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# Thermal Comfort Analysis of Art Centre Auditorium Utilizing R290 Refrigerant Chiller

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***Abstract*— Thermal comfort is an essential parameter for the well-being of occupants in buildings. This paper aims to analyze the thermal comfort of a 400-person capacity-art center auditorium at Universitas Indonesia. The physical parameters evaluated include temperature and humidity according to both ASHRAE-55-2010 and National SNI 03-6572-2001 standards on thermal comfort conditions. The auditorium air conditioning system utilized a 56-ton refrigeration air-cooled chiller with natural refrigerant R290 and was equipped with both refrigerant and watersides sensors and data acquisitions. A simulation of the airflow and temperature distribution of the auditorium was also developed. Experimental measurement using automatic data loggers was performed on-air dry-bulb temperature and humidity inside the auditorium during events with empty and full-capacity audiences. The results are compared to the simulation and standards. The simulations resulted in an average temperature difference of 12.7% compared to the temperature obtained from experimental data. According to the standards provided, the auditorium's chiller system can maintain thermal comfort with an average cooling load of 52.4% at COP of 4.34. The result shows that the auditorium can sustain a thermally comfortable indoor environment with an average of about an hour of thermal recovery time. The auditorium air conditioning system also shows that using an environmentally friendly refrigerant R290 with very low GWP refrigerant for building air conditioning systems can provide thermal comfort and energy-efficient solutions.**

***Keywords*—Thermal comfort analysis; chiller; R290; natural refrigerants.**

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## I. INTRODUCTION

With the growing environmental concern of the negative impacts of hydrofluorocarbon (HFC) and hydrochlorofluorocarbon (HCFC) on both the ozone and global warming, environmentally friendly refrigerants must be important not be neglected. Possessing low Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) values, hydrocarbons, a natural gas, could be used as refrigerants without the environmental drawbacks of HFC and HCFC-based refrigerants. Earlier conducted research concluded that an R290 based refrigerant chiller has a higher performance than the R22 refrigerant commonly used in refrigeration systems today [1]-[3]. Many research types have been done to support the efforts to persuade industry and consumers to use non-HFC and non-HCFC based refrigerants [4], [5] and its safety [6]-[9]. The literature on energy performance measurement of the AC system is available [10]-[12], where they were used to support Indonesia's energy labeling program. The airflow measurement is presented in the references [13],[14] for the fan and blower used in the air conditioning system.

Even with higher energy performance and better environmental impact, the thermal comfort of the conditioned space itself must still be seen to ensure well-being and satisfaction amongst the occupants. ASHRAE Standards 55 [15] defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment". The Indonesian tropical climate does not naturally provide comfortable indoor temperature and humidity. The appropriate cooling system and indoor air distribution must be made to ensure the satisfaction of occupants within the thermal environment, especially in a society accustomed to mechanical indoor air conditioning systems [15],[17] where 60% of energy consumption in the built environment is consumed by air conditioning systems [18].

This research intends to analyze an auditorium's thermal comfort by utilizing a mechanical air conditioning system with R290 as its refrigerant in empty and full-capacity audience situations. The research can be used as a showcase in developing and optimizing hydrocarbon refrigerants used in air conditioning systems to reduce environmental damage from HCFC & HFC-based refrigerants without compromising the air conditioning system's energy performance, and still prioritizing indoor environment quality to ensure comfort amongst its occupants. The system of interest also features the safety consideration of having separate refrigerant and chilled water loop specified for flammable refrigerant R 290.

## II. Material and Method

### A. Climate Condition

Makara UI Art Center, the hosting building of the auditorium is located on Jl. DR Mahar Mardjono, Universitas Indonesia, Depok, West Java. The coordinates for the facility are 6°20'52.1"S 106°49'46.7"E. The site is a 1A ASHRAE International climatic zone with boiling and humid outdoor condition. The average temperature and humidity are 26.7 °C and 80 %, respectively, and the maximum outdoor temperature and humidity are 32.5 °C and 85%, respectively. Based on the National Standard of SNI 6390, the design condition is 33 °C dry-bulb temperature and 63% relative humidity. Figures 1 and 2 depict the building orientation and annual climatic condition, respectively.

