Humidity control strategies in operation theatre Malaysia

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Abstract. Hospital buildings are complex indoor facilities with variable uses and functions that are deals with a higher number of people. Therefore, the air-conditioning (AC) system should be used to keep good indoor air quality (IAQ) for patients and medical staff to meet comfort and health reasons. Operation theatre is one of the important and critical rooms in the hospital building. Usually, operation process will take 5 hours until 12 hours depends on the operation or patience condition. Operation theatres required 100% for fresh air intake and 100% for exhaust air. Therefore, this study analyses the indoor air quality in Operation Theater (OT) at Malaysia. Then focuses on the humidity control strategies using psychrometric chart. AC system and selected IAQ parameter been monitored to understanding the quality of air and energy usage. The result shows carbon monoxide (CO2), carbon dioxide (CO) and temperature (T) level were within the range stipulated in ASHRAE standard 62.1-2016 but relative humidity (RH) in operation theatre exceed the acceptable range. AC system showed the cooling energy usage as 90.1 kW and the heating required 5.6 kW in standard AC system operation. Psychrometric chart analysis to meet the desired temperature and relative humidity been proposed which contribute cooling energy usage was 95.9 kW and heating energy required 12.2kW. Recommendation alternative strategies to reduce cooling and heating energy been highlighted in this study.

1. Introduction

Air-conditioning (AC) systems typically provide thermal comfort and good indoor air quality (IAQ) achieved by controlling the temperature, humidity level and cleanliness of the air distribution. Moreover, the design of the AC system involves calculation of peak cooling loads, specification of system, calculation of annual performance and calculation of cost [1]. On the other hand, the cooling loads estimation is very important to ensure proper removal of building heat loads. Building heat loads can be defined as internal and external loads. External loads occur due to heat transfer between the building and its’ surroundings and it is affected by outdoor conditions whereas internal loads are contributed by occupants, lighting and appliances. In modern commercial buildings, the leading sources of cooling loads are internal loads [2, 3].

The AC system was designed with cooling coils and the ability to cool and dehumidify the air as well as to meet sensible and latent heat loads in typical buildings or rooms. Sensible heat load arises from
dry bulb temperature. The sensible loads gain directly to the conditioned space by conduction, convection and radiation. Latent loads arise from moisture generated either from internal sources or from outdoor air ventilation to maintain the IAQ requirement [4]. Generally, comfortable indoor temperature is between 23 to 26 degree Celsius (°C) and relative humidity (RH) level is 40% to 70% (Malaysia Standard MS1525, 2010).

Hospital buildings are complex indoor facilities with variable uses and functions. Therefore, the AC system should be used to keep good IAQ for patients and medical staff to meet comfort and health reasons [5]. For surgery in operation theatres (OT), the requirement of fresh air intake is 100% and exhaust must be 100% considering it is in a critical area [6].

Table 1 shows the recommended design criteria for various places in health care facilities. The room must also follow the required room pressure control. Room differential pressure is focused on air balancing, proper maintenance of the AC system and continuous checking of the filter. It is recommended to add the differential room pressure monitoring [6]. In tropical climates, the influence of humid air may increase the AC system energy that is required to remove moisture before it is supplied to the OT. Murphy (2006) discusses how the temperature and humidity requirements of surgery rooms impact the design of the HVAC system and present system alternatives that can meet both of these requirements [7]. The design used the rule of thumb that hugely affects the energy and is unable to meet the requirements.

