SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

# Performance Improvement of The Radiant Cooling Panel Using Pressure-Vacuum Swing Adsorption with A Solid Desiccant Dehumidification

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**ARTICLE INFO**

***Article history:***
Received 31 January 2022
Received in revised form 20 April 2022
Accepted 23 April 2022
Available online 24 May 2022

***Keywords:***
Desiccant dehumidifier; radiant cooling panel; experiment; computational fluid dynamics; thermal comfort; predicted mean voted

**ABSTRACT**

A growing environmental Impact of global warming and rapidly increasing cost of the electrical energy cause researchers in the field of refrigeration and air conditioning to develop the sustainable cooling technologies. The aim of this study was to investigate and design a radiant cooling panel with solid desiccant dehumidifier which was suitable for tropical climate to achieve thermal comfort. The influence of an interior ventilation fan to thermal comfort assessment was also examined. The designed system with CFD (Computation fluid dynamics) simulation used ANSYS software to compare with the measured data. The total area of the ceiling and wall radiant cooling panels were 16.83 $m^2$ and 16.32 $m^2$ with 26.28 L/min of supplied water by the cooling tower. The solid desiccant dehumidifier was the pressure-vacuum swing adsorption technology with containing 20 kg of silica-gel. The flow rate of supply air was approximately 90 kg/h. The results indicated that the PMV (Predicted mean voted) could be improving with the uses of cooling panel with dehumidifier during the day. The lower temperature and humidity ratio can improve thermal comfort. The patterns of temperature, the relative humidity and the PMV from CFD simulation were in the same agreement with the experimental results. In the case of the ventilation fan installed in the radiant cooling panel with dehumidifier, the average value of predicted mean vote was -0.2. Consequently, the PPD (Predicted percentage dissatisfied) was reduced to 6.2%. The daily electric power consumption was 5.94 kWh which was lower than the conventional air conditioning system about 16.27%.

## 1. Introduction

Global electricity consumption is the steady increase over the period from 2000 to 2020, because of population and economic growth. Furthermore, higher combustion of fossil fuels for electricity production leads to the increase of greenhouse gas emissions, particularly $CO_2$ (Carbon dioxide), which contributes to global warming. EPPO (Energy Policy and Planning Office), Ministry of Energy, Royal Thai Government reported that the electricity consumption and greenhouse gas emissions were 190 TWh and 88.3 million tonnes of $CO_2$ equivalents in 2021, respectively. The air conditioners

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https://doi.org/10.37934/arfmts.95.2.6271

were widely used household appliances (approximately 30-40% of the residential electricity demand) and operated continuously throughout the year in tropical climate which was very hot and humid, and a lot of rain. Therefore, air conditioning system still have a large potential for energy saving. A principal purpose of HVAC (Heating ventilation and air conditioning) is to provide thermal comfort conditions for human which is the condition of mind that expresses satisfaction with the thermal environment. Temperature, air speed, humidity, and personal parameters of metabolism and clothing insulation are primary factors that directly affect energy flow and the thermal comfort. However, many secondary factors, age adaptation, sex, and seasonal and circadian rhythms are only slight differences in preferred of thermal comfort conditions. As reference by ANSI/ASHRAE Standard 55 (1992), the acceptable ranges of operative temperature and relative humidity are 20°C-26°C and 30%-60%, respectively. In the tropical region, such as Thailand climatic zones, the conditions at 26°C and 50%-60% relative humidity are considered as a comfortable environment condition [1-5]. The radiant cooling systems which are an alternative to convective air conditioning systems use temperature-controlled interior surfaces on the walls and ceiling. The temperature is maintained by cooled water passing through the radiant cooling panel which made from copper tube bond with aluminum sheet. The comfort levels can be better than other space conditioning systems because thermal loads are satisfied directly, air motion in the space corresponds is required only ventilation [6-10]. In the area of high humidity, the moisture presents the major problem for the human comfort and the condensation on cooling panel surface. Both mechanical refrigeration systems and desiccant material can remove the moisture from the supply air, whereas desiccant dehumidification is advantageous in dealing with latent load and improving indoor air quality because of adsorbing moisture directly. The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapour due to the difference of water vapour pressure between the surrounding air and the desiccant surface. Many desiccant materials are available, such as silica gel, activated alumina, molecular sieve (synthetic zeolite), alumina gel, etc. In other words, silica gel has a high capacity for water and no sulfur conversion reactions [11,12]. The solid desiccant dehumidifiers usually employ stationary beds or rotary wheel beds for packing the desiccant media. The desiccant column is also widely used in the process of air dehumidification or drying [13-18]. In a tropical humid climate, the energy consumption and the assessing thermal comfort can be improving in the conventional air conditioning system with the dehumidifier [19-24].