Fig. 1 Location and orientation of the Art Center building

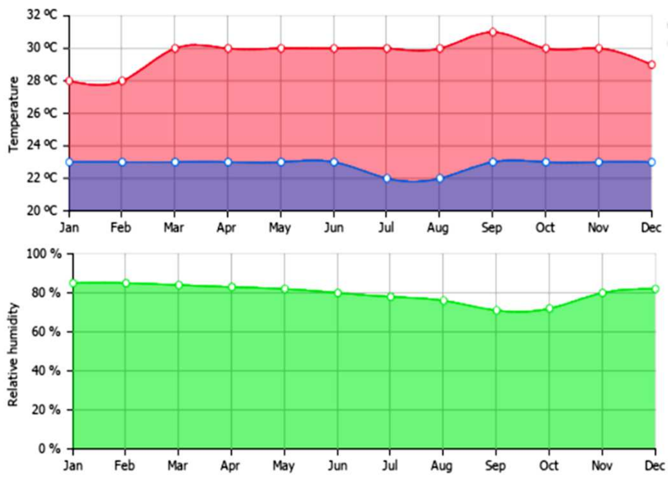


Fig. 2 Average temperature and humidity in Depok, West Java

### B. Building Specification

The Makara Art Centre is a building dedicated to art displays and performances, with an auditorium as its defining feature. The auditorium was designed specifically for the performing arts, with a floor space of 510 m². The auditorium has a seating capacity for 400 occupants, and the inside is divided into two main sections: the stage and sitting area.

The auditorium itself protects itself as much as possible from external heat load, as the left and right-side walls are connected to the auditorium's hallway, while the front and rear sidewalls are connected to a mechanically air-conditioned lobby area to decrease external heat load. The external roof of the auditorium building is open with 200 mm thick concrete, while the internal ceiling is insulated, and the flooring contains concrete of various thicknesses. Due to the interior being designed for an excellent acoustic environment, the external heat load is further reduced by noise-insulating components. It can be considered that the insulation inside prevents heat load from the sun radiation that affects the temperature inside the conditioned space.

Fig. 3 Photograph of auditorium interior

### C. Air Conditioning System Specification

An air-cooled chiller is used as the refrigeration unit installed in the auditorium of the Makara Art Centre of the University of Indonesia. The chiller specifications are depicted in Table 1.

TABLE I
CHILLER SPECIFICATION

| Specification | Unit/Information |
|---|---|
| Cooling Capacity | 56 TR / 197.6 kW |
| Total Power Consumption | 55.9 kW (Dual Compressors) |
| Total Rated Ampere | 101 A |
| Refrigerant | Propane HC290 (R-290) |
| Refrigerant Charge | 2 x 11 kg |
| Refrigerant Flow Control | Electronic Expansion Valve |
| Pressure Drop @ Nominal Flow | 30.0 kPa |
| Complementary Measurement Tools | Refrigerant Side & Water Side Measurement, Pressure Transducer, Temperature Transducer, Refrigerant Flow Meter, Water Flow Meter, Water Temperature Inlet & Outlet Chiller, kWh Energy Monitoring. |

### D. Experimental Setup

For this research, eight temperature loggers are strategically placed to record the auditorium's dry-bulb temperature and humidity without obstructing the view of the stage for the occupants. Six loggers are placed near return-side grilles, two under the seats. This research used two testing conditions to decide the thermal comfort inside the space: Full occupancy and Zero occupancy. The thermal comfort standard being used for this research is SNI (Indonesian National Standard) 03-6572-2001, which uses dry-bulb temperature and humidity to determine the thermal comfort of indoor space for a tropical area. ASHRAE-55-2010 standards are also used as a reference point. The thermal comfort SNI and ASHRAE standards are depicted in Tables 2 and 3, respectively.

