

# Improving the Energy Performance of HVAC Systems in Operating Theatres by Using Heat Recovery Devices

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**Abstract**-Heating, ventilation and air conditioning (HVAC) systems in operating theaters use fully fresh air, and return air is not allowed to be mixed with the fresh air. Therefore, HVAC systems in operating theaters are inherently energy-inefficient. In this research, the impact of heat pipe heat exchanger (HPHX) as a heat recovery device on the performance of an existing HVAC system of an operating theater was examined. The existing HVAC system, Plant A, was redesigned by the added HPHX as Plant B and C and the most suitable design in terms of energy consumption and provided air conditions was recommended for the system. TRNSYS simulation program was used for this purpose and a yearly operation of 8760 hours was considered. Based on the results, the application of HPHX, Plant C configuration, could decrease the energy demand of the system and it is recommended to be implemented in the existing HVAC system. Moreover, it was shown that the HPHX integrated system improves the room and supply duct air conditions.

**Keywords**-Energy consumption, heating, ventilation and air conditioning (HVAC) systems, heat pipe heat exchanger (HPHX), operating theaters, TRNSYS

## 1. Introduction

With increasing trend of energy demand, there are a lot of concerns over energy supply and it is a major issue for the policy makers. Globally, buildings consume about 40% of the total world annual energy consumption and most of this energy is used for the purpose of heating, ventilation and air conditioning (HVAC) systems [1]. Normally in buildings, more than 50 % of the energy is consumed by the HVAC systems, especially in hot regions [2]. Therefore, engineers and researchers try to find new energy recovery technologies to enhance the performance of the HVAC systems in terms of air quality and energy consumption level. Furthermore, increasing awareness of the environmental impact of CFC refrigerants, make the engineers to implement environmentally friendly energy recovery technologies.

According to the ASHRAE requirements, the air needs to be changed at least 20 times per hour in operating

theaters[3]. In the operating theaters, the exhaust air is not allowed to be mixed with fresh outdoor air; therefore, the possibility of energy recovery is expected to be considerable. In addition, the dehumidification capability of the cooling coils is expected to be improved by the pre-cooling effect of energy recovery devices.

Besides the energy aspect, providing an appropriate and clean indoor air for the operating theaters is an important task for the designers. ASHRAE standard recommends 20-24 and 30-60% relative humidity (RH) for the operating theaters [3]. Moreover, ASHRAE recommends RH values higher than 70% for the low-velocity ducts and indoor spaces to prevent fungal growth [4]. In addition, RH higher than 70%, can cause some sorts of diseases, which is mostly happens in high humid spaces. Therefore, maintaining the supply air RH value lower than 70% is strongly recommended [5].

One effective way of reducing HVAC systems energy consumption level is employing heat pipe heat exchangers

(HPHXs). HPHXs are passive heat transfer devices that have recently been used for energy recovery purposes. A HPHX consists of individual externally-fined heat pipe tubes that are charged with a proper refrigerant. HPHXs have several advantages over conventional heat recovery devices. One of the main advantages is that HPHXs do not require external power to operate [6].

HPHXs technology has been applied in many fields including HVAC systems. In HVAC systems, HPHXs application for energy recovery is achieved by the process of pre-cooling the outside air [7-15]. For instance, Abtahi et al. [7] investigated the dehumidification characteristics of the HPHXs in humid condition. It was reported that dehumidification of the system was improved by lowering the sensible cooling fraction of the system. In another research, Mathur [8] employed the BIN weather data to study the effect of a six-row HPHX in the energy consumption level of an HVAC system. Mathur [9] also studied the effect of a two-phase natural circulation heat recovery loop heat exchanger on the performance of an existing five-ton HVAC system. It was found that by application of the two-phase heat recovery loop in the system, the operational saving was US\$933.6/year without considering the peak demand and US\$2334/year by taking the peak demand into account. The effect of HPHXs on the enthalpy change of a tropical HVAC system was investigated by Yau [10]. The HVAC system with and without an eight-row HPHX were tested. It was found that the cooling capability of the cooling coil was improved with the added HPHX.