The purpose of this study was to investigate and design a radiant cooling panel with solid desiccant dehumidification which was suitable for tropical climate to achieve thermal comfort. The dehumidifiers were used in dehumidifying the ventilation air stream by forcing it through a structured packing impregnated with silica gel for the thermal comfort improvement of the radiant cooling system. In this paper, the CFD simulations were used to predict the thermal comfort assessment and air phenomena profile in the laboratory.

## 2. Methodology

### *2.1 Experimental Setup and Method*

In this study, the laboratory consisted of dehumidifier and radiant cooling panel was set up at the 2nd floor of the experiment house in Prince of Songkla University, Hatyai campus, Songkhla Province located in the Southern part of Thailand, as shown in Figure 1. The radiant cooling system was designed using cool water supplied from cooling tower passing through the radiant cooling panel which made from copper tube bond with aluminum sheet. The cooling panels were installed at the ceiling and the opaque wall in the laboratory. The total area of the ceiling and wall radiant cooling panels were 16.83 $m^2$ and 16.32 $m^2$, respectively. The 26.28 L/min of cool water was supplied to cooling panels and continuously circulated to cooling tower with closed system. Cooling tower produced cool water and stored in the storage tank. Moreover, the circulated pump was operated using solenoid valve received signal from temperature sensor, as Figure 2. The dehumidification system used the solid desiccant within the pressure-vacuum swing adsorption to remove water vapour from the ventilation air before passing into the laboratory. The dehumidifiers consisted of a desiccant column containing 20 kg of silica gel. The flow rate of supply air was kept around 90 kg/h by a ventilation fan driven by an inverter. The spherical particles of silica gel were used as the working desiccant in the dehumidifier. The physical properties of silica gel were 3 mm of diameter, porosity 0.4 (the open volume fraction of the medium) and bulk density 670 kg/m$^3$.