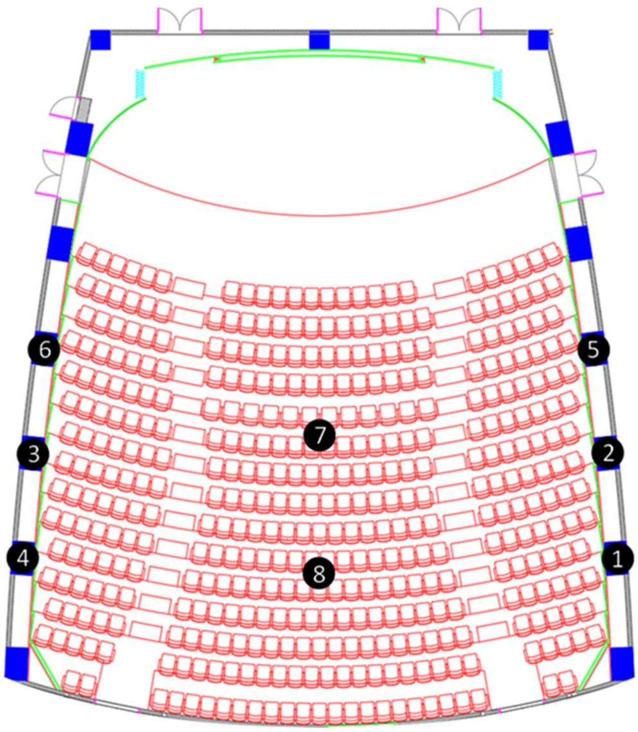


Fig. 4 Top-view of the auditorium with logger placements

SNI Standards say that for indoor spaces located in tropical areas, the approved humidity range is between 40-50%; however, in spaces where people's density is high, the humidity range is still permitted between 55 – 60% [19]. Meanwhile, ASHRAE does not have a lower humidity limit and uses operative temperature, not dry-bulb temperature, to measure comfort.

TABLE II
SNI 03-6572-2001 INDOOR THERMAL COMFORT STANDARD

| Comfort Category | Temperature Range (°C) | Humidity Range (%) |
|---|---|---|
| Cool Comfort | 20.5 - 22.8 | 40 – 60 |
| Optimum Comfort | 22.8 - 25.8 | 40 – 60 |
| Warm Comfort | 25.8 - 27.1 | 40 – 60 |

TABLE III
ASHRAE-55-2010 INDOOR THERMAL COMFORT STANDARD

| Comfort Category | Temperature Range (°C) | Humidity Range (%) |
|---|---|---|
| 1.0 clo zone | 20.0 – 25.0 | 0 - 80 |
| 0.5 clo zone | 25.0 – 28.0 | 0 - 62 |

However, assumptions can be made to assume that the operative temperature is the same as the dry-bulb temperature, which is as follows:

- There is no radiant and radiant panel heating or radiant panel cooling system.
- The following equation decides the average U-factor of the outside window/wall:

$Uw < \frac{50}{t_{d,i} - t_{d,e}}$ Uw = average U-factor of window/wall, W/m2 ·K

td,i = internal design temperature, °C (°F)

td,e = external design temperature, °C)

- Window solar heat gain coefficients (SHGC) are less than 0.48.
- There is no major heat-generating equipment in the space.

This research aims to maintain the temperature and humidity within “cool comfort” and “optimum comfort” territory, ensuring that the thermal comfort never reaches above or below those levels. It has to be noted that personal comfort in an indoor space is related to thermal comfort, health, and control availability [20]. Due to the limitations of this research, an assumption is made that the dry bulb temperature is equal to space's operative temperature.

## III. RESULTS AND DISCUSSION

The results of this research are divided into two parts to separate the conditions in which the data was recorded. Each division contains temperature, humidity, cooling load, and COP data with analysis regarding thermal comfort inside the auditorium.

### A. *Full Occupancy*

The auditorium was filled with 400 occupants who do not include the performers and control room crew. Temperature and humidity data were recorded during this time, as shown below in Table 4.