Although there are valuable research studies on the subject; however, research studies based on Typical Meteorological Year (TMY) data for a whole year of operation (8760 hours) for a building located in tropical region is limited. In this research, the possible improvement in the existing HVAC system of an operating theater in the Putrajaya Hospital, Malaysia as a high energy demanding space by the application of the HPHXs was examined for a whole year of operation. HPHXs with different numbers of rows namely, two, four, six, and eight-row were examined to determine the most proper configuration. HPHXs impact was examined and the system responses for the whole year were simulated. For this purpose, TRNSYS software was employed to study the systems performance for a yearly operation of 8760 hours.

## 2. Research Methodology

Three HVAC configurations, namely, Plant A, Plant B, and Plant C are the subjects of these simulations. Plant A represents the existing HVAC system of the space; Plant B is the HVAC system with the added HPHX, and Plant C illustrates the HVAC system with the HPHX and without heater element. The existing HVAC system (i.e. Plant A) was redesigned as Plant B and Plant C to determine the most proper design from the provided air conditions and energy performance point of view. For each plant, the needed TRNSYS circuits were assembled to study the plants performances.

## 3. TRNSYS Overview

TRNSYS as a transient, complete and extensible simulation environment is applied for the simulations in this research [16]. The program uses TMY weather data to simulate the system performance for the whole year of operation in hourly basis. To simulate the systems, the components of the systems are assembled in the TRNSYS studio by using the software standard library. Normally, standard components are available in the software library and can be used for the simulation purposes. However, the TRNSYS program enables the users to add the non-standard components into the standard library of the program. To this end, the performance characteristics of the equipment needs to be written in a programming language such as FORTRAN to present the equipment mathematically in the TRNSYS studio.

## 4. HVAC Systems Simulation in TRNSYS

In this section, the simulation process of the three plants, namely, Plant A, Plant B, and Plant C are described. Plant A simulation process is described in subsection 4.1 and Plant B and Plant C will be explained later in subsections 4.2 and 4.3.

### 4.1. Plant A

In order to simulate Plant A as the existing HVAC system, the air conditions of the room, technical specifications of the equipment, and operational principles of the existing system should be obtained. Therefore, fieldwork study was conducted to measure and record the data and needed information.

#### 4.1.1. Fieldwork study

The operating HVAC system is a fully fresh air system and return air dose not allowed to be mixed with fresh outdoor air, as the requirements for the operating theaters based on the ASHRAE standards. In the existing HVAC system, an energy recovery wheel has already been placed between the fresh outdoor and exhaust air for the energy recovery purposes [17]. Therefore, energy recovery is obtained with implementation of the recovery device between the cool exhaust and fresh hot outdoor air streams. Fieldwork measurements were conducted to determine the operating behavior of the existing HVAC system. For this purpose, the dry bulb temperature (DBT) and RH of the room were measured, and it was found that the mean room temperature and RH is 20.4 and 60.5%, respectively [17,18].

#### 4.1.2. Plant A Simulation

To simulate the Plant A configuration in TRNSYS studio, the HVAC equipment was considered. The standard HVAC components are available in the software library and can be assembled. However, the specifications of the equipment should be defined in the standard components to represent the equipment performance accurately. In order to simulate the non-standard equipment, the performance characteristics of the equipment can be written employing the FORTRAN programming language and added into the program library. To define the building, the architectural and internal conditions of the building was obtained and defined in Type 56a component. Figs. 1 and 2 show the Plant A schematic diagram and simulation layout, respectively [17].

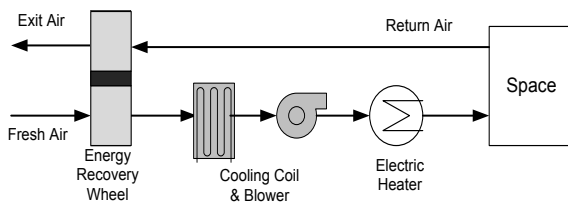


Fig. 1. Schematic diagram\_Plant A, [17]

TRNSYS simulation makes it possible to study the system performance hour-by-hour for a whole year of operation. The existing HVAC system was simulated and the air conditions were obtained. According to the simulation results, the indoor temperature fluctuate between 18.54 and 20.68 with the mean value of 19.54 and RH varies from 58.24% to 62.46% with the mean value of 59.03% [17]. In order to validate the simulation, the simulation values were compared with the fieldwork measurements and an acceptable agreement were found between them (see Table 1). The mentioned small deviations in Table 1 implied that the simulation responses are valid for further investigation in this study.

