasonic FV-1VQ3), which have a manufacturer rating of 110 CFM but measured ventilation rate capacities of 51 to 72 CFM as shown in Table 1. The operations of the fans are automatically controlled with a pre-set ventilation time schedule eight hours a day; four hours in the morning (7 am to 11 am) and another four hours in the evening (6 pm to 10 pm). The same time-controlled ventilation strategy is implemented in all suites to synchronize the fans’ operations and avoid intra suite airflow. All the suites are heated by electric baseboard heaters while the corridors are heated by a forced-air heating system.

CALIBRATION

To assess the level of variations in temperature and humidity among the rooms in the same suite, temperature and relative humidity data loggers (HOBO Onset U12-011 and Onset U12-013) were placed in each bedroom, kitchen, bathroom and living room of each suite at 2.0 m high from the floor level. In addition, two data loggers installed in the north and east corridors, one each, to simultaneously capture the corridor air temperature and relative humidity conditions. The temperature and relative humidity monitoring of the 22 rooms and two corridors started on May 15, 2010 and concluded on October 20, 2011. The HOBOs log data every two minutes and the data was downloaded on a computer once a month. To correlate the indoor and outdoor climatic conditions, the local outdoor air temperature and relative humidity are measured every minute and downloaded to a computer once a month. The weather sensors were bought for the project and assumed to be within the manufacturer's calibration range. The indoor temperature and humidity data loggers (HOBOs) were calibrated in-house using a climatic chamber. Figure 1 shows the temperature and relative humidity readings of the data loggers at the three reference environments: 35%, 52% and 70% relative humidity and 21°C. As shown in the figure, the HOBO readings at all three settings are consistent. The relative humidity difference between the maximum and the minimum readings at given set points are under 2.5%. Thus in general, the accuracies of the data loggers are within the range of the manufacturer specifications (2.5%). The result of this calibration exercise suggested that the data loggers' readings can directly be used in further analysis.