TABLE IV
THERMAL DATA IN A FULLY OCCUPIED AUDITORIUM

| Minutes | Average Temperature (°C) | Average humidity (%) |
|---|---|---|
| 0 – 10 | 20.55 | 63.66 |
| 11 – 20 | 20.87 | 62.41 |
| 21 – 30 | 21.13 | 61.17 |
| 31 – 40 | 21.35 | 59.98 |
| 41 – 50 | 21.52 | 59.39 |
| 51 – 60 | 21.70 | 58.62 |
| 61 – 70 | 21.84 | 58.01 |
| 71 – 80 | 21.97 | 57.19 |
| 81 – 90 | 22.09 | 56.55 |
| 91 – 100 | 22.11 | 57.00 |
| 101 – 110 | 22.06 | 57.40 |
| 111 – 120 | 22.19 | 57.01 |
| 121 – 130 | 22.08 | 57.69 |
| 131 – 140 | 22.18 | 57.06 |
| 141 – 150 | 22.29 | 56.70 |
| 151 – 160 | 22.37 | 56.06 |
| 161 – 170 | 22.45 | 55.64 |
| 171 – 180 | 22.18 | 56.80 |

Fig. 5 shows that the temperature data is primarily comfortable, except in the first half-hour of the event, where the temperature is below comfort levels and can be considered too cold. This result may be caused by over-cooling, as the chiller has been activated long before recording data. The auditorium was left empty for an hour before the show started, allowing the auditorium's temperature to decrease. This is relevant for loggers 1 to 4, which are located at the highest level of the auditorium, having the lowest distance between the seating position and the supply air vents releasing cold air into space. Fig. 6 shows the humidity levels in the auditorium.

Fig. 6, however, shows that the humidity is too high for an hour, and it would take 60 minutes after the beginning of the event for the space to be entirely comfortable following the SNI standards. Fig. 7 simplifies Fig. 5 and Fig. 6 to see the comfort category in the space over time. The doors were opened for about 20 minutes to allow people into the auditorium. The sudden increase in humidity may be attributed to the possibility of factors such as short-cycling, the possibility of outside-air infiltration, as the air outside the auditorium was very humid due to rain, and also the high likelihood of high latent heat from occupants, which increases humidity without increasing the dry-bulb temperature.

