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Design and operation optimization of an air conditioning system through simulation: an hour-by-hour simulation study

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ABSTRACT

In the present research, performance validation of a Heating, Ventilation, and Air Conditioning (HVAC) system operating in a library building was conducted. The operating HVAC system was studied in terms of the provided indoor air conditions and energy consumption level. The fieldwork measurements showed that the HVAC system is not capable of providing the desired indoor air conditions based on the ASHRAE standards. Therefore, two deciding design and operating parameters namely, chilled water cooling coil number of rows and chilled water temperate were investigated to achieve possible improvement in the system performance. For this purpose, different numbers of rows for cooling coil design at different chilled water temperatures were examined. TRNSYS software was employed to investigate the hourly effect of the variables on the system for a whole year of operation.
Based on the simulation results, the provided indoor air conditions were appropriate and within the comfort area with the two-row configuration cooling coil. However, the energy performance of the system indicated that the two-row configuration with 10°C chilled water temperature was superior in terms of energy consumption, and could provide the desired indoor air conditions, thus it was recommended to be implemented in the existing system.

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1. Introduction

To establish a comfortable indoor air for the occupants in buildings, most of the buildings are equipped with Heating, Ventilation, and Air Conditioning (HVAC) systems. Usually in the HVAC systems, the air dehumidification is obtained by reducing the temperature below the dew point in the cooling coils. Considerable external energy is then required to reheat the off coil air before entering into the space. HVAC systems are designed to exhaust conditioned indoor air and replace it with up to 100% fresh outdoor air. This exchange of indoor air for outdoor air represents significant energy consumption, especially in spaces

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which require higher rate of air change per hour.

In terms of occupant's health, space humidity control is an important task for the HVAC systems. If the air handling units (AHUs) provide a high relative humidity (RH) supply air, this will lead to fungus growth in air-tight buildings and affect the health of the occupants. HVAC systems are responsible for keeping allowable indoor air quality for the air-tight buildings; thus, inefficient performance of the HVAC systems will cause ineffective removal of contaminated indoor air and display symptoms of sick building syndrome. Studies have revealed that sick building syndrome such as fungus growth in the space would have a serious impact on occupants' health [1,2]. Therefore, considering all the above, proper design and efficient operation of the HVAC systems have a significant effect on the occupants health and buildings energy consumption.

Buildings energy performance and indoor thermal comfort normally are optimized by the building design considerations and control process [3-7]. In addition, energy recovering equipments are also recommended for this purpose [8-11]. For instance, the impact of comfort control on the air conditioner energy consumption in a humid climate was examined by Henderson et al. [7]. Martin et al. [8] tested the thermal comfort established by a combined recovery equipment consisting of a ceramic semi-indirect evaporative cooler and a heat pipe to energy recovery at low temperature in an air conditioning system. In another study, Martinez et al. [9] designed a mixed energy recovery system consisting of two heat pipes and indirect evaporative recuperators for air conditioning.

Application of energy recovery devices are also recommended by some designing engineers. For instance, Yau [10] explored the application of double heat pipe heat exchangers for a building. The study showed an improvement in the HVAC system performance in terms of provided indoor air end energy consumption. In a separate research, Ahmadzadehtalatapeh, and Yau [11] recommended the application of double configuration heat pipe based on heat recovery technology for system performance enhancement for hospitals.

HVAC systems are normally designed based on the available technical data of the considered building. Then, the technical data together with the available specification of the manufactured AHUs were used by the designing engineer to recommend the proper AHUs to the space. In the designing process, the engineer normally employs the available software's for cooling and heating loads estimations, which is common in the field of HVAC designing.

In this case study, the operating AHUs in the Balai Ungku Aziz Library (BUAL), University of Malaya, Malaysia were considered and the practical established indoor air conditions by the installed HVAC system were monitored to study the compliance with the available standards. Furthermore, the existing system was investigated in terms of the energy consumption and its capability to provide the desired indoor air conditions for the whole year. For this purpose, temperature and RH of the library space were recorded and were compared with the standards. The existing system was simulated using the TRNSYS software to understand the performance of the installed HVAC system for the whole year. Then, the design and operating parameters of the AHUs were modified to determine the appropriate design and operating conditions.