Table 1. Room air conditions for the Plant A [17]

	Room Temperature (°C)	Room RH (%)
Field measurements	20.4	60.5
Simulation values	19.6	58.9
Deviation (%)	3.9	2.6

4.2. Plant B Simulation

As mentioned earlier in the paper, in order to energy recovery, an energy recovery wheel has already been used. In the existing system, the energy recovery wheel has been located between the fresh and return air and only the pre-cooling effect of the energy recovery wheel is used. Moreover, because of the working principles of the energy recover wheel, they are always liable to cross-contamination and they do not efficiently drain condensation [2]. HPHXs as efficient heat transfer devices are free of these disadvantages and were examined in this study. Therefore, the system was redesigned by the application of the HPHXs. Fig. 3 shows the schematic diagram of the HPHX integrated system as Plant B. In this design, energy recovery wheel was replaced with a HPHX and the fresh hot outdoor air is pre-cooled in the evaporator side of the HPHX. Then, the off coil air is reheated by the heater and condenser section of the HPHX to reach to the desired temperature.

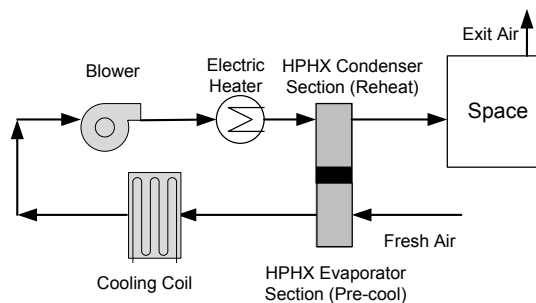


Fig. 3. Schematic diagram\_Plant B

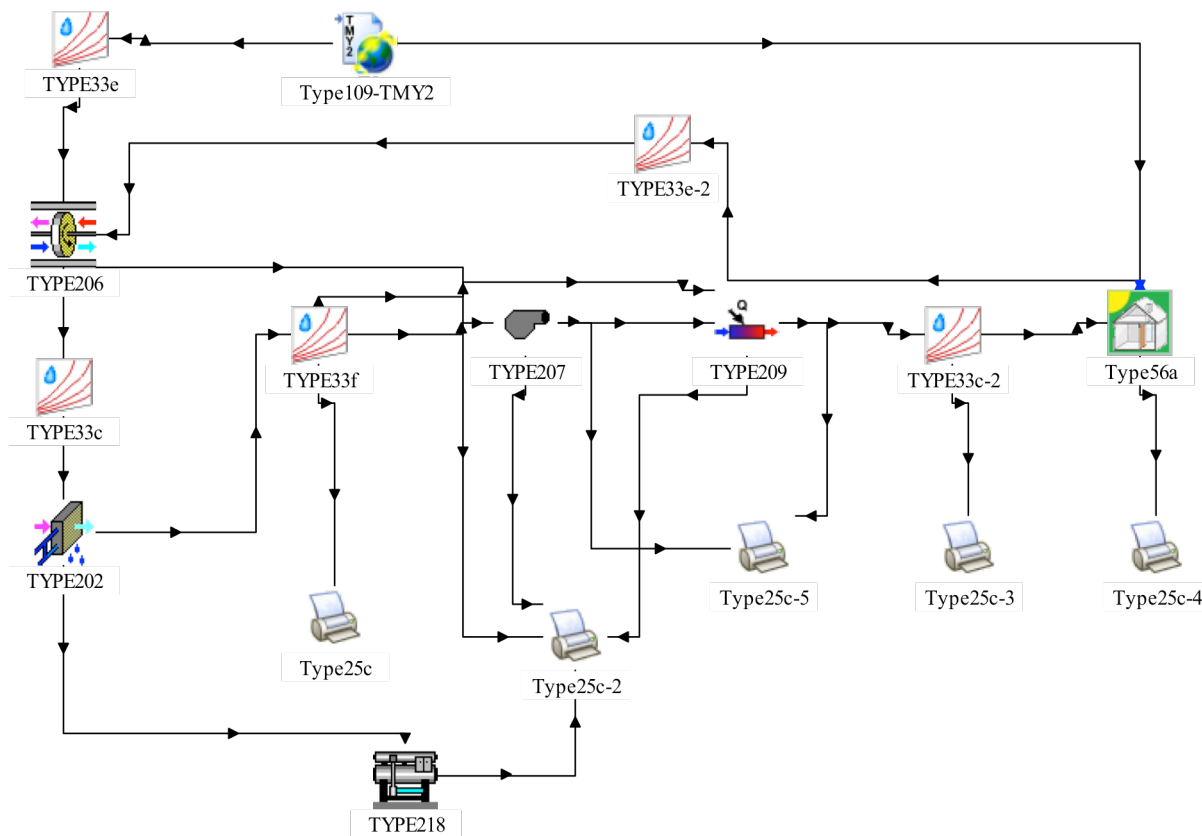
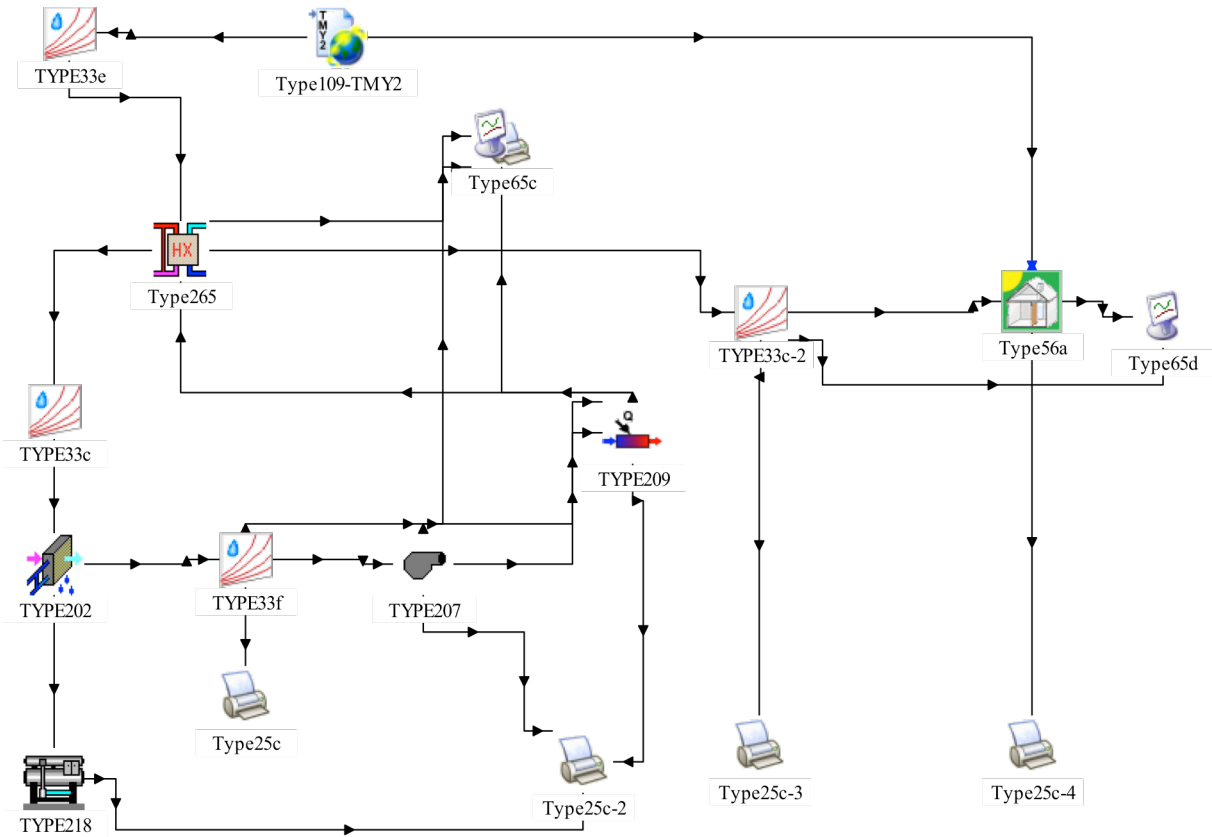


Fig. 2. TRNSYS components to simulate responses of HVAC system\_Plant A, [17]