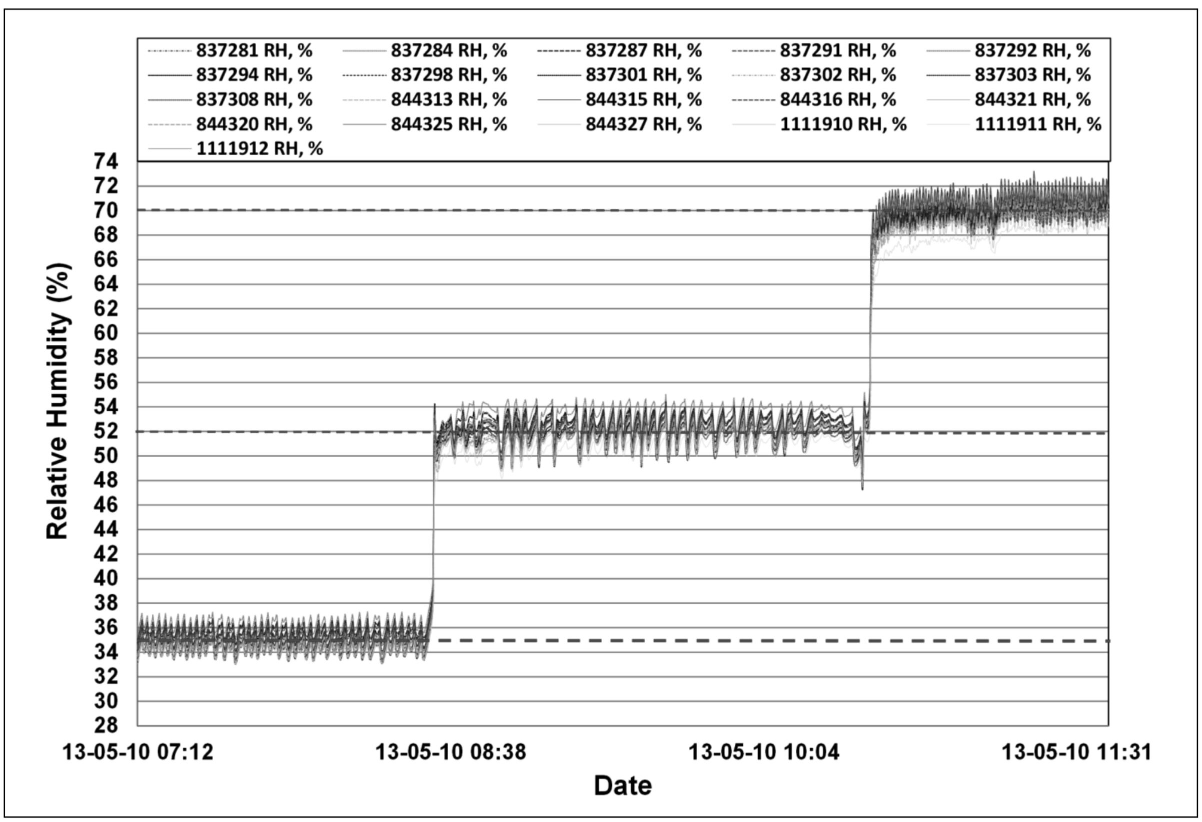

FIGURE 1: RELATIVE HUMIDITY READINGS OF HOBO DATA LOGGERS DURING THE CALIBRATION PROCESS.

RESULTS

In this section, the indoor temperature and excess humidity distributions in the 22 rooms during the winter and summer periods and the hygrothermal simulation results of the suites' exterior walls are presented. Excess humidity is defined as the difference between the indoor and outdoor absolute humidities, quantities that are derived from the simultaneously measured temperature and relative humidity of the indoor and outdoor locations. In this study, the winter and summer periods are defined from December to February and from June to August, respectively.

INDOOR TEMPERATURE DISTRIBUTIONS WITHIN SUITES

The average winter temperatures of the 22 rooms are shown in Figure 2 a). The seasonal average temperatures in the bathroom are higher than those of the other rooms in the suites, which is attributed to the small volume of the bathroom and the local heat gains from the light bulbs. The seasonal average temperature difference between a bathroom and other rooms in a suite with the lowest temperature can be as high as 3.6^{o}C.