Nomenclatures

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
AHU	Air Handling Unit
HVAC	Heating, Ventilation and Air Conditioning
L.L	Latent Load
P	Power
RH	Relative Humidity
R.RH	Room RH
R.T	Room Temperature
S.RH	Supply RH
S.T	Supply Temperature
S.L	Sensible Load
T.L	Total Load

TMY	Typical Meteorological Year
TRNSYS	Transient System Simulation Software

2. Research Methodology

This study is divided into two main sections as follows: HVAC system simulation process, and simulation results and discussions. First, in Section 3, the fieldwork measurements and the simulation process for the HVAC system under different operating conditions will be presented. Then, the performance of the HVAC system will be analyzed in terms of the provided indoor air conditions and energy consumption level in Section 4.

3. HVAC System Simulation

3.1. Fieldwork study

The BUAL building consists of three levels and library is located on level two. Eleven AHUs operate in the building and two out of the eleven are used to provide the conditioned air into the library space. AHUs, namely, AHU-A and AHU-B consist of four rows of tubes, single pass with 60 and 28 tubes in every row, respectively. There is no heating equipment in the HVAC system; therefore, off coil air directly enters into the library space, as shown in Fig. 1.

The library building space physical conditions such as: temperature, RH, and the amount of supply and return air were recorded. For this purpose, the measuring instrument was located one meter up the floor as this is the approximate distance for a seating person [12]. Temperature and RH of the supply and return air were measured and collected from each diffuser in the library and tabulated in Table 1. AHU-A and AHU-B are used to provide the air for the same thermal zone; therefore, data are combined to find out the mean indoor temperature and RH values. It was found that the mean indoor temperature and RH of the space are 20.9 $^{\circ}C$ and 64.1% [13,14]. In reference to the thermal comfort zone in the ASHRAE standard, it is clear that the air condition in the library space is out of the recommended comfort zone. Moreover, the measurements revealed that the supplied air RH was 79.1%, which is not within the recommendation (Note: the maximum recommended supply duct air RH is 70%) [15].

3.2. Simulation of the HVAC system in TRNSYS

TRNSYS simulation software as a transient system simulation software for the transient simulation of the HVAC systems in buildings was employed for hour-by-hour simulation of the HVAC system performance in this study. To simulate the HVAC system in TRNSYS studio, all the operating equipment needed to

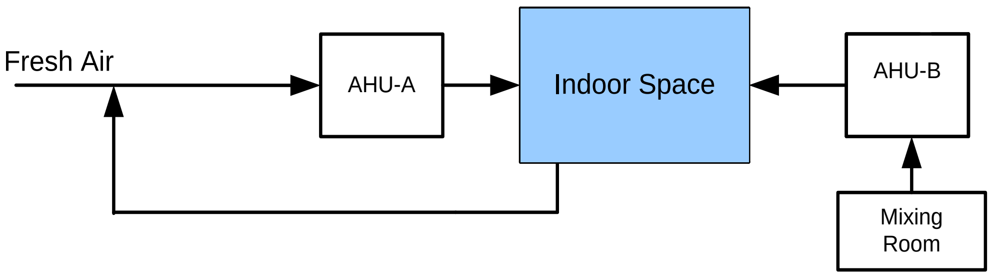


Fig. 1. Schematic diagram of the building HVAC system.

Table 1. Field measurements and simulated values for the BUAL space [14]

	S.T ($^{\circ}C$)	**S.RH (%)**	**R.T ($^{\circ}C$)**	**R.RH (%)**
Field measurement results	13.9	79.1	20.9	64.1
Simulation values	14.7	85.3	20.2	63.5
Deviation (%)	5.4	7.2	3.3	0.9

be defined as the components of the simulation. Most of the equipment being used in the HVAC systems are available in the TRNSYS library and can be used for simulation purposes. However, the modular nature of the software makes it possible to add the non-standard components into the TRNSYS library and being used in the simulation process. To this end, the performance characteristics of the equipment can be written as a FORTRAN source code to represent the equipment mathematically in TRNSYS studio [13].