### Table 1. Recommended design criteria in health care facilities

| Function Space                                      | Minimum Pressure Relation to Adjacent Areas | Minimum Air Changes of Outside Air per Hour | Minimum Total Air Changes per Hour | All Air Recirculated within Room Units | Air Recirculated Within Room Units | Relative Humidity (%) | Design Temperature, °C |
|----------------------------------------------------|--------------------------------------------|--------------------------------------------|-----------------------------------|--------------------------------------|-----------------------------------|-----------------------|------------------------|
| Surgery and Critical Care                           |                                            |                                            |                                   |                                      |                                   |                       |                        |
| Operating room (class B and Positive C surgical)    | Positive                                   | 4                                          | 20                                | -                                   | No                                | 30 to 60              | 17 to 27               |
| Operating/ surgical cystoscopic rooms[^a][^b][^c]  | Positive                                   | 4                                          | 20                                | -                                   | No                                | 30 to 60              | 20 to 23               |
| Delivery room[^d]                                   | Positive                                   | 4                                          | 20                                | -                                   | No                                | 30 to 60              | 20 to 23               |
| Recovery room[^e]                                   | -[^f]                                      | 2                                          | 6                                 | -                                   | No                                | 30 to 60              | 24 ± 1                 |
| Critical or incentive care (burn or intermediate)   | Positive[^g]                               | 2                                          | 6                                 | -                                   | No                                | 30 to 60              | 21 to 24               |
| Newborn intensive care                              | Positive[^h]                               | 2                                          | 6                                 | -                                   | No                                | 30 to 60              | 22 to 26               |
| Treatment room[^i]                                  | -[^j]                                      | 2                                          | 6                                 | -                                   | 30 to 60                          | 21 to 24               |
| Nursery suite                                       | Positive[^k]                               | 5                                          | 12                                | -                                   | No                                | 30 to 60              | 24 ± 1                 |
| Trauma room[^l][^m]                                 | Positive[^n]                               | 5                                          | 12                                | -                                   | No                                | 30 to 60              | 22 to 26               |
| Trauma room (crisis or shock)                       | -[^p]                                      | 3                                          | 15                                | -                                   | No                                | 30 to 60              | 22 to 26               |
| Anaesthesia gas storage                             | Negative[^q]                               | -                                          | 8                                 | Yes                                 | -                                 | 30 to 60              | 20 to 23               |
| GI endoscopy[^r][^s]                                | -[^t]                                      | 2                                          | 6                                 | -                                   | No                                | 30 to 60              | 20 to 23               |
| Bronchoscopy[^u]                                   | Negative[^v]                               | 2                                          | 12                                | Yes                                 | -                                 | 30 to 60              | 20 to 23               |
| Emergency waiting rooms                             | Negative[^w][^x]                           | 2                                          | 12                                | Yes                                 | -                                 | 30 to 60              | 22 to 26               |
| Triage areas                                        | Negative[^y]                               | 2                                          | 12                                | Yes                                 | -                                 | 21 to 24               |
| Radiology waiting rooms                             | Negative[^z]                               | 2                                          | 12                                | Yes                                 | -                                 | 21 to 24               |
| Procedure room (class A surgical)                   | Positive                                   | 3                                          | 15                                | -                                   | No                                | 30 to 60              | 21 to 24               |

Improper analysis of the dehumidification process for the AC system may lead to high cooling energy and thus affecting the RH in an indoor environment. Cooling coils in the AC system requires extra energy and this causes inefficiency in the system. In terms of IAQ, RH must follow the standards for health and comfort reasons. High RH may lead to uncomfortable and stuffy conditions, while low RH will lead to the occupants' complaints such as dry nose, throat, eyes and skin [8]. High RH levels will also lead to mold and fungus growth and affect the IAQ inside the building. These microorganisms’ spores travel by air and cause infectious diseases, allergies and other respiratory irritations to occupants.
A major concern on energy conservation has led to the development of energy efficiency of the AC systems while improving indoor air quality in the buildings. Therefore, the aim of this paper is to monitor indoor air in OT. Then, a discussion using psychrometric chart will be presented to strategize on how to improve humidity control in OT.

2. Methodology

2.1 Indoor Air Quality (IAQ) Monitoring

IAQ represents the indoor air concentration of pollutants. IAQ monitoring needs to be conducted to identify the comfort, health and environmental satisfaction, the number of sampling points and sample position for IAQ was based on the Industry Code of Practice (ICOP) Indoor Air Quality (IAQ) Department of Occupational Safety and Health (DOSH) Malaysia 2010. Table 2 shows the minimum number of sampling points recommended by DOSH Malaysia and he proposed IAQ parameter in this study were:

- i. Temperature
- ii. Humidity
- iii. Carbon dioxide (CO₂)
- iv. Carbon monoxide (CO)

The indoor air was monitored for 24 hours for a period of 4 days and the data was logged for every 30 minutes of each logged data. The average of 3 hours calculated. One sensor for temperature, relative humidity (RH), CO and CO₂ sensor were installed in the OT.

| Total floor area (equipped system MVAC) (m²) | The Minimum number of samplings points |
|--------------------------------------------|---------------------------------------|
| < 3,000                                    | 1 per 500 m²                          |
| 3,000 ≤ 5,000                              | 8                                     |
| 5,000 ≤ 10,000                             | 12                                    |
| 10,000 ≤ 15,000                            | 15                                    |
| 15,000 ≤ 20,000                            | 18                                    |
| 20,000 ≤ 30,000                            | 21                                    |
| ≥ 30,000                                   | 1 per 1,200 m²                        |