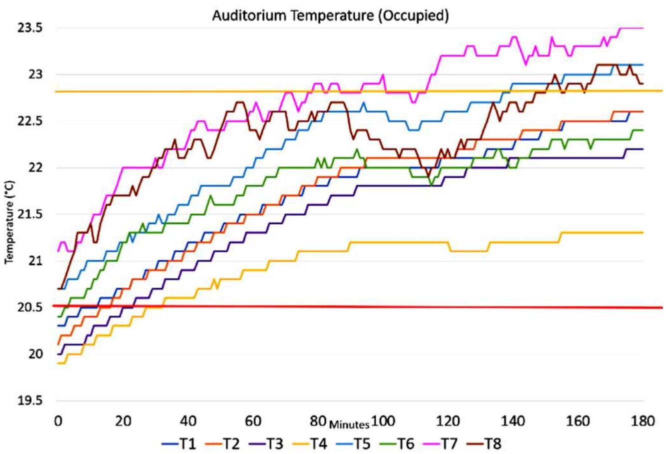


Fig. 5 Temperature data over time in the fully occupied auditorium

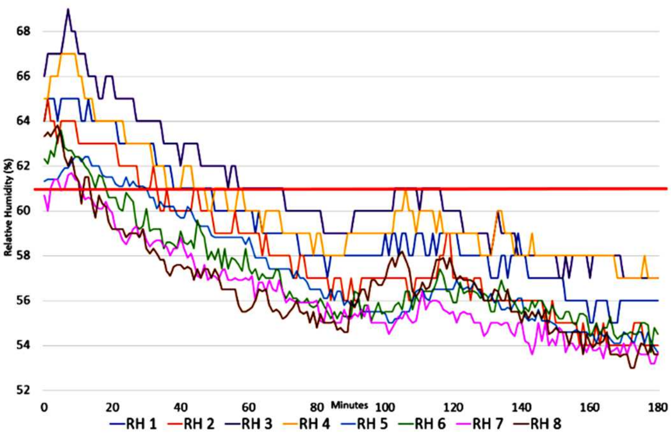


Fig. 6 Humidity data over time in the fully occupied auditorium

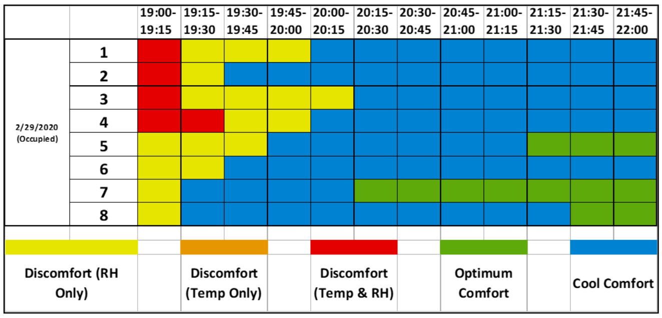


Fig. 7 Psychrometric analysis of the auditorium during a full occupancy

During the event, the cooling load trend must be shown to see changes in cooling load following the number of people inside the space and substantial modifications to load in time. Fig. 8 and Fig. 9 below exhibit the difference in cooling load and COP following time, respectively.

The cooling load percentage data shows a fluctuating range of cooling loads, never indeed stabilizing following time. With the trendline showing a peak of 62% at the top and 40.4% at the bottom. The cooling load averages 52.4%.

The COP values are shown in Fig. 9. The COP of the system rises over time, with a peak COP of 4.34 around 100 minutes. Due to the high cooling load and constant compressor work, the COP levels are high. This number shows that the COP is affected by a stable compressor electricity consumption, as cooling load and COP have a similar pattern.

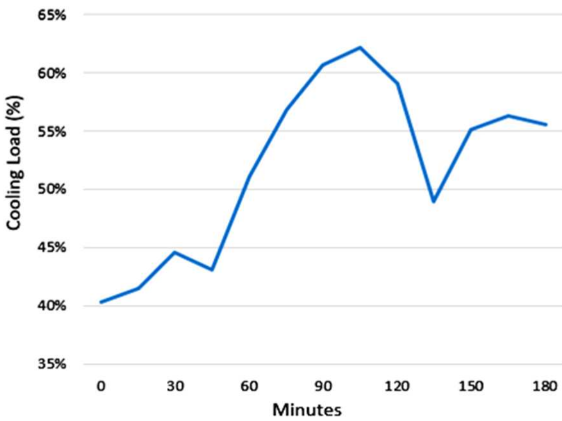


Fig. 8 Changes in cooling load over time in a full auditorium

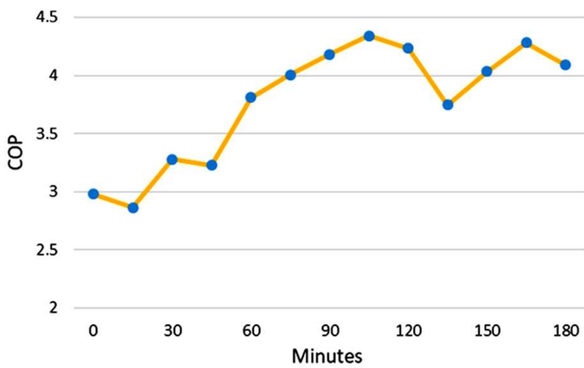


Fig. 9 Changes in COP over time in a full auditorium

## B. *Zero Occupancy*

The same experiment is run. The data loggers are made to run for the same time and sampling rate, the only exception being that the auditorium was empty during this recording, as shown in Table 5. The next figures will show the changes in temperature, relative humidity, cooling load, and COP over time.