Library building was defined in TRNSYS studio as the Type 56a component. For this purpose, the architectural design and internal conditions were obtained from the maintenance office of the building and used in the Type 56a details. The standard detailed type of chilled water cooling coil components (Type 52b) was used to represent the performance of the AHUs in the TRNSYS studio and Tee Pieces (Type 11g) component was used to introduce the mixing room for the AHUs [13].

In order to control the working hours of the chiller and AHUs, which is from 8:00 am till 18:00 pm, the time controller component (Type 14h) was added to the simulation studio (see Fig. 2). The components and functions in Fig. 2 are tabulated in Table 2.

In the HVAC system, the chiller as the Type 230 component supplies chilled water to the AHUs. The AHUs mainly consist of a cooling coil and an electrical driven fan. Chilled water cooling coils are normally designed in full (single), half and three quarter circuits or passes. In the present HVAC system, the full pass has been used. The operating AHUs are illustrated in Fig. 3.

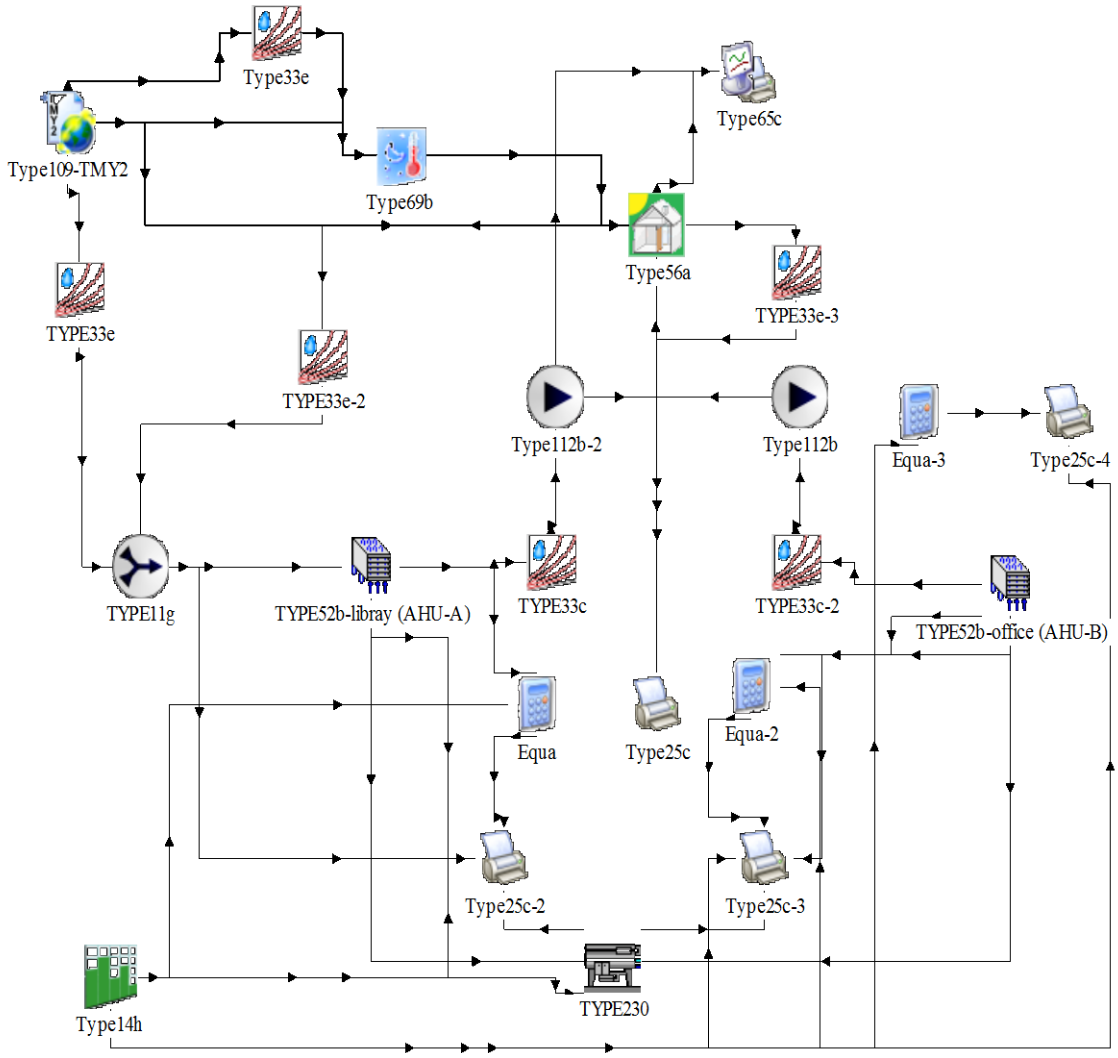


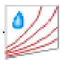
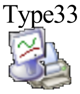
Fig. 2. Simulation layout for building the HVAC system

(a): AHU-A

(b): AHU-B

Fig. 3. Operating AHUs in the HVAC system

Table 2. The processes and functions in Fig. 2

Label	Function and description of the components
 Type109-TMY2	Region Weather Data, This component reads TRNSYS TMY2 format weather file to determine the outdoor condition
 Type56a	Space, This component takes the inlet DBT, RH and air flow and calculates the space DBT and RH
 TYPE52b	Cooling Coil, This component uses the inlet air properties to calculate the cooling coil outlet air properties
 Type112b	Blower, This component uses the inlet air DBT and RH to calculate the leaving air DBT and RH
 Type14h	Time Controller, This component controls the working hour of the chiller.
 TYPE11g	Air Mixer, This component uses the air properties at branches one and two to calculate the mixed air properties
 TYPE230	Chiller, This component uses the total load of the AHUs to calculate the power consumption
 Type33	Psychrometric Calculator, This component uses any two properties of moist air to calculate all other properties of moist air
 Type65c	Online Plotter, This component illustrates the simulated data on the screen and saves them into a specified file
 Equa	Equation, This component allows user-defined equations