2.2 AC System Performance Monitoring

The OT was served by one air handling unit (AHU). The floor area of the OT was 54.93 meter² with a ceiling height of 3.5 meters as shown in Figure 1. The air was supplied at a constant volume with a valve based on room temperature and RH with setpoint temperature of 21°C (60.8°F) and RH 50%. Three electrical heaters of 3 kW each were used to control the temperature to meet the temperature requirement. The AHU takes 100% fresh air for supply to the OT as it is the standard requirement. The system has heat wheel recovery between the fresh air and the exhaust air, where the flow rate of the air is the same as the supply air. Designed volume flow rate supply air is 2.16m³/s. The designed cooling loads for the OT was 69.64 kW (237800 BTU/hr) with the chilled water flow rate for the AHU cooling coil controlled by a motorized valve based on room temperature and RH with setpoint temperature of 21°C (60.8°F) and RH 50%. Three electrical heaters of 3 kW each were used to control the temperature to meet the temperature requirement. The AHU takes 100% fresh air for supply to the OT as it is the standard requirement. The system has heat wheel recovery between the fresh air and the exhaust air, where the flow rate of the air is the same as the supply air.
Temperature and relative humidity sensor were installed in the air side of the AC system when the AC system is running in normal operation based on set pint required. Figure 2 illustrates the proposed sensor’s location for the AC system performance monitoring at operation theater (OT). All temperature and humidity were recorded at some points to get the cooling energy required. The sensor was labeled by:

i. S1 : fresh air temperature and relative humidity : FA  
ii. S2 : after heat wheel air temperature and relative humidity : AHW  
iii. S3: supply air temperature and relative humidity after cooling coil : SA  
iv. S4: after heater supply air: SA’

2.3 Cooling Energy Calculation
Sensible and latent loads need to be determined in a cooling load estimation. Both of the loads are required in order to calculate room sensible heat factor (RSHF). The RSHF will show how cold and dry the supply temperature needs to be in order to meet the desired temperature and RH level in the building [12] (ASHRAE, 2009). RSHF can be expressed using Eq. 1

\[
\text{RSHF} = \frac{\text{room sensible heat load}}{\text{room total heat load}}
\]  

The slope of RSHF was plotted on the protractor in the psychrometric chart. The line passing through from RA and parallel to the RSHF line on the protractor was drawn to intersect with the saturation curve.

Figure 1. Monitoring location OT no 3

Figure 2. The schematic diagram for proposed sensor’s location at OT
(100% RH). This is known as the apparatus dew point temperature (ADP) and the supply air must lie somewhere on the RSHF line. The total cooling energy can also be determined by taking the heat contents i.e. enthalpies from points MA and SA. After a complete air-conditioning cycle process, the actual sensible loads ($Q_S$), latent loads ($Q_L$) and total loads ($QT$) can be expressed using Eq. 2, Eq. 3 and Eq. 4 (ASHRAE Fundamental 2009):

$$Q_S = 1.21 \text{ (sensible heat factor)} \times V \times \Delta t$$  \hspace{0.5cm} (2)

$$Q_L = 3.01 \text{ (latent heat factor)} \times V \times \Delta \omega$$  \hspace{0.5cm} (3)

$$QT (\text{total load}) = Q_S + Q_L \text{ or } 1.2 \times V \times \Delta h$$  \hspace{0.5cm} (4)

The flow rate can be calculated using the formula,

$$V = A \times v$$  \hspace{0.5cm} (5)

Where:
- $V$ = Volumetric flow rate ($m^3/s$),
- $\Delta t$ = Differential temperature ($^\circ C$)
- $\Delta \omega$ = Differential humidity ratio ($kg/kg$)
- $\Delta h$ = Differential enthalpy ($kJ/kg$)
- $V$ = Volumetric flow rate ($m^3/s$)
- $A$ = Area ($m^2$)
- $v$ = Velocity ($m/s$)

3. Result & Discussion

3.1 Temperature Monitoring in OT

Figure 3 illustrates the indoor temperature monitoring versus time for average every 3 hours in the OT. The temperature has been complied with the standard according to ASHRAE standard 62.1-2004 and ASHRAE HVAC application with the range required between 20°C to 23°C for surgical rooms. The high temperature obtained was 21.8°C in 30 hours of monitoring (day 3) and the minimum obtained was 20.5°C at 6 hours (Day 1). The average temperature for the OT obtained was 21°C.

![Figure 3. Graph of temperature ($^\circ C$) versus time](image)

3.2 Relative Humidity (%) Monitoring in OT

Figure 4 illustrates the indoor RH (%) monitoring versus time for average every 3 hours in the OT. The RH did not comply with the standard according to ASHRAE standard 62.1-2004 and ASHRAE HVAC application that required the RH to be within the range of 30% to 60%. The highest temperature obtained
was 71.8% at 6 hours of monitoring (day 1) and the minimum obtained was 66.1% at 6 hours (day 7). The average RH for the OT obtained was 60%. The high RH needed to be reduced to follow the requirement to avoid condensation inside the room and increase in the mold growth.