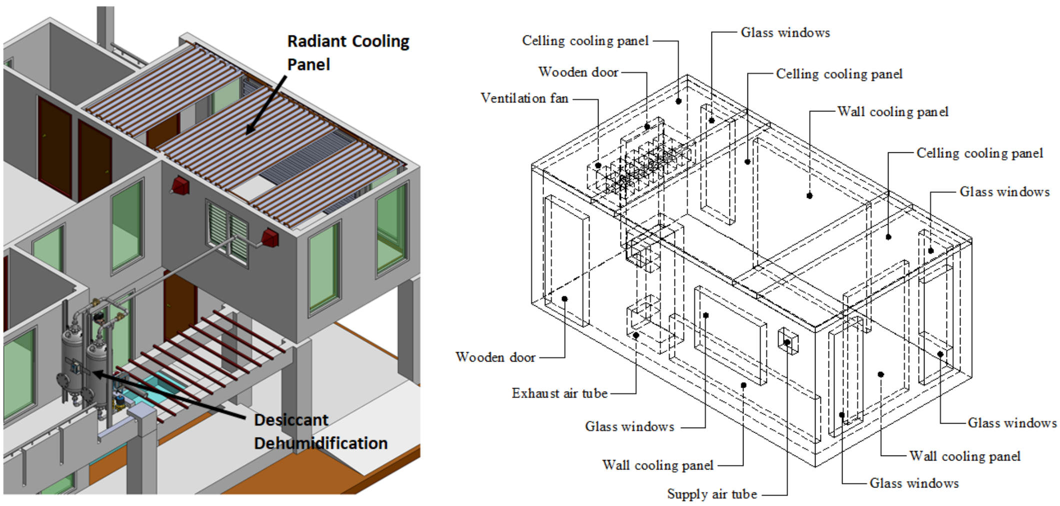


**Fig. 1.** Experimental setup: a laboratory

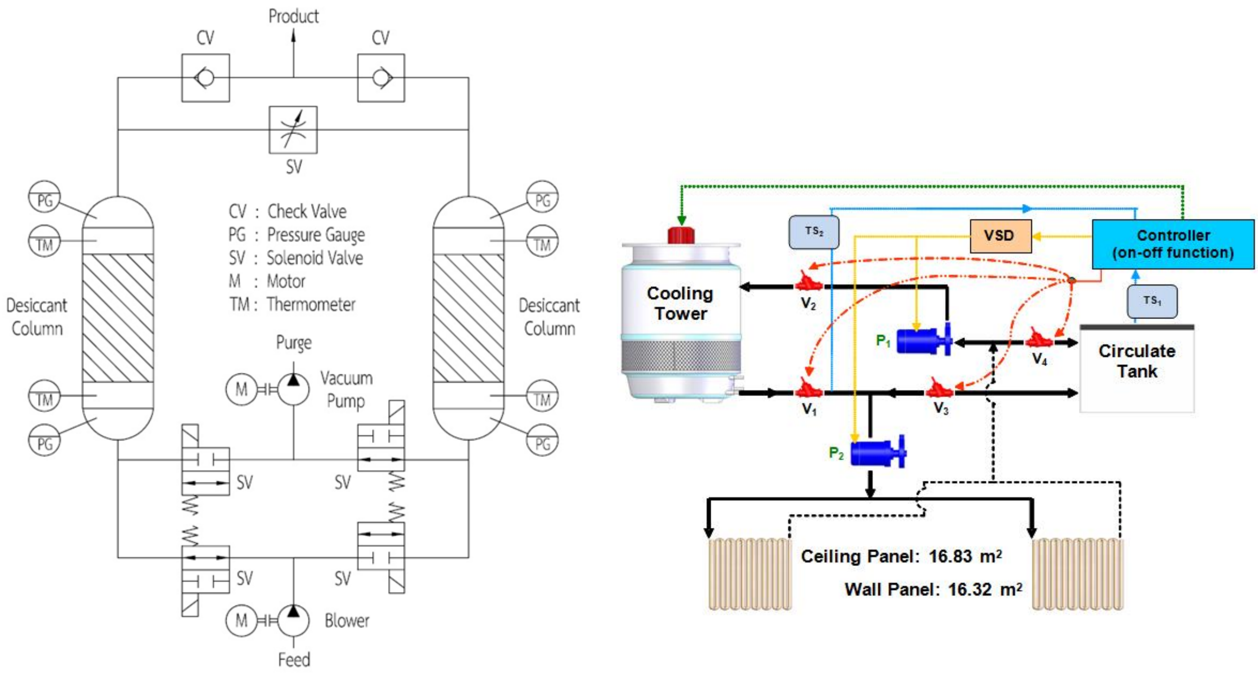


**Fig. 2.** Radiant cooling panel with a solid desiccant dehumidification; (a) Pressure-vacuum swing adsorption, (b) Radiant cooling panel