As mentioned earlier in the paper, the established indoor air conditions are not within the recommendations by the standard; therefore, the operating parameters were examined to determine the most desirable performance in terms of indoor air conditions and energy consumption level. In this study, two main parameters namely, chilled water cooling coil number of rows and entering chilled water temperature were examined and the effect of these parameters on the indoor air conditions and energy consumption level of the system was tested. The design specification of the AHUs cooling coils have been tabulated in Table 3.

The chilled water cooling coil with two, four and six numbers of rows was tested to determine the effect of number of rows on the HVAC performance. Moreover, chilled water temperatures of 6 $^{\circ}C$, 8 $^{\circ}C$, and 10 $^{\circ}C$ were examined. The effect of variables on the provided indoor air conditions was studied for the hottest month of the year. However, the energy consumptions were estimated for a yearly operation of 8760 hours. TMY weather data for Kuala Lumpur, Malaysia was used for this purpose.

4. Simulation Results and Discussion

4.1. Existing HVAC system simulation results

The hottest month of the year is normally considered for cooling design conditions [16]; therefore, the HVAC system performance for the hottest month of the year is considered. Figure 4 shows the hour-by-hour responses for the air temperature and RH. Based on the simulation results, the supply duct air temperature varies from 14.1 $^{\circ}C$ to 15.3 $^{\circ}C$ with a mean value of 14.7 $^{\circ}C$. Furthermore, the RH value for the supply duct air varies from 83.8 to 86.5% with a mean value of 85.3%.

The indoor air conditions are also presented in Fig. 4. As illustrated in Fig. 4, the indoor temperature fluctuates between 19.4 $^{\circ}C$ and 21.1 $^{\circ}C$ with a mean value of 20.2 $^{\circ}C$. The indoor RH value fluctuates between 61.3 and 65.1% with a mean of 63.5%. A comparison between the field measurements and the HVAC system simulation results shows an acceptable agreement between the simulated values and the field measurements (see Table 1).

In the HVAC system, the blowers and chiller as the main energy consuming devices were considered for the energy analysis. The cooling loads and energy consumptions of the AHUs will be discussed latter in Section 4.3.

4.2. Indoor and supply duct air conditions

As mentioned in the previous section, the current operating situation is not capable of providing the desired thermal comfort for the occupants thus, the system operating performance needed to be modified. Therefore, the effect of two explained variables i.e.