Figure 4. Graph of relative humidity (%) versus time

3.3 Carbon Dioxide (CO₂) Monitoring in OT
Figure 5 illustrates the indoor CO₂ monitoring versus time for average every 3 hours in the OT. The CO₂ concentration complied to the standard according to ASHRAE standard 62.1-2004 and ASHRAE HVAC application with the highest limit of 1000 ppm. The highest CO₂ obtained was 488.3 ppm at 93 hours of monitoring (day 7) and the minimum obtained was 439.1 ppm at 6 hours (day 1). The average CO₂ for OT obtained was 460 ppm for the 7 days of monitoring. Since 100% fresh air is used for ventilation intake for the OT, it resulted in good CO₂ levels in the room and maintained the lowest CO₂ level.

Figure 5. Graph of carbon dioxide (ppm) versus time

3.4 Carbon Monoxide (CO) Monitoring in OT
Figure 6 illustrates the CO concentration (ppm) versus time for average every 3 hours in the OT. The CO concentration complied to the standard according to ASHRAE standard 62.1-2004 and ASHRAE HVAC application with highest limit of 10 ppm. The highest CO obtained was 1.9 ppm in 36 hours of monitoring (day 3) and the minimum CO obtained was 0.5 ppm in 90 hours of monitoring (day 7). The average obtained was 2 ppm for 7 days of monitoring.
3.5 Cooling Energy Analysis Using Psychrometric Chart

Based on the measurements obtained, the psychrometric chart can be plotted to illustrate the cycle of air for the air-handling unit (AHU) system. The cycle of air relates between the FA, AHW, SA and SA’ involved in the AHU system. Figure 7 illustrated the general cooling process plotted in the ASHRAE psychrometric chart for one cycle for the OT AHU system. The parameter involved included the dry bulb temperature, wet bulb temperature, relative humidity, specific volume, humidity ratio, specific enthalpy and dew point. Two parameters were known and the other properties were obtained using psychrometric chart.

Table 3 shows the average result temperature and humidity for the 3 days was plotted in psychrometric chart to get the enthalpy and humidity ratio for the average supply air (SA), the average after heater supply air (SA’), the average after heat wheel air (AHW), the average fresh air (FA) and the average return air (RA’). The highest enthalpy and humidity ratio came from the fresh air intake with 81.41 kJ/kg and 20.37 g/kg respectively. The heat wheel reduced the temperature and humidity ratio from FA with the difference in temperature and humidity ratio reduced by 2°C and 3.7 g/kg respectively.
The AHW passed the cooling coil in the AHU and reduced the air temperature again from 27.2°C to 13°C. The air humidity ratio was reduced with a difference of 5.52 g/kg but increased the RH from 71.5% to 87.5%. Electrical duct heater was used to reheat the air back and increased the temperature air from 13°C to 15.2°C and the humidity ratio remained unchanged. The changes of air properties had resulted in the RA temperature of 20.5°C with RH 66% where the RH did not meet the standard requirement. These differences in the temperature and humidity ratio were used to determine the sensible and latent loads. The sensible loads (Qs), latent loads (Ql) and total loads (Qt) were expressed using eq. 2, eq. 3 and eq. 4 between AHW and SA. The heating element also used the same equation between SA and SA’. It required the volume flow rate to calculate the Qs, Ql and Qt.

**Table 3. Results of AC System Monitoring OT**

| Description                     | Temperature (T) (°C) | Relative Humidity (RH) (%) | Enthalpy (h) (kJ/kg) | Humidity Ratio (ω) (g/kg) |
|----------------------------------|----------------------|----------------------------|----------------------|---------------------------|
| Average Supply Air (SA)          | 13.00                | 87.50                      | 33.60                | 8.150                     |
| Average After Heater Supply Air (SA’) | 15.20                | 75.30                      | 37.74                | 8.150                     |
| Average After Heat Wheel Air (AHW) | 27.20                | 71.50                      | 68.85                | 16.67                     |
| Average Fresh Air (FA)           | 29.20                | 79.20                      | 81.41                | 20.37                     |
| Average Room Air (RA)            | 20.50                | 66.10                      | 45.88                | 9.95                      |

Table 4 shows the resulting measurement of velocity and ducting size that was measured from the supplied air as the system had no return air with the constant volume air flow rate. Compared to the existing design volume air flow rate, the measurement resulted in a reduction of 1.89% based on the designed volume flow rate of 2.16 m³/s.