In the experimental room, temperature sensors, humidity sensors, thermocouple, and globe thermometer were installed to measure temperatures of interior and exterior air, relative humidity of interior and exterior air, surface temperatures of radiant cooling panels, and mean radiant temperature of interior air, respectively. For the dehumidification system, the temperature and relative humidity of the ventilation air were measured by temperature and humidity transmitter, and a pressure drop in dehumidifier was measured by differential pressure transmitter. Moreover, the power consumption of the air conditioning system was collected by the power meter. The measurement data were recorded every one minutes using data logger. In addition, the thermal comforts (PMV and PPD) were calculated using the equations proposed by Fanger, P.O. (1970). The PMV is an index that predicts the mean value of the subjective ratings of a large group of people on a seven-point thermal-sensation scale as follows: +3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, and -3 = cold. The PPD is an index that predicts the percentage of a large group of people likely to feel thermally uncomfortable as anybody not voting -1, +1, or 0. The functional relationships between PMV and PPD are given by Eq. (1) and Eq. (2).

$$PMV = \left[0.303\exp(-0.036M) + 0.028\right]L \quad (1)$$

$$PPD = 100 - 95\exp[-(0.0335\,PMV^4 + 0.2179\,PMV^2] \quad (2)$$

where predicted mean vote (dimensionless), PMV, predicted percentage dissatisfied (dimensionless), PPD, the rate of metabolic heat production ($W/m^2$), M and the thermal load on the body ($W/m^2$), L

*2.2 Numerical Simulation*

The ANSYS software, a CFD (Computation fluid dynamics) program which is often used to solve the governing equation of the fluid dynamic and heat transfer problems such as the Navier-Stokes or energy equations by numerical method, was used to explain the phenomena of the temperature distribution in the experiment room with radiant cooling panel and the dehumidifier. The grid size of mesh independency and time step used for this simulation were 0.015 m and 1 s, respectively. The governing equations for this fluid flows problem were three-dimensional, viscous-turbulent, incompressible and transient heat transfer. Both the radiation and the natural convection heat transfer were investigated. The physical properties of the air, laboratory room and radiant cooling panel were assumed to be constant. In this simulation, the moist air was involved modeling the multiphase flow as fluid mixture between dry air and water vapour. Mixture model in the Euler-Euler approach is a simplified multiphase model. It can be used to model multiphase flows where the phases move at different velocities. The k-ε equations were solved for turbulence closure. A simple algorithm gives a method of calculating pressure and velocities. Under the finite volume method, although the first-order upwind scheme discretization can yield better convergence, it generally will lead to less accurate results with only first-order accuracy. Therefore, the QUICK (quadratic upwind differencing) scheme discretization with third-order accuracy was used in calculating momentum, volume fraction, turbulence kinetic energy and its dissipation rate. Moreover, two system configurations were investigated. The first system was only the cooling panels with the dehumidifier. The second system couples a ventilation fan installation to the radiant cooling system. In this assessing thermal comfort level, the occupants were assumed to have a clothing insulation value of 1 clo. This corresponds to an office worker dressed in slacks, shirt, shoes, and socks. The occupants were also assumed to be doing sedentary work, with a metabolic rate of 1.2 met.

In the numerical simulation, the phenomena of the interior air conditions of the laboratory were investigated, such as the temperature profile, the relative humidity profile, the air flow rate distribution, or the predicted mean vote. The previous experimental data were used as input for the simulation. The temperature and relative humidity of the exterior air, the temperature surface of the cooling panels, or the temperature and relative humidity of ventilation supply air were used for the boundary and initial conditions.

