MONITORING INDOOR RELATIVE HUMIDITY FLUCTUATIONS ASSOCIATED WITH INTERMITTENT OPERATION OF AIR-CONDITIONERS

J.L. Niu and J. Burnett
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hunghom, Kowloon, Hong Kong SAR, China

ABSTRACT

In residential buildings, air-conditioners are usually operated in intermittent mode. This intermittent mode may complicate many aspects of indoor environments. Indoor humidity excess is a major problem, since humidity excess is associated with biological pollution and formaldehyde emission. This paper reports our monitoring of indoor air temperature and relative humidity in a real life building in the hot humid Hong Kong climate. These monitored results indicate that, in residential buildings, occupants' habits in using windows for natural ventilation exacerbate indoor relative humidity excess. The outdoor air moisture is the major moisture source, and when this air encounters the pre-cooled thermal masses within the building at off-hours, indoor relative humidity is raised. For residential buildings, a constant ventilation rate at the on-time of air-conditioner is desirable, while it is not desirable to have high natural ventilation rate at off-time. These monitoring results also validated our simulation results reported in an earlier publication.

INTRODUCTION

It is well known that indoor molds/mildew growth is a common problem in ordinary households in hot and humid climates. One report of the investigation of indoor moisture excess and its impact on indoor biological pollution concluded that summer humidity above 60% in one week will cause indoor air problem for the whole year [1]. Other indirect health effects of indoor air humidity are reviewed in an ASHRAE publication [2]. How the use of window-type air conditioners in residential buildings helps to reduce or exacerbate the humidity problem is an issue of scientific investigation.

As described in the ASHRAE handbook [3], window-type room air conditioners are typically designed with an adjustable built-in thermostat. The thermostat and unit controls may operate in one of the following modes:

a). The circulation fan runs without interruption while the thermostat cycles the compressor on and off.

b). A two- or three-stage thermostat can reduce the fan speed, and further cycle the compressor at the low fan speed.

c). Both the fan and the compressor are cycled simultaneously by the thermostat. This cycling can occur automatically at the reduced speed with mode b), or at any possible manually-set fan speed with some units.

Cycling control of an a/c unit virtually changes the ratio of sensible to total heat removal capacity. Data from Khattar et al. [4] show that the ratio of sensible to total heat changes at start-up - implying that sensible and latent cooling capacities changes at different rates with cycling. Parken et al. [5] reported on field tests where latent capacity was delayed 1 to 2 minutes at start-up. Mathematical models are required for quantitative evaluation of the impact on indoor air humidity. Henderson [6] used an exponential function with a dead time to represent latent and sensible capacity. Coupled with a thermostat model and building model, the effects of a/c system constants, over-sizing, and latent delay time in cycling on energy use and room relative humidity were investigated. However, their results indicated that any reasonable mismatch in latent and sensible capacity has only a small impact on humidity. Nguyen and Goldschmidt [7] and Nelson [8] particularly examined the effect of thermostat time constant on the cycling period, using mathematical modeling method. The effects on humidity control and energy performance of a/c cycling under different thermostat controls were both experimentally [5] and mathematically studied [9]. In one simulation study reported by Henderson [9], the effect of building thermal mass, thermostat, and equipment sizing on the a/c cycling rate and energy use were studied for a summer day (July 23) in a typical 140 m^2 wood-frame house located in Florida. These studies have led to greater understanding of the effects on humidity control and energy performance of the thermostat design parameter, and sensible and latent cooling capacity ratio of an a/c unit in relation to the building thermal dynamics.