**Fig. 4.** TRNSYS components to simulate responses of HVAC system\_Plant B

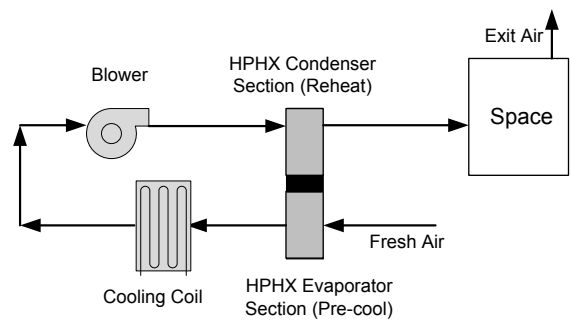
Four HPHXs with different numbers of rows as two, four, six, and eight were fabricated and R-134a as an environmentally friendly refrigerant was used as the working fluid during the fabrication process. HPHXs were experimentally examined in operating conditions similar to the actual HVAC system in terms of the evaporator inlet air condition and evaporator coil face velocity. The fabricated HPHXs were tested in an experimental set-up located in the HVAC & R Laboratory, University of Malaya, Malaysia. Then, the test runs were conducted for the period of one week (168 hours) to find out the actual performance of the HPHXs [19].

After obtaining the actual performance of the HPHXs, the HPHXs components were defined as a new component in the software to be used in the simulation process. For this purpose, the performances of the HPHXs, were written as FORTRAN source codes and added to the TRNSYS library. Fig. 4 shows the simulation layout for the Plant B configuration.

**4.3. Plant C Simulation**

As illustrated in Fig. 5, the added HPHX can be used for pre-cooling and reheating purposes. In Plant C configuration, the heater element was replaced by the condenser section of the HPHX. It is expected that by removing the heater in the system and replacing it with the free heat provided by the condenser section of the HPHX, considerable amount of energy could be saved in a yearly operation. However, this configuration should provide the indoor air conditions within

the recommendations for the space. Fig. 6 shows the simulation layout for the Plant C configuration.



**Fig. 5.** Schematic diagram\_Plant C

**5. Results and Discussions**

The simulated provided air conditions and energy consumptions of the HVAC configurations are presented in present section. The simulation results for the Plant A configuration are described first at subsection 5.1 and the simulation responses for the Plant B and Plant C configuration will be explained later on subsections 5.2 and 5.3, respectively.

**5.1. Simulation Responses- Plant A**

Fig. 7 shows the simulation results for the room temperature and RH. The simulation presents the hourly fluctuations of the room temperature and RH for a yearly operation. According to the results, the existing system