## 3. Results and Discussion

### *3.1 The Temperature Distribution*

The experimental results in cases of without and with radiant cooling panel were examined. The first case was the laboratory without cooling panel. The second case was the cooling panel installation. Moreover, the moisture content was reduced by the dehumidifier in the second case. For the first case, the temperature and relative humidity of the exterior air were in the range of 26.0 to 34.5°C (29.4°C average) and 61.4 to 83.4% (75.3% average), while, the average temperature and relative humidity of the interior air were 30.3°C and 72.8%, as given in Figure 3. The average moisture content of the interior air was 19.9 $g_w/kg_{da}$. The surface temperature of the cooling panels was around 24.0 to 29.6°C (26.8°C average) in case of with radiant cooling panel. The temperature and relative humidity of the exterior air were in the range of 25.8 to 34.8°C (29.6°C average) and 60.7 to 83.4% (73.6% average), while, the average temperature and relative humidity of the interior air were 28.4°C and 80.9%, as illustrated in Figure 4. The mean radiant temperatures of the radiant cooling panel were in the interval of 25.2 to 30.6°C (27.6°C average). Moreover, the average moisture content of the interior air was 19.8 $g_w/kg_{da}$.

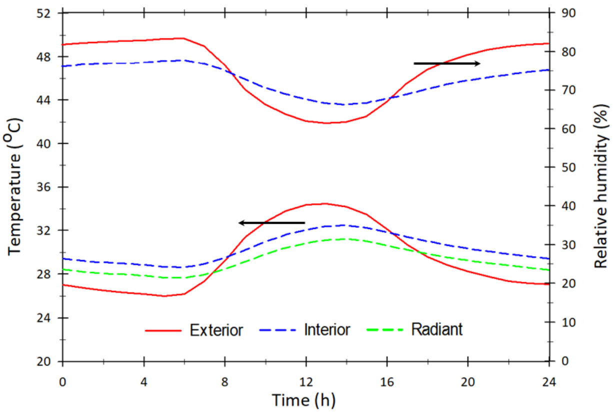


**Fig. 3.** Air temperature, relative humidity, and radiant temperature without cooling panel

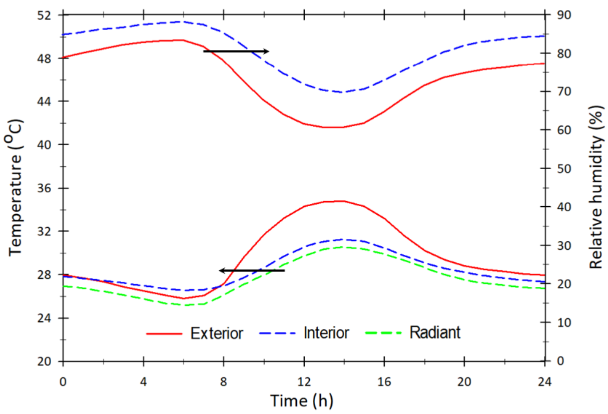


**Fig. 4.** Air temperature, relative humidity, and radiant temperature with cooling panel

In case of using cooling panel with dehumidifier, the surface temperature of the cooling panels was in the range of 24.6 to 29.2°C (26.6°C average). The temperature and relative humidity of the exterior air were in the range of 26.2 to 34.1°C (29.3°C average) and 62.7 to 82.5% (75.5% average), while, the average temperature and relative humidity of the interior air were approximately 28.7°C and 41.7%, as seen in Figure 5. The mean radiant temperature of the radiant cooling panel with dehumidifier were in the range of 25.8 to 34.8°C (27.8°C average) and the average moisture content of the interior air was reduced to 10.3 $g_w/kg_{da}$.