However, these studies basically focused on the 'on' period behavior of the a/c. No systematic researches addressing the alternate a/c running and window-opening practice in residential environments in hot and humid climates are reported in the literature. Depending on the habits of the occupants, the air conditioners in residential buildings may only run intermittently. This intermittent operation mode can be attributed to several factors. Most people prefer to keep their windows closed when running their air-conditioners. Then in the relatively cool period of the day, they switch off their air-conditioners, and also tend to open the window to obtain ventilation. In reality, the use pattern of window and air-conditioners can be very much diversified. In hot humid climates, outdoor air temperature and humidity can hover around 30°C (86°F), and 80% for a long continuous period. With the use of air-conditioning, indoor air temperature will reach as low as 23°C (73.4°F), depending on the occupants' preferences. When the outdoor warm and humid air gets into the room by natural infiltration, it will be mixed with indoor air to raise the indoor air humidity and temperature. One important fact here is that the interior envelope surfaces, furniture and other contents in the room are cooled during the a/c on-period. These inside temperatures may be well below the dew point of the outdoor air. On the other hand, the surface temperatures will rise due to conductive and radiative heat gains. In other words, the surface temperature rise and the indoor air humidity rise occur simultaneously. The local relative humidity near a cold wall surface may become too high, if the rise the wall surface temperature lags behind the rise of the indoor air moisture content. In turn, the rate of the surface temperature rise will depend on the mass and thermodynamic properties of the wall material. Therefore, in reality indoor air humidity is further complicated by the alternate use of a/c and windows.

METHOD

In order to understand the mechanisms of indoor relative humidity fluctuations associated with this practice, real life measurements and simulation were conducted. Moisture models are implemented into a building thermal simulation program called ACCURACY [10]. Site measurements were taken to establish the natural ventilation rates, which are used as input for the program. The construction of the moisture simulation model and the preliminary simulation results can be found in an earlier publication of the authors [10]. The simulation results indicated that the intermittent use of a/c and combined use of window causes relative humidity excesses. It seems that heavier building envelope masses exacerbate the situation, and that day time natural ventilation, coupled with the night-time cooled walls, tend to increase the day time relative humidity. This paper mainly presents the monitored indoor and outdoor relative humidity and temperature variations in the course of the day.

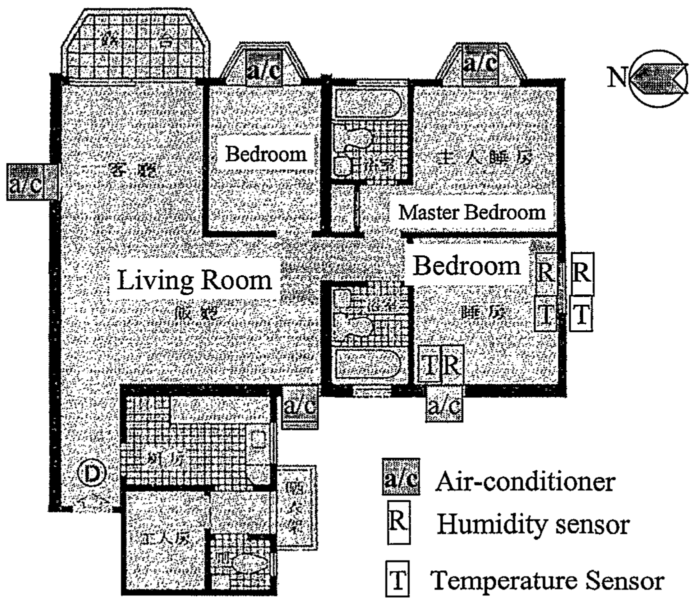

Figure 1 Plan layout of the monitored residential flat unit

MONITORING OF RH AND TEMPERATURE IN A FLAT

The building description

To reveal the above problems, a typical high rise residential building was selected for relative humidity and temperature monitoring. The building has 29 stories, with 4 flats on each floor. A flat situated on the 18th floor, was selected for monitoring. The flat unit basically is south- and east-facing, with 50% of the north-facing wall adjacent to the closed staircase of the building (Figure 1). The west side is shaded by the adjacent unit. The unit flat has a floor area of round 100 m^2. There are five window-type air conditioners - two for the living room, and each for the three bedrooms. Typically, the three air-conditioners for the bedroom are operated during nighttime, and switched off during the day. In the morning hours, all the air-conditioners are off, and all the windows and the sliding glazing door to the terrace are opened to obtain some natural ventilation. In the later afternoon hours, one of the air-conditioners in the living room may be switched on, and the doors between the living room and the bedrooms would be closed. The child may have an after lunch nap, and in this case, the air-conditioner in the child's bedroom will be operated for one or two hours in the afternoon.