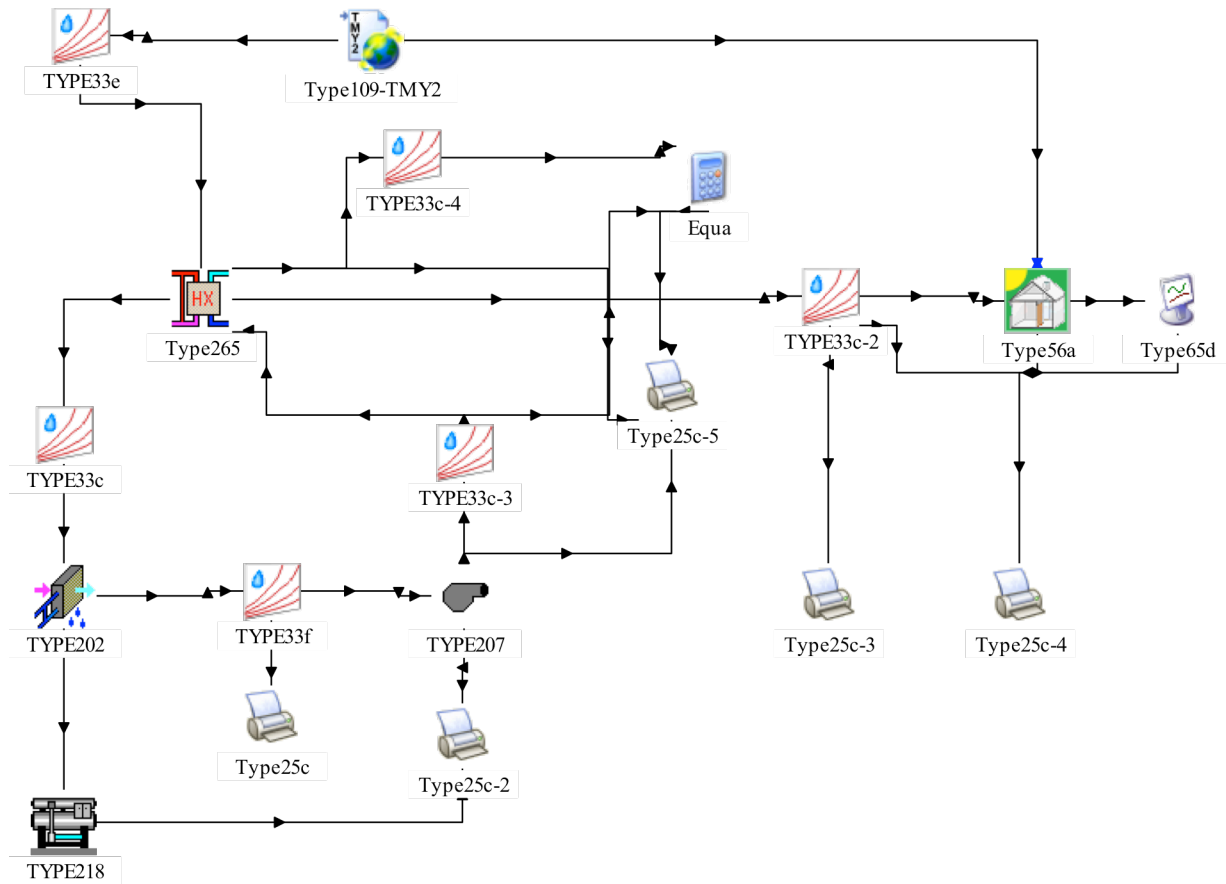


Fig. 6. TRNSYS components to simulate responses of HVAC system Plant C

provides the room air temperature and RH at the mean values of 19.6 °C and 58.9%, respectively. Moreover, the simulation indicates a high RH value for the supply duct air in Plant A at 77.8% [17,18].

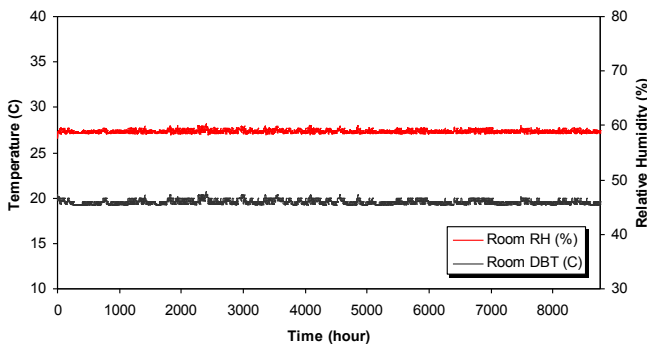


Fig. 7. TRNSYS results for simulating responses of HVAC system Plant A

Table 2. Energy consumption of the Plant A, [17]

Equipment	Energy Consumption (kWh)	Percentage (%)
Chiller	34,016.24	47.07
Heater	30,660	42.42
Energy recovery wheel	1,629.36	2.25
Blower	5,956.8	8.23
Total	72,262.4	

The Plant A performance in terms of energy consumption were estimated for a yearly operation of 8760 hours and summarized in Table 2. According to the results, Plant A configuration consumes a total amount of 72,262.4 kWh energy in a year. The chiller consumes about 47% of the total energy consumption, followed by the heater at 42% [17].

5.2. Simulation Responses- Plant B

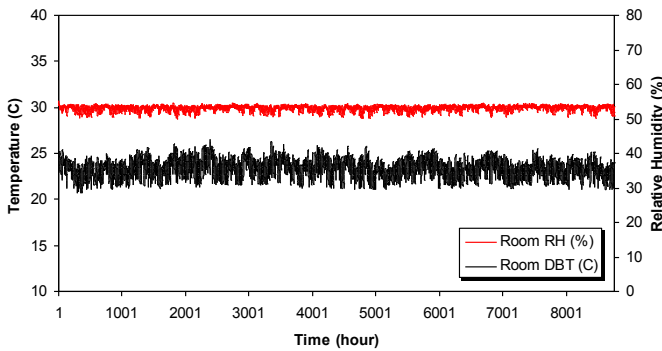
Fig. 8 shows the hourly simulation for the Plant B configuration with the two-row HPHX as the representative. However, for more convenient, the simulation results for Plant B configuration are tabulated in Table 3. As indicated in Table 3, Plant B configuration could maintain the room temperature at 23.4 , 24.2 , 24.6 , and 24.8 with the added two, four, six and eight-row HPHXs, respectively. In addition, Plant B configuration could keep the room RH at 53%, 49.1%, 47.7%, and 46.4% with the HPHXs, respectively. The Plant B configuration performance in terms of provided air conditions indicates that the established air conditions with the added four, six, and eight-row HPHXs are not within the recommendations by the ASHRAE standard. Moreover, the performance of Plant B configuration in terms of energy consumption indicates that the total energy consumption of the Plant B configuration is higher than the Plant A configuration. As tabulated in Table 4, the total energy consumption of the Plant B is 87,106.26 kWh, 84,585.43 kWh, 83,683.17 kWh, 83,018.26 kWh, with the added HPHXs, respectively.