Table 3. Design specification of the chilled water cooling coils

Number of rows	Two, Four, and Six
Number of tubes	AHU-A: 60 AHU-B: 28
Outside tube diameter	12.7 mm
Inside tube diameter	11.9 mm
Fin Spacing	1.95 mm
Centre-to-centre tube spacing	Transverse: 31.75 mm Longitudinal: 19.8 mm
Fin thickness	0.127 mm
Duct height	AHU-A: 2428 mm AHU-B: 1616 mm
Duct width	AHU-A:1940 mm AHU-B: 880 mm
Flow rate of air	AHU-A: 13.6 kg/s AHU-B: 4.66 kg/s
Flow rate of water	AHU-A: 9.9 kg/s AHU-B: 3.3 kg/s
Chilled water temperature	6 $^{\circ}C$, 8 $^{\circ}C$, and 10 $^{\circ}C$

cooling coils number of rows and chilled water temperature was examined on the system performance. In this section, the simulation results are presented and discussed.

Three numbers of rows were examined for the AHUs cooling coils as two, four, and six.

In addition, three different chilled water temperatures of $6\,^{\circ}C$, $8\,^{\circ}C$, and $10\,^{\circ}C$ were tested for every number of row separately. Figs. 5-7 show the simulation responses for the two, four, and six rows at the $6\,^{\circ}C$ chilled water temperature, respectively. Figs. 5-7 are presented as the representative of the situations examined. For more conveniency, simulation results for all the examined situations are tabulated in Table 4.

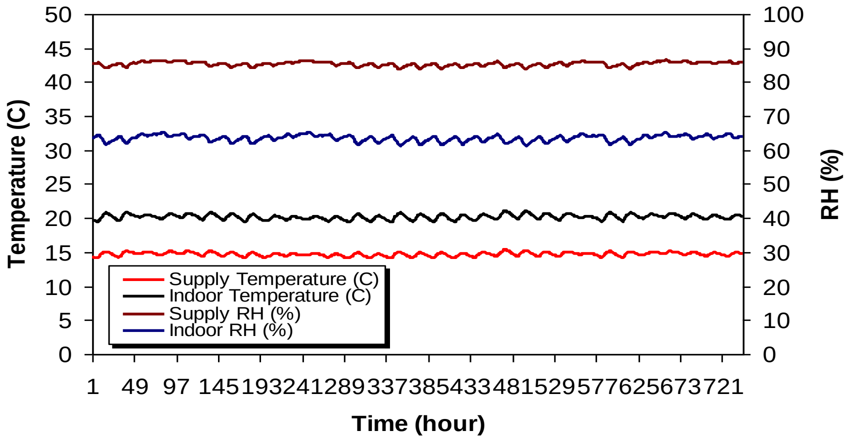


Fig. 4. Simulation responses for the HVAC system

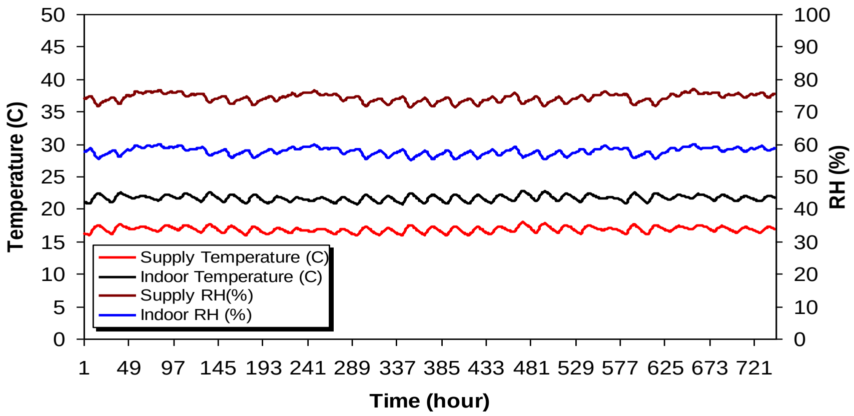


Fig. 5. Simulation responses for the two-row configuration at $6\,^{\circ}C$ chilled water temperature