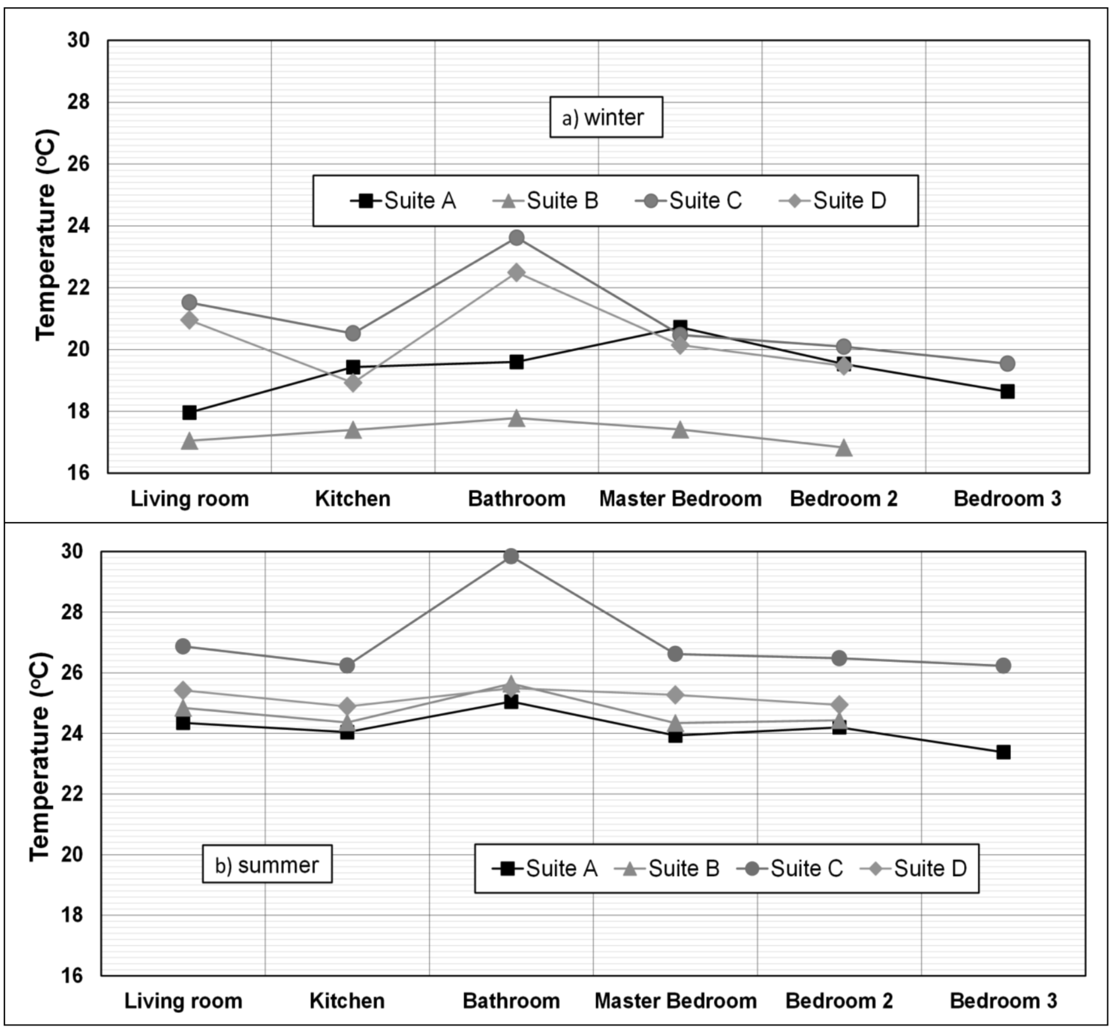

FIGURE 2: AVERAGE TEMPERATURE OF THE 22 ROOMS DURING THE WINTER a) AND SUMMER b) PERIODS.

Since the occupants in Suite ‘A’ use a portable heater and humidifier in the master bedroom, the temperature and humidity in this room are relatively high. In general, the master bedrooms are relatively warmer than the other occupied bedrooms. The differences, however, are within 1.0°C. The living room and the master bedroom temperatures differences are also within 1.0°C. As shown in Figure 3, the temperature fluctuations within the rooms are similar in all the suites except Suite ‘A’. Based on the data presented in this paper, during the winter period, the temperature difference between rooms excluding bathrooms are within 2.0°C and the standard deviations of the temperature fluctuations within the rooms are about 1.0°C. During the summer period, the temperature fluctuations within the rooms are relatively high compared to that of the winter period as indicated by the higher standard deviation values of about 2.0°C (twice of the winter period). The seasonal average temperatures of the rooms excluding the bathrooms, however, are close and are within a 0.5°C difference. The nearly uniform and highly fluctuating indoor temperatures in the suites during the summer period are attributed to the modest air mixing in the suites and the variable natural ventilation caused by wind and occupants’ window opening, respectively.