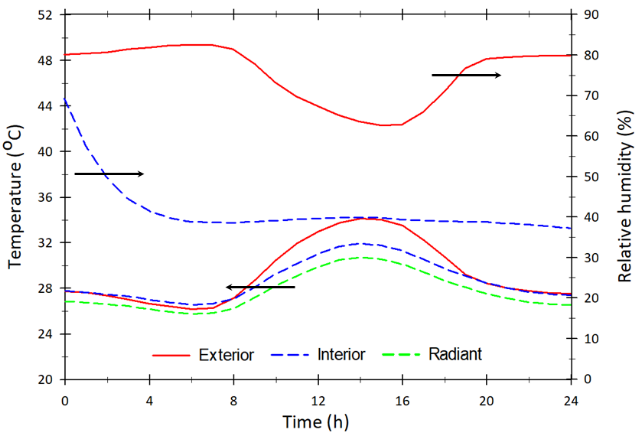


**Fig. 5.** Air temperature, relative humidity, and radiant temperature with cooling panel and dehumidifier

In the simulation result, the patterns of temperature, the relative humidity and the predicted mean volte were in the same agreement with the experimental results. The air temperature and the relative humidity distribution inside central plane (front view, top view, and side view) of the laboratory for the radiant cooling panel with dehumidifier at 8:00 am were shown in Figure 6 and Figure 7, respectively. The average temperature and relative humidity of the interior air were 27.2°C and 36.9%. Moreover, the average moisture content of the interior air was 8.7 $g_w/kg_{da}$.

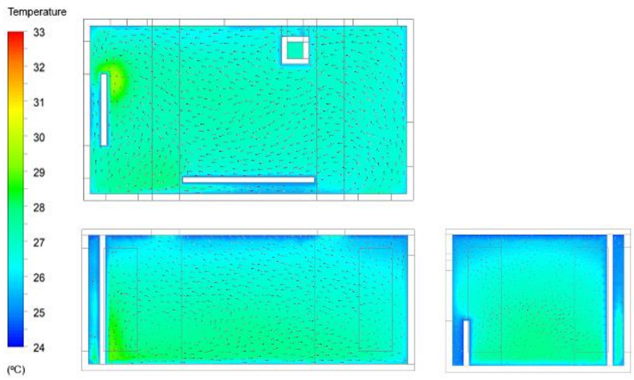


**Fig. 6.** Contour plots inside central plane of air temperature for the radiant cooling panel with dehumidifier at 8:00 am

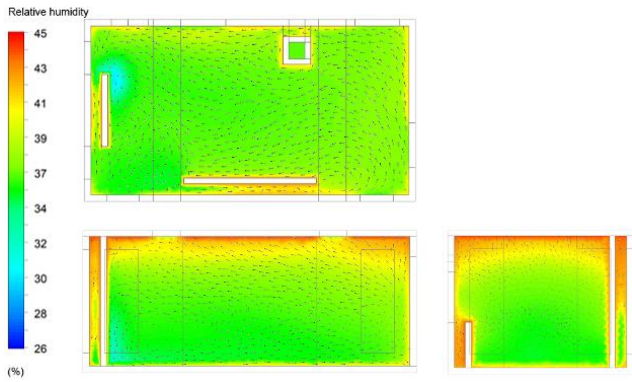


**Fig. 7.** Contour plots inside central plane of relative humidity for the radiant cooling panel with dehumidifier at 8:00 am

In the case of the radiant cooling panel and dehumidifier with ventilation fan in the laboratory, the air temperature and the relative humidity distribution inside central plane (front view, top view, and side view) at 8:00 am were shown in Figure 8 and Figure 9, respectively. The average temperature and relative humidity of the interior air were 26.1°C and 38.6%; and the average moisture content was 8.4 $g_w/kg_{da}$. Moreover, the average local air velocity increased to 0.5 m/s.

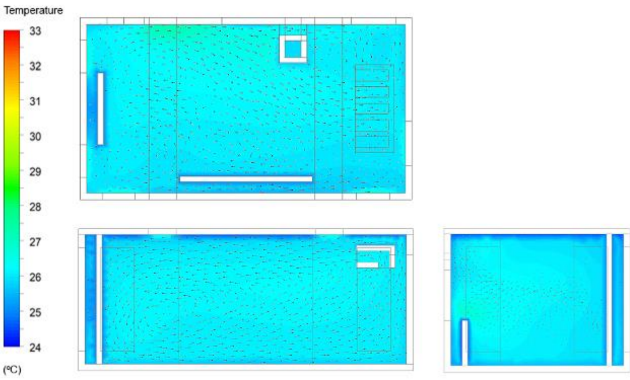


**Fig. 8.** Contour plots inside central plane of air temperature for radiant cooling panel and dehumidifier with ventilation fan at 8:00 am