The bedroom

The child's bedroom is selected for measurement. The room size is 3 x 2.9 x 2.7 m^3. The room has two external walls facing south and west respectively, with the west-facing wall shaded by the adjacent tower block. The wall is typically of 100 mm thick light concrete slab for high rise residential buildings, and the floor is heavy concrete slab with wooden floor covering. The room is equipped with one window-type air-conditioner. The window type air-conditioner has two fan speeds. The speed can be manually set by the occupants at 'high' or 'low' positions. The thermostat set-point can be adjusted by the occupants from 'high cool' to 'low cool' positions. The design is such that the fan keeps running all the time once the air-conditioner is switched on, while the compressor is cycled on and off by the thermostat. In this room, the fan speed was set at the 'low' position, and the thermostat was set at the 'moderate' cool position. These were actually the usual settings by the user of the flat. The temperature and humidity monitoring was carried out from 29 August to 3 September 1997. Two temperature and humidity sensors (VAISALA HMW 20 YB RH&T Transmitters) were used to monitor the indoor and outdoor temperature and rh simultaneously. For the outdoor measurement, the sensors were located on the outside windowsill, and for the indoor measurement, the sensors were placed at the corner of the south facing external wall and floor.

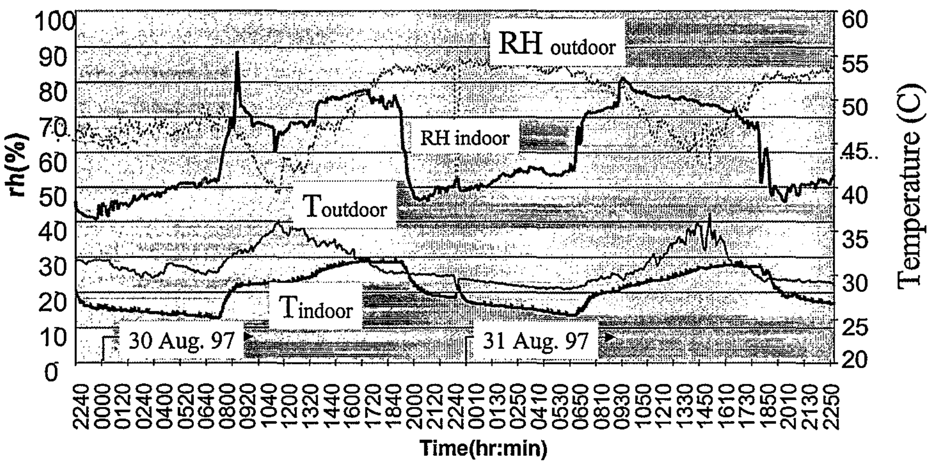

Figure 2. Monitored RH and temperature on the 1st and 2nd day

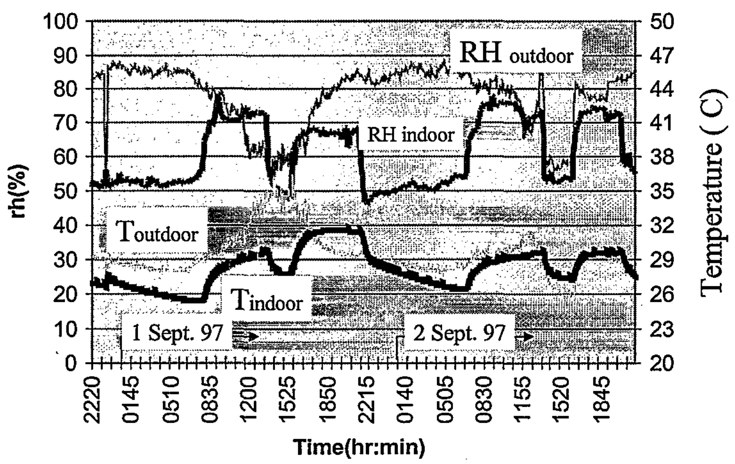

Figure 3. Monitored indoor and outdoor RH and temperature on the 3rd and 4th days