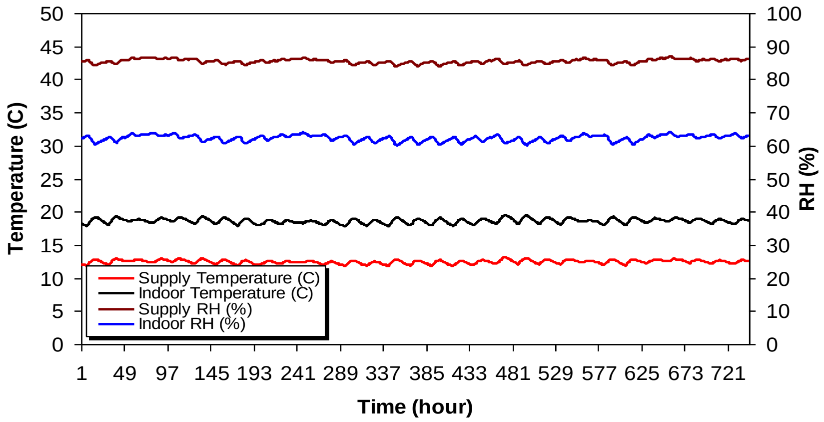


Fig. 6. Simulation responses for the four-row configuration at $6\,^{\circ}C$ chilled water temperature

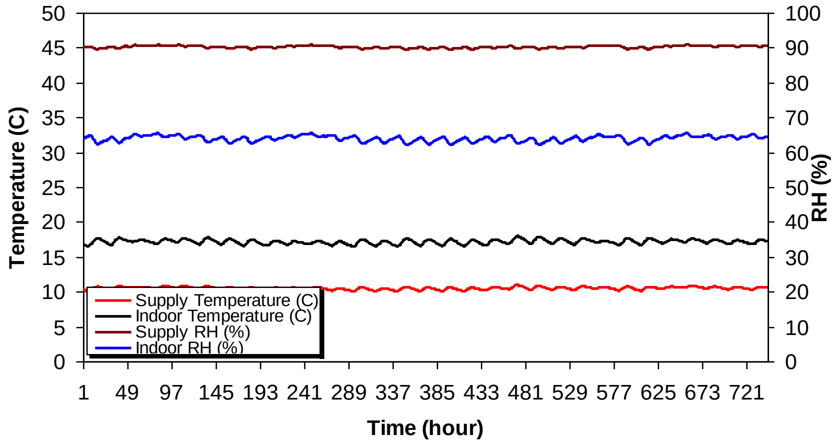


Fig. 7. Simulation responses for the six-row configuration at 6 $^{\circ}C$ chilled water temperature

As tabulated in Table 4, the HVAC system is capable of providing the desired indoor air conditions by the two-row design cooling coils. In the two-row configuration, the established indoor air temperature and RH values are 21.6 $^{\circ}C$ and 57.7%, 22.5 $^{\circ}C$ and 58.2%, and 23.4 $^{\circ}C$ and 58.9% for 6 $^{\circ}C$, 8 $^{\circ}C$, and 10 $^{\circ}C$, respectively. This result implies that the indoor air conditions with the two-row cooling coil are within the comfort zone recommended by the ASHRAE standard. It is evident that the indoor air condition is the most desirable condition at 10 $^{\circ}C$ chilled water temperature, which is 23.4 $^{\circ}C$ and 58.9%. Moreover, the simulations showed that the supplied RH could be improved with the two-row design from 79.1 to 74%, which is significant.

The simulation results indicate that the system performance with the four and six-row chilled water cooling coil is not suitable for the system and as such, it is not recommended. The provided indoor air temperature and RH for the case of four and six-row are tabulated in Table 4.

4.3. Energy analysis

The two-row cooling coil configuration is recommended as the proper configuration for the HVAC system in Section 4.2. In this section, the cooling loads, energy and power consumption of the AHUs were estimated and analyzed for the recommended configuration to determine the most appropriate operating condition in terms of energy performance. To this end, the energy consumption of the system was estimated for a whole year of operation using the TMY weather data.