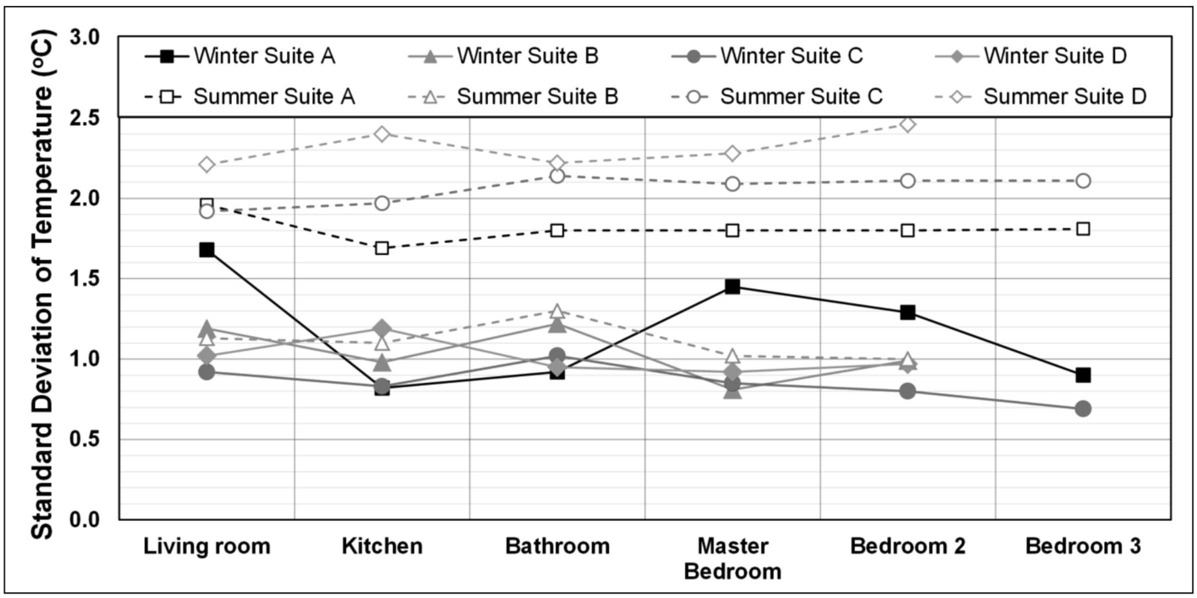

FIGURE 3: STANDARD DEVIATION OF TEMPERATURE VARIATIONS IN THE 22 ROOMS DURING THE WINTER AND SUMMER PERIODS

Excess humidity distribution within Suites

The seasonal average excess humidity in the living rooms, kitchens, bathrooms and bedrooms of the four suites are presented Figure 4. As can be seen in the Figure 4 a), during the winter period, the measurement shows two groups of suites with low and high excess humidity levels, under 3.0 g/m³ and over 4.0 g/m³, respectively. With the exception of the master bedroom in Suite ‘A’, which has a portable humidifier, the excess humidities distributions within the suites are fairly uniform with no significant difference between rooms to room of the same suites.

During the summer period, Figure 4 b), the excess humidity in the suites varies from 1.2 g/m³ to nearly 4.0 g/m³. They are generally lower than the winter values due to the increase in natural ventilation during the summer period. Similar to the winter period, the excess humidity within the suites is fairly uniform with slightly higher values in the kitchens. The excess humidity differences between rooms in the suites excluding the kitchens are less than 1.0 g/m³. As shown in Figure 5 the excess humidity fluctuations (standard deviation) in the rooms of the same suite are fairly the same. Unlike the indoor temperature in Figure 3, the excess humidity fluctuations within the rooms during the winter and summer periods are close. In general, with the exception of the master bedroom in Suite 'A', the excess humidity fluctuations in the 21 rooms are within a standard deviation range of 0.8 g/m³ and 1.2 g/m³ during both winter and summer periods.