RESULTS

On 29 August 1997, around 20:30, the 'night mode' started. The monitoring started around 22:40. Around 8:00, 30 August 1997, as the child woke up, the daytime mode started. Such pattern was repeated in the next few days. The monitored results for the first two days are shown in Figure 2. It can be seen that the night temperature was maintained between 25 and 27.5 °C, and rh between 45 to 55%. The daytime rh remained above 70% most of the time. Outdoor temperature and rh are also plotted in Figure 2. What should be noted is that the rh maximum occurred at late morning time. The overall indoor rh profile validates the hypothesis we put forward in this paper. An air-conditioner can maintain room humidity at desired values at operation period when the fan speed and thermostat are properly set. At off-period, when the windows was open, indoor rh can go excessively high, due to the effect of cooled-envelop. It should be noted that, judged from the temperature profile during the on hours, it seems that the air-conditioner was never cycled during the monitoring period. Rather, the temperature was being continuously lowered. It seems that the room was not cooled down to the set-point yet, and that cooling down was occurring all the time during the on hours. This obviously depends on the matching between the room cooling load and the cooling capacity, as well as the set-point. The cooling capacity is affected by the fan speed, which was always set at the low speed by the user in this room, partly because of the high noise that would be generated at high speed.

Some continuous monitoring results in the following two days more or less repeat the above pattern (Figure 3). In these two days, the effects of running the air-conditioners in the child's afternoon nap hours can be seen. Also in the plotted profiles both in Figure 2 and 3, there are several data points, which seems indicating the approaching values between indoor and outdoor. This is because the sensors were moved to another room for data downloading during the measurement. Therefore, this indicated the good sensitivity of the sensors used during the measurements.

CONCLUSIONS AND DISCCUSIONS

With the intermittent a/c unit use pattern and open-window practice in residential buildings, indoor air humidity behavior is complicated by the many factors which include building thermal masses, and the size and characteristics of a window-type air conditioner, and day and night natural ventilation or infiltration rates. One unique characteristic is that, in hot and humid climate, outdoor air is the dominating moisture source. As the building envelope and the air-conditioner modify the indoor temperature, relative humidity may become too high in the off period of the air conditioner. This unique moisture dynamic behavior is confirmed in our measurement in an actual bedroom in use in Hong Kong, and indoor humidity above 75% rh occurred most of the time during the summer days monitored. It should be noted that the lowest temperature during the night was always above 25°C in the tested bedroom. Many users tend to have a much lower room set-point. It can be expected that the lower the temperature of the wall during the on-hours, the higher the RH during the off hours. In fact, this was 'tested' in our earlier simulation studies [10]. The general conclusion that might be drawn from these preliminary studies is that air-conditioners certainly improve the thermal comfort during its operation. However, in the current residential building design in warm and humid climates, how to obtain ventilation is very much a matter of occupants' habits and preferences. While ventilation presumably dilute any indoor-originated pollutants including radon, VOCs, and other bio-effluents from occupants, it also brings in moisture. When interacting with the mechanically cooled building thermal masses, excessive relative humidity, even condensation occurs in some cases. At extreme cases, a TV failed to start due to this condensation problem. The most common problem would the microbial pollution associated with moulds/mildew growth, and the dust mites multiplication on beddings and in wardrobes. The presence of a moldy odor in turn may intrigue the occupants to over-ventilate their rooms, which will further exacerbate the situation. The actual prevalence of the associated microbial pollution should deserve further investigations.

Good engineering solutions should embrace the conflicting requirements for moisture control and energy use. Unlike office buildings, occupancy patterns in residential buildings are more irregular, and internal pollutant and moisture load and ventilation requirements tend to vary with a wider range. For instance, high moisture contents tend to be generated in very short period during cooking, diner, and bathing activities. If an all-round air-conditioning system is provided, the peak capacity required would be very high, and the system will operate inefficiently at low load conditions. To achieve an overall comfortable and healthy indoor environment, a complete system that integrates, and yet de-couples cooling, dehumidification, and ventilation control will be required. A complete new design concept will be required.

With the current typical design in hot and humid climates, a sensible use pattern of the equipment and window should be considered as essential part of house keeping practices. It is better to maintain minimum but adequate ventilation when the air conditioner is running, by setting the exhaust flap of the air-conditioner at open positions. On the other hand, when the air-conditioner is off and the building is not occupied, it is better not to open the window, so that less amount of the more humid outdoor air enter the cooled rooms. In this way, the humidity peaks associated with the off-period may be lowered. When occupants return home, windows may be re-opened for a short interval to flush any possibly accumulated indoor pollutants before the air-conditioner is switched on. Further monitoring of the other pollutants levels including radon, VOC and particulate levels is still underway to assess the overall indoor conditions with the alternative use pattern.

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