TABLE V
THERMAL DATA IN AN EMPTY AUDITORIUM

| Minutes | Average Temperature (°C) | Average humidity (%) |
|---|---|---|
| 0 – 10 | 24.11 | 50.54 |
| 11 – 20 | 23.69 | 50.45 |
| 21 – 30 | 23.27 | 50.28 |
| 31 – 40 | 22.84 | 50.73 |
| 41 – 50 | 22.53 | 50.88 |
| 51 – 60 | 22.23 | 50.90 |
| 61 – 70 | 21.39 | 54.65 |
| 71 – 80 | 21.71 | 51.01 |
| 81 – 90 | 21.50 | 51.01 |
| 91 – 100 | 21.30 | 52.30 |
| 101 – 110 | 21.29 | 54.20 |
| 111 – 120 | 21.29 | 55.43 |
| 121 – 130 | 21.29 | 56.33 |
| 131 – 140 | 21.32 | 57.38 |
| 141 – 150 | 21.35 | 58.22 |
| 151 – 160 | 21.36 | 57.88 |
| 161 – 170 | 21.23 | 56.24 |
| 171 – 180 | 21.02 | 55.03 |

Fig. 10 shows air temperature progress inside the auditorium. During the initial stages of data recording, the temperature decreases over time and stops after 90 minutes, where the air temperature stabilizes to a certain extent. The chiller was only activated about 90 minutes before data retrieval, which may be why the auditorium's temperature is still decreasing for some time. The temperature can still be considered comfortable, except after 160 minutes where some loggers detected that the space's temperature is too cold. However, it must be considered that the temperature of the space is never considered too hot to be uncomfortable and follows the indoor thermal comfort standards used for this analysis.

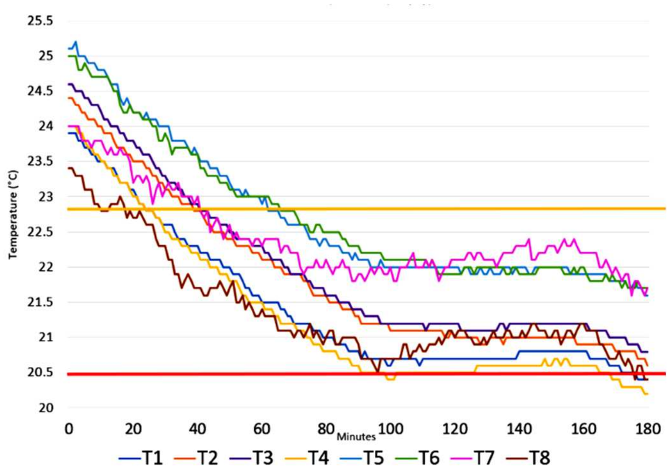


Fig. 10 Temperature data over time in the empty auditorium

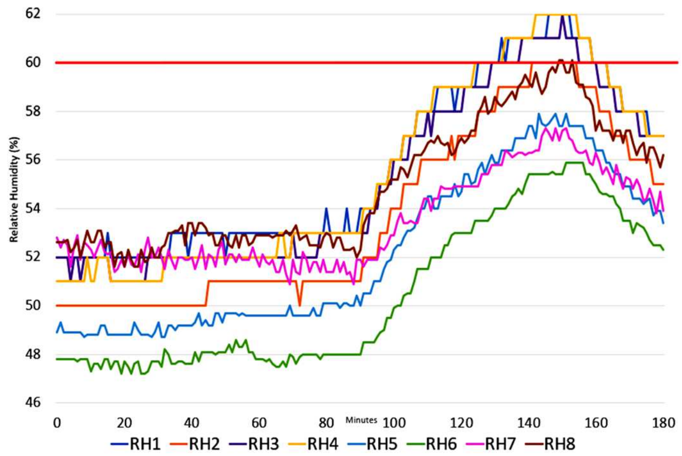


Fig. 11 Humidity data over time in the empty auditorium

The relative humidity data shows good comfort, as depicted in Fig. 11. However, the chiller's compressor settings were manually interfered with, one of the compressor's pistons was bypassed, decreasing the overall work of the compressor, which increased the indoor humidity significantly, as the compressor turned on and off often, which caused the humidity inside the evaporator coils to be brought inside the auditorium, causing discomfort. Even though the humidity inside was increasing rapidly, the temperature inside the space does not seem to be affected. Fig. 12 simplifies Fig. 10 and Fig. 11 to see the comfort category in the space over time.