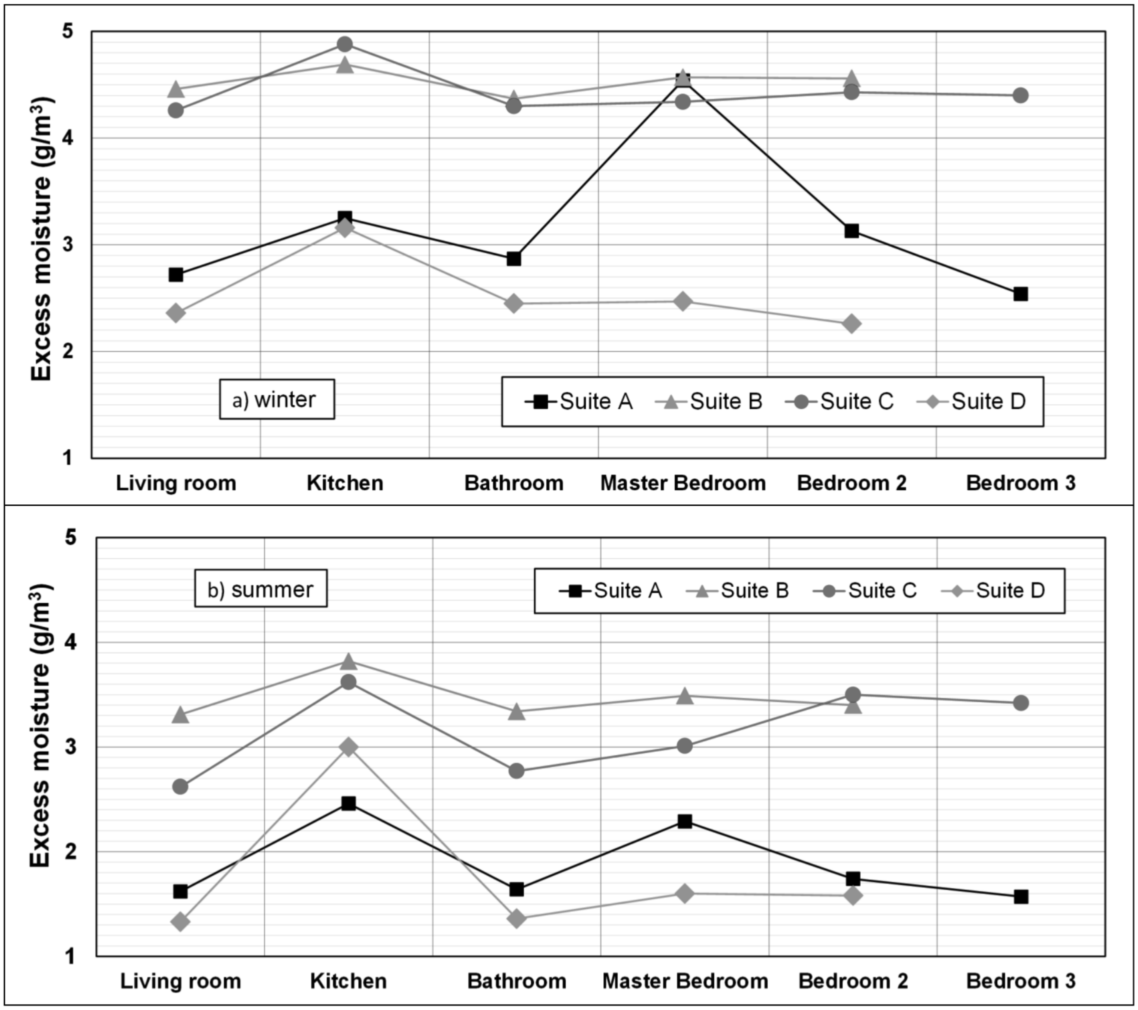

FIGURE 4: AVERAGE EXCESS HUMIDITY OF THE 22 ROOMS DURING THE WINTER a) AND SUMMER b) PERIODS.

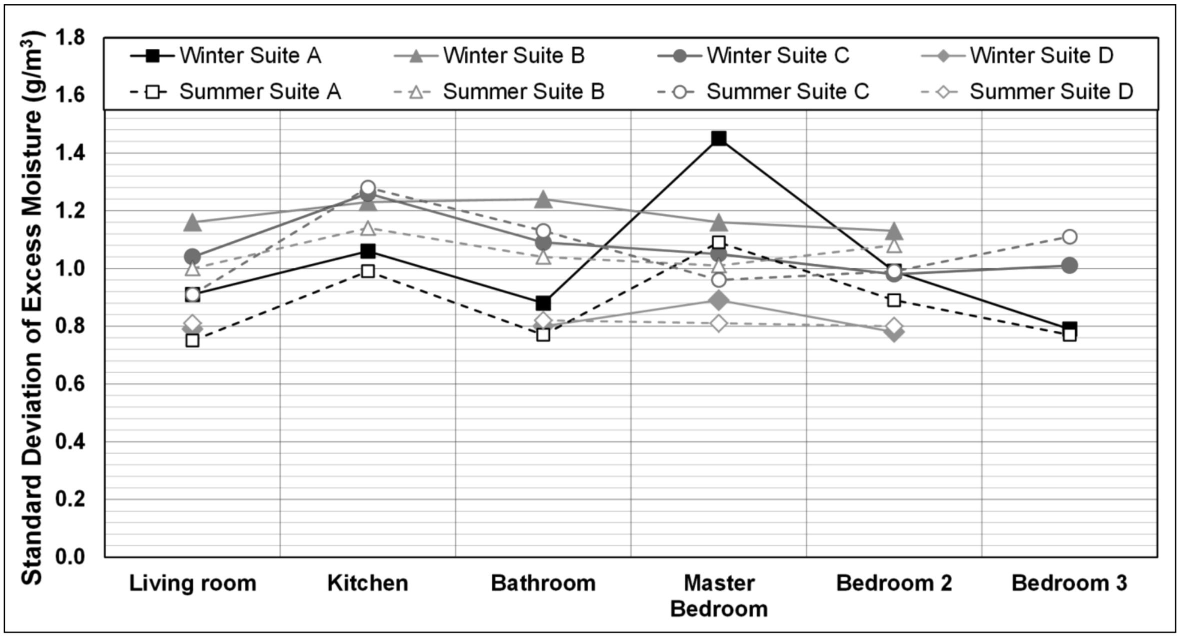

FIGURE 5: STANDARD DEVIATION OF EXCESS HUMIDITY VARIATIONS IN THE TWENTY-TWO ROOMS DURING THE WINTER AND SUMMER PERIODS.