**Table 4. Volume flow rate for the specific location**

| Location            | Average velocity (m/s) | Area ducting (m²) | Total volume flow rate (m³/s) |
|---------------------|------------------------|-------------------|-------------------------------|
| Supply Air (SA)     | 2.22                   | 0.95              | 2.11                          |

The cooling energy usage consisted of the AHU system handling the sensible and latent loads with 100% volume flow rate FA intake. Figure 8 showed the components of cooling energy. The total cooling energy required was 90.1 kW. Ql present was 60% and Qs was 40% of the total loads. Electrical heating used was 5.6 kW to increase the temperature from SA to SA’ and to obtain the average room temperature 21°C but the RH was still not in the range required.

![Figure 8. Results of Cooling Energy and Heating Required for AC system OT](image-url)
3.6 Humidity Control Strategies in OT

It was found that the temperature in the OT meets the desired temperature but the RH was out of range. Table 5 shows the RA comparison between standard requirements, measurements and proposed set point, the proposed temperature and humidity can be plotted on the same psychrometric chart.

**Table 5.** Comparison room air (RA) between measurement, requirement and proposed set point

| Description                     | Temperature (T) (°C) | Relative Humidity (RH) (%) | Enthalpy (h) (kJ/kg) | Humidity Ratio (ω) (g/kg) |
|---------------------------------|----------------------|---------------------------|----------------------|---------------------------|
| Average room Air measured       | 20.50                | 66.10                     | 45.88                | 9.95                      |
| Requirement room air            | 20.00-24.00          | 50-60                     | -                    | -                         |
| Proposed set point room air     | 22.00                | 55.00                     | 45.17                | 9.06                      |

Figure 9 illustrates the proposed cooling process to meet the temperature and RH set point which were at 22°C and RH 55% respectively. The slope between RA and SA’ was the RSHF that was 5.9 and it would be parallel to the proposed RA. The difference in humidity ratio between RA and proposed RA was used to obtain the new SA which was 0.89 g/kg. Humidity ratio for SA needed was deducted by the difference in humidity ratio between RA and proposed RA resulting in 7.26 g/kg. By using the same slope between AHW and SA, the new SA can be on the same line of humidity ratio at 7.26 g/kg. New SA’ was found using RSHF 5.9 based on the proposed RA. Table 6 shows the component of air properties for a new cooling process at the OT to meet proposed set point RA. The cooling energy was calculated using eq. 2, eq. 3 and eq. 4 between AHW and new SA properties as the highest cooling energy usage.

**Figure 9.** Propose cooling process to meet temperature and RH set point for OT
Table 6. New cooling process to meet RA set point

| Description                        | Temperature (T) (°C) | Relative Humidity (RH) (%) | Enthalpy (h) (kJ/kg) | Humidity Ratio (ω) (g/kg) |
|------------------------------------|----------------------|---------------------------|----------------------|--------------------------|
| Average new Supply Air (SA)        | 12.20                | 82.20                     | 30.57                | 7.26                     |
| Average new After Heater Supply Air (SA') | 17.00               | 60.00                     | 35.40                | 7.56                     |
| Average After Heat Wheel Air (AHW) | 27.20                | 71.50                     | 68.85                | 16.67                    |
| Average Fresh Air (FA)             | 29.20                | 79.20                     | 81.41                | 20.37                    |
| Average Proposed Room Air (RA)     | 22.00                | 55.00                     | 45.17                | 9.06                     |

Figure 10 showed the components of the cooling energy to meet the set point temperature and RH. The total cooling energy required was 95.9 kW. Ql present was 60% and Qs was 40% of the total loads. Electrical heating used was 12.2 kW to increase the temperature from the new SA to new SA'. Extra cooling energy and heating was required to meet the set point temperature and RH of 22°C and RH 55% respectively.

![Cooling energy and heating for OT Room with proposed RA set point](image)

**Figure 10.** Results of Cooling Energy and Heating Required AC system for OT

4. Conclusion
The existing system may only use cooling energy of 90.1 kW and heating of 5.6 kW. It was found that the room RH did not meet the requirement which 66.1%. The desired temperature and relative humidity been proposed which contribute cooling energy usage was 95.9 kW and heating energy required 12.2 kW. Additional cooling and heating energy required to meet the 22°C and RH 55%. For the future work, an additional system as heat pipe heat exchanger (HPHX) can be proposed to reduce energy usage in AHU and maintain the temperature and RH significantly [13, 14].

As a conclusion, this paper able to gives idea and prevention measure to engineer once deal with humidity problem. Besides that, suggestion of additional equipment such HPHX also gives a good of return in the future.

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