Table 4. Mean supply and indoor air temperature and RH for the hottest month of the year

Cooling coil entering temperature ($^{\circ}C$)				
6 $^{\circ}C$				
	S.T ($^{\circ}C$)	S.RH (%)	R.T ($^{\circ}C$)	R.RH (%)
Two- row	16.8	74.2	21.6	57.7
Four- row	12.4	85.4	18.6	62.2
Six- row	10.5	90.2	17.1	63.9
8 $^{\circ}C$				
Two- row	18.1	74.0	22.5	58.2
Four- row	14.0	85.3	19.7	63.1
Six- row	12.2	90.2	18.4	65.0
10 $^{\circ}C$				
Two- row	19.3	74	23.4	58.9
Four- row	15.6	85.3	20.8	64.1
Six- row	14.0	90.2	19.6	66.2

Figure 8 illustrates the cooling loads of the system for a typical operating day at $8\,^{\circ}C$ chilled water temperature as the representative. The latent, sensible, and total cooling rates for the two-row configuration at three chilled water temperatures have been tabulated in Table 5.

According to the estimations, the sensible cooling load of the AHUs is 423.2, 386.5, and 349.9 MWh for $6\,^{\circ}C$, $8\,^{\circ}C$, and $10\,^{\circ}C$ chilled water temperatures, respectively and the latent cooling load of the AHUs is 206.8, 171.4, and 133 MWh, respectively.

In order to estimate the amount of power consumption by the system, the cooling equipment efficiency and total cooling rates needed to be considered. The estimation for a whole year of operation revealed that the HVAC system would consume a total amount of 117, 103.5, and 89.7 MWh at $6\,^{\circ}C$, $8\,^{\circ}C$, and $10\,^{\circ}C$ chilled water temperatures, respectively (see Table 5). Fig. 9 illustrates the power consumption by the system for a typical operating day for the two-row configuration and examined chilled water temperatures.

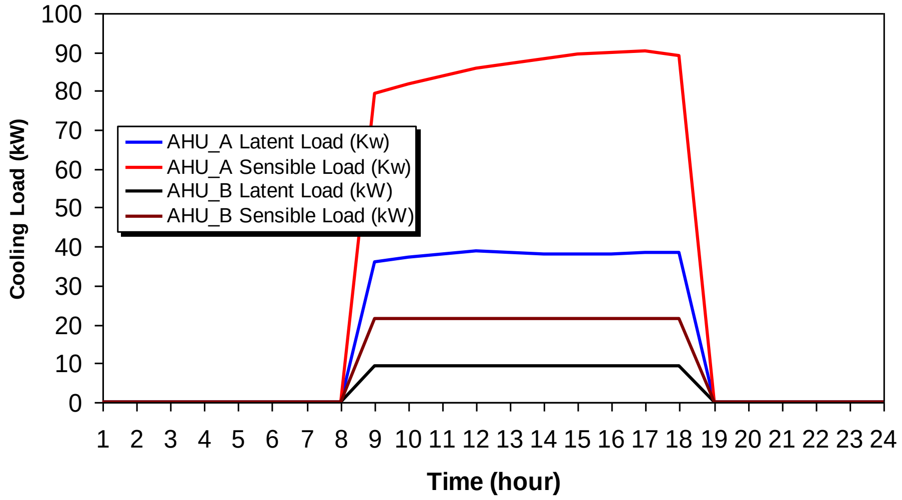


Fig. 8. Latent and sensible loads of the AHUs for the two-row configuration at $8\,^{\circ}C$ chilled water temperature for a typical operating day

Table 5. Sensible, latent and total cooling rate for the AHUs (cooling coils) for the entire year for the two-row configuration

Cooling coil entering temperature ($^{\circ}C$)				
	L.L (MW)	**S.L (MW)**	**T.L (MW)**	**P (MW)**
		$6\,^{\circ}C$		
AHU-A	159.1	332.5	491.7	91.3
AHU-B	47.7	90.7	138.4	25.7
Total	206.8	423.2	630.1	117
		$8\,^{\circ}C$		
AHU-A	137.9	307.8	445.6	82.7
AHU-B	33.5	78.7	112.2	20.8
Total	171.4	386.5	557.8	103.5
		$10\,^{\circ}C$		
AHU-A	114.5	283.0	397.5	73.8
AHU-B	18.5	66.9	85.4	15.9
Total	133	349.9	482.9	89.7