Hygrothermal performance assessment of the suites' exterior walls

The moisture performances of the exterior walls for the four suites considered in this study are assessed using an advanced hygrothermal model called HAMFit (Tariku 2008 and Tariku et al. 2010). The benchmarking, validation and application of the transient model can be found in (Tariku et al. 2009, Tariku et al. 2010). As shown in the previous section, the humidity in the master bedrooms is generally higher than the other rooms, which makes the exterior walls in these rooms at a relatively higher risk of moisture damage in comparison with the other rooms. Here, the exterior walls of the master bedrooms are considered for hygrothermal modelling. The walls have the following configurations: latex painted drywall at the interior followed by steel stud cavity filled with fiberglass butt insulation (R-8), exterior gypsum sheathing, self-adhesive membrane, semi-rigid mineral wall insulation, air space and stucco cladding on the exterior. The thermal and moisture transport and storage properties of the materials are taken from the ASHRAE research project RP-1018 (Kumaran et al. 2002) and the IEA/Annex-24 Task-3 report (Kumaran, 1996). The measured indoor temperature and humidity in the master bedrooms and the local outdoor climatic conditions from a rooftop weather station are used to establish the indoor and outdoor boundary conditions for the hygrothermal simulation.

Simulation Results

The hygrothermal simulations are carried out for the period starting August 1, 2010 to September 30, 2011. For the wall system considered in this study, the critical layer that is highly susceptible to moisture damage is the sheathing board—exterior grade gypsum layer. Thus, here, the moisture profiles of this critical layer during the one year simulation period is reported (other simulation results are not reported due to space limitation. Figure 6 and Figure 7 show the relative humidity conditions of the interior surface and the total moisture content of the exterior gypsum board in the four suites' exterior walls, respectively. The moisture content of the exterior gypsum increases during the fall period and peaks during the winter period before starting to dry in the spring and continuing to dry in the summer period.

Based on the simulation result, the moisture condition of the sheathings of all the master bedroom's walls, with the exception of that of Suite 'D', have excessive moisture accumulations during the winter and the spring periods. The moisture condition of the sheathing in Suite 'D' is acceptable as it always remains under 80% relative humidity. The relative humidity of the interior surface of the sheathing in Suite 'A' and Suite 'C' are comparable and are under 90% almost all of the time. However, the relative humidity of these surfaces remains above 80% for an extended period of time (November to April). According to the ASHRAE 160 Standard (2009), the maximum period of relative humidity over 80% is limited to 30 days to avoid moisture damage. The conditions of the exterior sheathings in Suite 'A', 'B' and 'C' can be problematic. Of the three, the moisture accumulation on the exterior sheathing of Suite 'B' is significantly higher than the other two, which is attributed to the relatively high humidity and low temperature conditions of the indoor air. During the winter period, Suite 'A' has excess moisture higher than Suite 'C', which promotes more condensation. Despite the higher excess moisture condition in the master bedroom of Suite 'A', the moisture accumulation in the exterior gypsum of Suite 'A' is comparable to that of Suite 'C'. This is due to the fact that the sheathing in Suite 'A' is slightly warmer than that of Suite 'C' as a consequence of warmer master bedroom temperatures. As shown in Figure 6 and Figure 7, the moisture in the exterior gypsum in Suite 'B' is significantly higher, over 95% relative humidity for more than 60 days and over 80% relative humidity from November to the end of May (over 200 days).