**Table 3.**Room air conditions for the Plant B

	Room Temperature (°C)	Room RH (%)	Supply RH (%)
Two-row HPHX	23.4	53	66.7
Four-row HPHX	24.2	49.1	61
Six-row HPHX	24.6	47.4	58.7
Eight-row HPHX	24.8	46.4	57.3

**Table 4.**Energy consumption of the Plant B

	Energy consumption of the equipment (kWh)				
	Chiller	Heater	Energy Recovery Wheel	Blower	Total
Two-row HPHX	49568.3	30,660.0	--	6,877.96	87,106.26
Four-row HPHX	46457.6	30,660.0	--	7,467.83	84,585.43
Six-row HPHX	44737.2	30,660.0	--	8,285.97	83,683.17
Eight-row HPHX	43562.0	30,660.0	--	8,796.26	83,018.26



**Fig. 8.**TRNSYS results for simulating responses of HVAC system\_Plant B: added two-row

5.3. Simulation Responses- Plant C

The simulation results for the Plant C configuration are presented in this section. As explained in the previous section, the provided air conditions with the Plant B configuration is mostly out of the range recommended for the operating theater and only the air provided by the added two-row HPHX are within the recommendations. Moreover, the total energy consumption of the Plant B configuration is more than existing HVAC system. Therefore, another design as Plant C to achieve energy efficient HVAC system was studied.

In Plant C configuration, the heater was replaced with the condenser section of the HPHX to benefits the free heating effect of the HPHX condenser section. The simulation results for Plant C are tabulated in Table 5. According to the results, Plant C configuration with the added two-row HPHX is marginally out of the recommendations. However, room air conditions provided by the four, six and, eight-row HPHXs are within the recommendations. Fig. 9 shows the simulation responses for

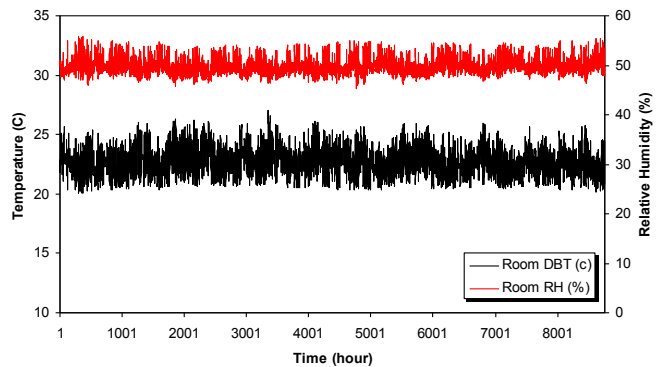
the Plant C configuration for the added eight-row HPHX as a representative. The Plant C configuration energy performance is tabulated in Table 6.

**Table 5.** Room air conditions for the Plant C

	Room Temperature (°C)	Room RH (%)	Supply RH (%)
Two-row HPHX	20.9	60.6	78.9
Four-row HPHX	22.0	54.0	69.0
Six-row HPHX	22.4	51.4	65.3
Eight-row HPHX	22.7	49.8	63.1

**Table 6.** Energy consumption of the Plant C

	Energy consumption of the equipment (kWh)				
	Chiller	Heater	Energy Recovery Wheel	Blower	Total
Two-row HPHX	47,395.7	--	--	6,877.96	54,273.66
Four-row HPHX	41,573.0	--	--	7,467.83	49,040.83
Six-row HPHX	38,958.0	--	--	8,285.97	47,243.97
Eight-row HPHX	37,366.6	--	--	8,796.26	46,162.86