As depicted in Figure 13, the air's unstable condition in the initial stages causes the cooling load to increase significantly, decreasing over time as the need for cold air decreases. However, the capacity control causes the compressor work and cooling load to increase.

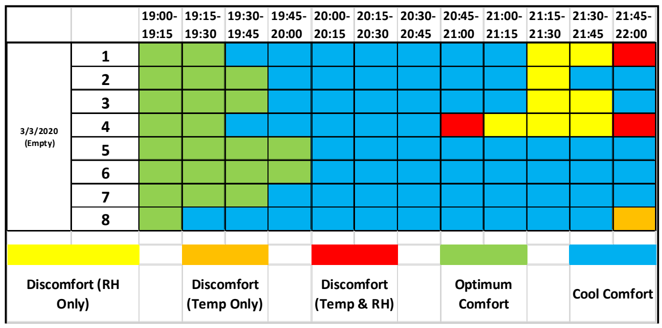


Fig. 12 Psychrometric analysis of the auditorium during zero occupancy

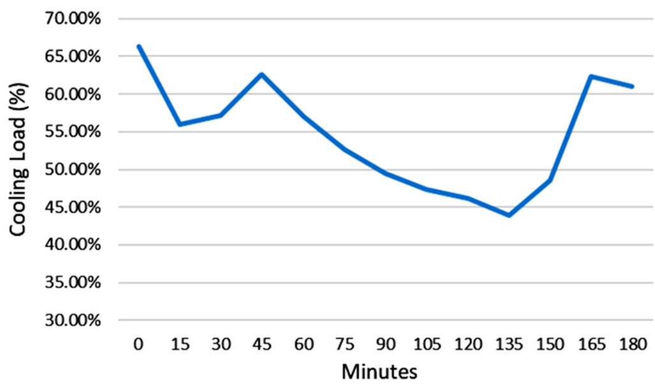


Fig. 13 Changes in cooling load overtime in the empty auditorium

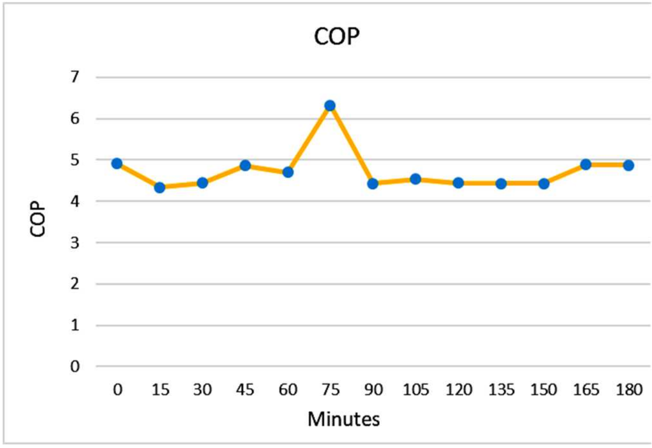


Fig. 14 Changes in COP over time in the empty auditorium

Meanwhile, as shown in Figure 14, the COP is very high due to manual interference, causes a substantial drop in compressor work, and the high cooling load causes the COP to increase to very high levels. The auditorium can maintain a comfortable space providing the compressor setting is not tampered with when occupants are inside the auditorium to prevent sudden changes in the compressor functionality.

*C. Computational Analysis*

An analysis was done using computational fluid dynamics (CFD) simulation to predict air distribution patterns inside the auditorium's space. The analysis was commissioned and done to summarize the auditorium's HVAC system, and the simulation itself was done to see the distribution of temperature, airspeed, and air pressure [21]. This analysis's main focus is to predict the temperature distribution and compare the analysis results to the real data taken inside the auditorium. According to the analysis, the air distribution's common pattern is dispersed evenly throughout the space, except for the area near the entrance, where the temperature is slightly higher.