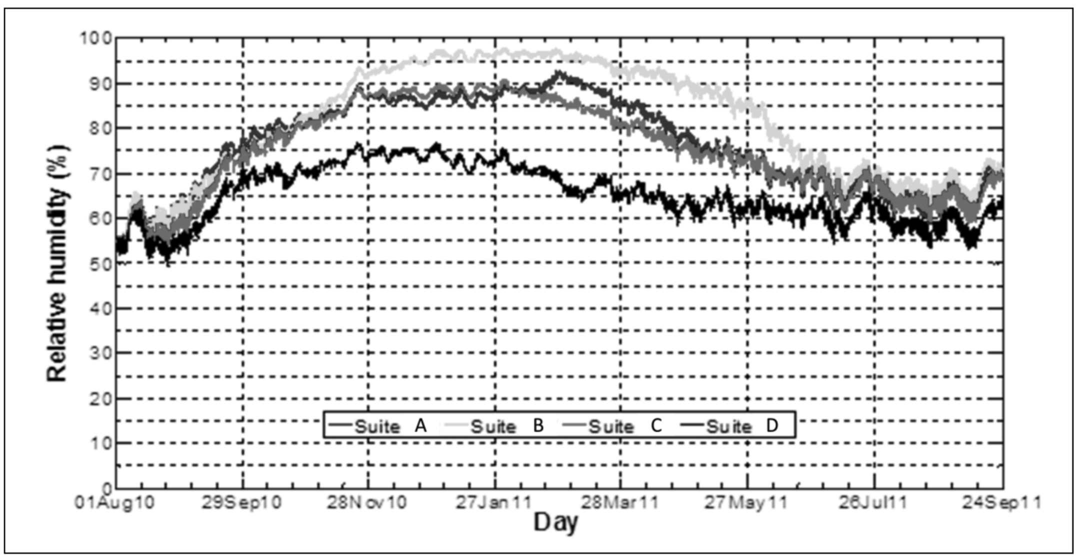

FIGURE 6: RELATIVE HUMIDITY OF EXTERIOR GYPSUM LAYER AT THE INTERIOR SURFACE FOR FOUR SUITES.

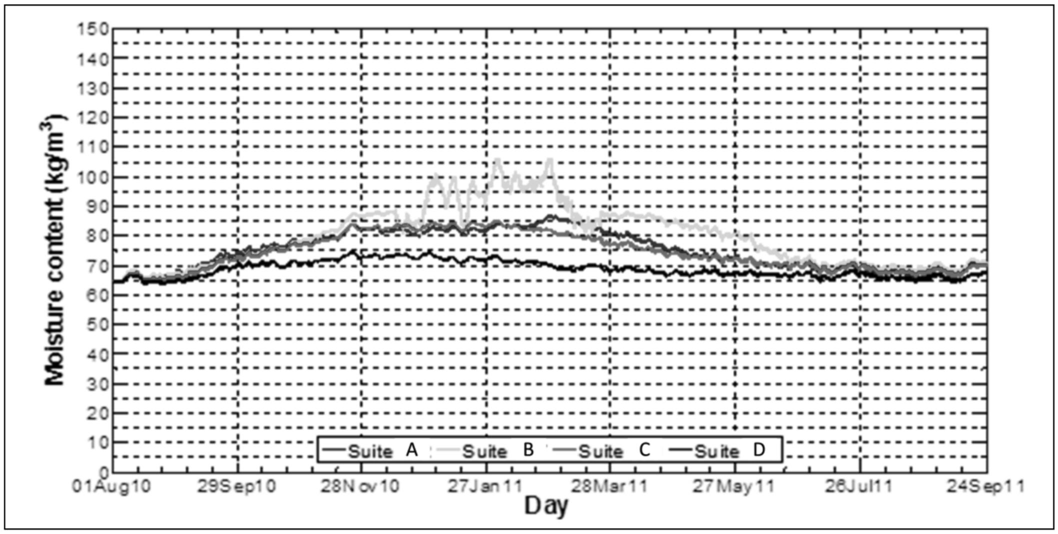

FIGURE 7: EXTERIOR GYPSUM LAYER MOISTURE CONTENT FOR FOUR SUITES.

CONCLUSION

During the winter period, the temperature fluctuations in rooms are relatively low, but the temperature differences between rooms in a suite can be as great as 2°C. During the summer period, however, the temperature variations within the rooms are large (standard deviation of about 2°C) while the differences between the rooms are small, which are the direct opposite of the winter period conditions. These seasonal temperature distributions are related to the levels of air movement in the two seasons. Higher natural ventilation in the summer period results in higher air circulation and more uniform temperature distribution within the suites, and the low natural ventilation and thermostat control during the winter results in less indoor air mixing and less variation in room temperature. During both winter and summer periods, the excess humidity differences in the rooms, excluding the kitchens, are in the range of 0.2 g/m^3 to 1.0 g/m^3, while the excess humidity fluctuations in the rooms have similar standard deviations (about 1.0 g/m^3).

The hygrothermal performance analysis of the exterior walls for the suites under consideration indicates that for the wall system to maintain acceptable building envelope performance, the winter indoor conditions in the suites should be maintained at seasonal average temperature of 20°C and relative humidity of below 40%.

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