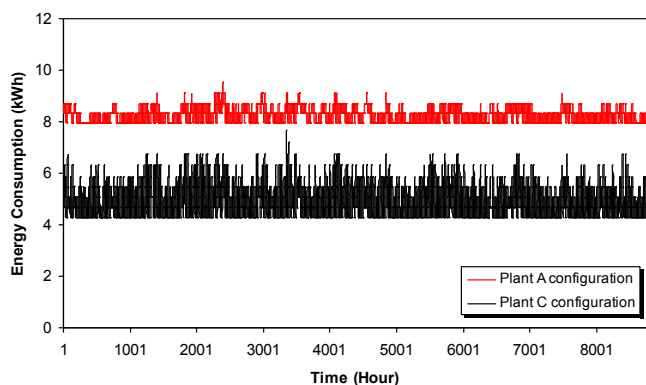
**Fig. 9.** TRNSYS results for simulating responses of HVAC system\_Plant C

The energy saving potential of the Plant C was tabulated in Table 7. As indicated in Table 7, the Plant C configuration with the eight-row HPHX has the highest energy saving capability of 26,099.54 kWh. The estimations show that the total energy consumption of Plant C with the eight-row HPHX is about 46,162.86 kWh in comparison to the existing system at 72,262.4 kWh (see Fig. 10).

**Table 7.** Yearly energy consumption and saved energy (kWh)

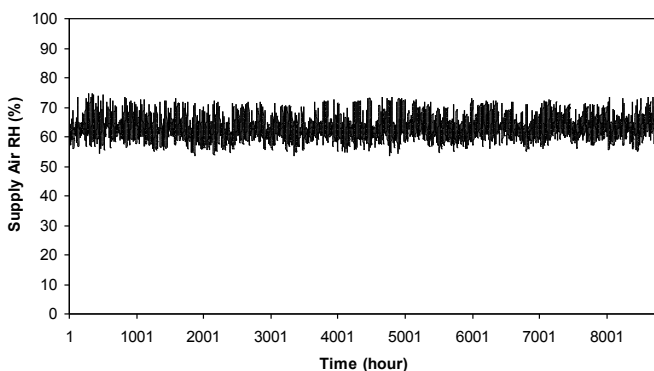
System	Chiller	Heater	Energy Recovery Wheel	Blower	Total	Saved Energy (kWh)
Plant A	34,016.24	30,660	1,629.36	5,956.8	72,262.4	--
Plant C: Eight-row HPHX	37,366.6	--	--	8,796.26	46,162.86	26,099.54





**Fig. 10.** Hourly comparison of the total energy consumption of Plants A and C configurations

The supply duct air RH was also studied for the Plant C configuration with the eight-row HPHX and the results were illustrated in Fig. 11. As shown in Fig. 11, the Plant C configuration with the eight-row HPHX could provide most of the hours in less than 70% with the mean value of 63.1%. With considering all the above, the Plant C configuration with the eight-row HPHX are the most proper configuration in terms of energy consumption level and provided air conditions and recommended to be implemented in the existing HVAC system.



**Fig. 11.** TRNSYS results for simulating responses of HVAC system\_Plant C: added eight-row HPHX

## 6. Conclusion

The existing HVAC system of the fully fresh HVAC systems in operating theaters is found to be energy inefficient and can be further improved by the application of HPHXs. Therefore, the existing HVAC system of an operating theatre, Plant A, was redesigned with the application of a HPHX. The redesigned configurations as Plant B and Plant C were simulated and the performances of the configurations were examined hour-by-hour for a whole year of operation. The simulation results showed that the chiller and heater in Plant A consumes 47% and 42.4% of the system energy, respectively. Moreover, the RH value for the supply duct air was found at 78%, which is higher than the maximum 70% recommendation. Based on the results, it was found that Plant B configuration keeps the supply duct air in less than

70%. However, room air conditions are mostly out of the recommended range. Moreover, the energy consumption level of Plant B configuration is higher than Plant A configuration. Therefore, another configuration as Plant C was studied. In Plant C configuration, the heater equipment was replaced by the condenser section of the added HPHX to benefit the free reheated provided by the HPHX. The simulation responses showed that room air conditions and supply duct air RH are within the recommendations with the four, six, and eight-row HPHX. Moreover, the energy consumption level of Plant C indicates that Plant C configuration with the eight-row HPHX has the capability of saving a total amount of 26,099.54 KWh energy in a year.

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