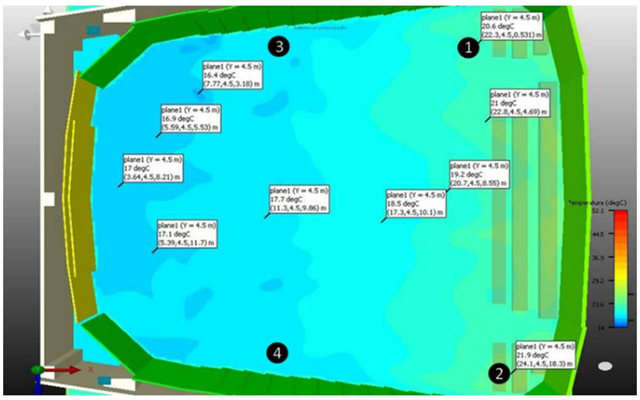


Fig. 15 Simulated Temperature Distribution at XZ, Y =4.5 m

Theoretically, the air has more room to travel, causing the stage area's temperature to be lower. However, this simulation is done under the conditions that the space is empty. The average temperature in the auditorium is 20.8°C at Y = 4.5 m. After using the simulation, 4 points of temperature are compared and validated to see how much the error is between simulation and reality. The results are shown in the table below, with the difference shown using temperature and percentages.

TABLE VI
COMPARISON BETWEEN SIMULATED AND RECORDED DATA

| Point | Simulation (°C) | Recorded data (°C) | Difference (°C) | Difference (%) |
|---|---|---|---|---|
| 1 | 20.6 | 21,4 | +0.8 | 3.8 |
| 2 | 21.9 | 21.3 | -0.6 | 2.8 |
| 3 | 17.5 | 22.7 | +5.2 | 25.9 |
| 4 | 17.7 | 22.7 | +5.0 | 24.8 |
| Avg. | 19.4 | 22.03 | +2.63 | 12.7 |

Table 6 shows that the maximum percentage difference lies with point 4, with a 24.8% difference, with the smallest percentage difference being point 2, with 2.8%. Therefore, the average percentage difference is 12.7%.

There are differences between simulated and recorded data collected for the unoccupied auditorium. The recorded data shows that the area near the entrance has a lower temperature, while the simulation shows that the entrance area is warmer than the stage area. Table 6 above shows the temperature difference at points 3 & 4, reaching a difference greater than 24%, which is caused by several factors. First, the simulation data points are taken at the height of 4.5 meters relative to the stage floor, which is why points 3 & 4 have a large temperature difference.

The data points for the simulation are located near the air supply, while for the recorder data, the loggers are placed near the return air vents with the height relative to the occupants' seating position (1 meter). Then, the loggers are also located near auditorium lighting, which causes the heat load from the lamp to increase the temperature of the auditorium during a performance. Meanwhile, the auditorium simulation does not include the heat load from the light bulbs as well.

## IV. CONCLUSION

This research examines the thermal comfort inside the Makara UI Art Centre building auditorium, in which a chiller uses R290 as its refrigerant is installed. The field data collected included temperature and humidity and were compared with thermal comfort standards according to SNI 03-6572-2001 and ASHRAE-55-2010. The results show that the auditorium could maintain thermal comfort but could not accommodate sudden rises in humidity. The data shows that outside air infiltration caused humidity levels to spike beyond comfort levels, and the chiller system showed no change to accommodate the sudden increase in humidity. This pattern was exaggerated as the manual interference in capacity control caused compressor work to decrease, increasing humidity levels significantly. However, the temperature levels showed no issue due to this change in compressor work. The cooling system can maintain thermal comfort during partial load and low load conditions in a stable condition. According to the standards provided, the auditorium’s chiller system can maintain thermal comfort with an average cooling load of 52.4%. The compressor settings are not tampered with during an event to prevent unpredictable changes in humidity.

Computer simulations of the auditorium with temperature distribution were developed with the temperature difference between simulation and recorded data of 12.7%.

The thermal comfort can be improved by applying a control system to detect humidity levels to activate the dehumidifier inside the air handling unit. Another suggestion is adding an air curtain to mitigate the entry of hot and humid outside air into the auditorium.


## ACKNOWLEDGMENT

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