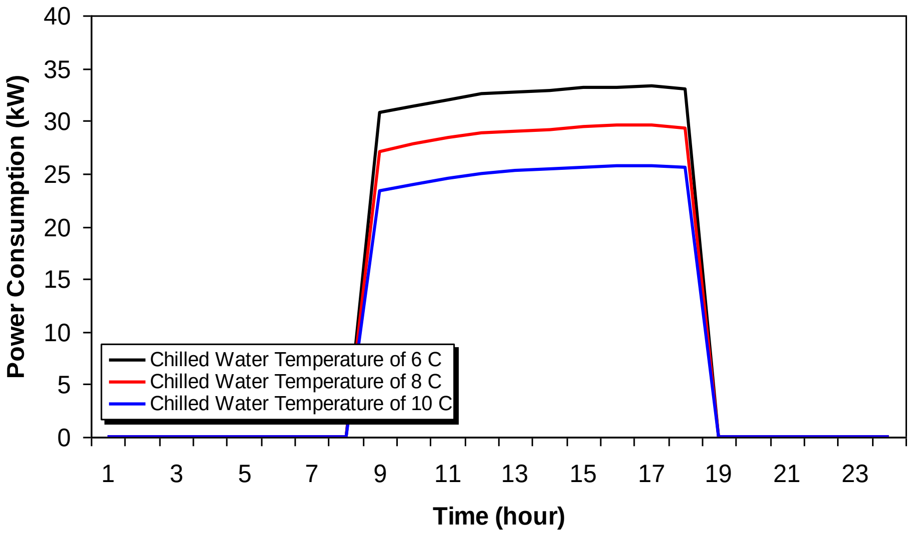


Fig. 9. Power consumption for the two-row cooling coil configuration at three different chilled water temperatures for a typical operating day

By considering all the above, it is evident that the HVAC system with the two-row configuration and 10 $^{\circ}C$ chilled water temperature operates at an energy efficient manner, and could provide the desired indoor air conditions into the space; therefore it is recommended for the HVAC system of the building.

5. Conclusions

According to the field measurements, the established indoor air conditions by the operating HVAC system operating in the Balai Ungku Aziz Library (BUAL), University of Malaya, Malaysia are not within the standard recommendations. Therefore, the HVAC system was studied to determine the current capability and energy consumption level. Then, the system was studied using a building energy simulator, TRNSYS to make appropriate sizing and operating optimization. In this study, two deciding parameters namely, AHUs chilled water cooling coils number of rows and chilled water entering temperature were considered. Chilled water cooling coil with two, four, and six numbers of rows at $6^{\circ}C$, $8^{\circ}C$, and $10^{\circ}C$ chilled water temperature were simulated to determine the most appropriate performance in terms of the provided indoor air conditions and energy consumption level. Based on the simulation results, the HVAC system with the two-row configuration could keep the library space temperature and RH at 21.6 $^{\circ}C$ and 57.7%, 22.5 $^{\circ}C$ and 58.2%, and 23.4 $^{\circ}C$ and 58.9% for $6^{\circ}C$, $8^{\circ}C$, and $10^{\circ}C$ chilled water temperature, respectively. This result implies that the indoor air condition with the two-row cooling coil is within the comfort zone recommended by the ASHRAE standard; however, it is clear that the indoor air condition is the most desirable condition at $10^{\circ}C$ chilled water temperature, which is 23.4 $^{\circ}C$ and 58.9%.

Power consumption by the system was also analyzed for the two-row configuration. The estimations for a whole year of operation showed that the HVAC system would consume a total amount of 117, 103.5, and 89.7 MWh at $6^{\circ}C$, 8 $^{\circ}C$, and 10 $^{\circ}C$ chilled water temperatures, respectively. Therefore, it is clear that the HVAC system with the two-row configuration and $10^{\circ}C$ chilled water temperature operates at an energy efficient manner, and could keep the indoor air conditions within the standard recommendations; therefore, it is recommended to the HVAC system of the library building.

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