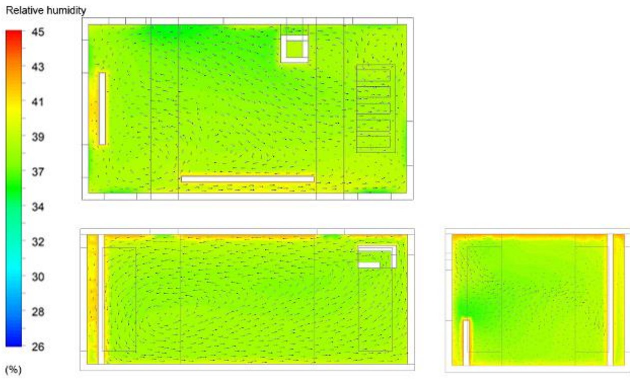


**Fig. 9.** Contour plots inside central plane of relative humidity for radiant cooling panel and dehumidifier with ventilation fan at 8:00 am

The cooling panels with cool water supplied from cooling tower and the dehumidifier with desiccant media (silica gel) can improve thermal comfort in the tropical climate, as shown in Figure 10. The experimental results indicated that the average values of predicted mean vote in case of without cooling panel, cooling panel, and cooling panel with dehumidifier were 1.5, 0.9 and 0.6, respectively. Moreover, the numerical simulation shown the average value of PMV for the interior air was 0.6 in case of the radiant cooling with dehumidifier. On the other hand, it was -0.2, when installing the ventilation fan in the experiment room and PPD was reduced to 6.2%.

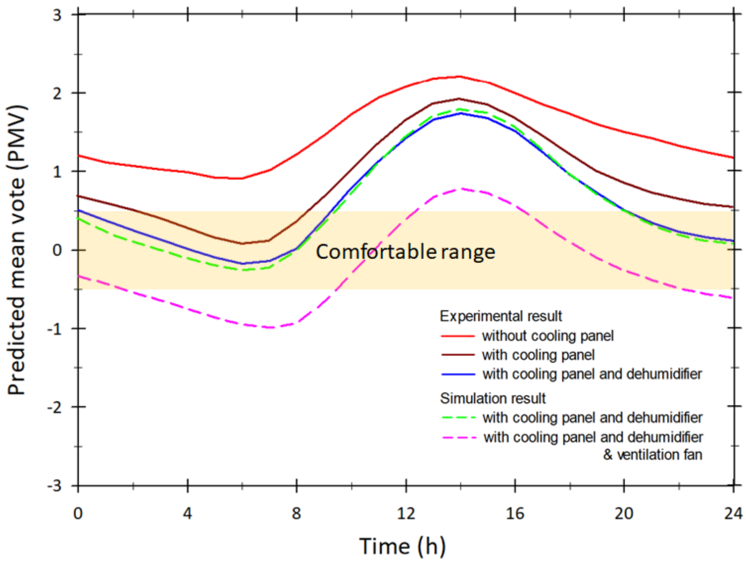


**Fig. 10.** The predicted mean vote from measured values and numerical simulation

### *3.2 The Energy Consumption*

The results of energy consumption measurements for the air conditioning system were summarized in Table 1. The 12,000 BTU/h of wall type with inverter air conditioner, Carrier 42TEVGB013-703, was used for comparison. In 2011, TISI (Thai Industrial Standard Institute) indicated that the daily electric power consumption of the Energy Efficiency Label No.5 air conditioner was about 7.09 kWh. In this study, the experimental results indicated that the electric power consumption of the laboratory with cooling panel was lower than the conventional air conditioning system about 52.68% and 20.50% for the laboratory with cooling panel and dehumidifier. Moreover, the ventilation fan installed in the radiant cooling with dehumidifier was 5.94 kWh/24 h (16.27% of energy saving), as Figure 11.

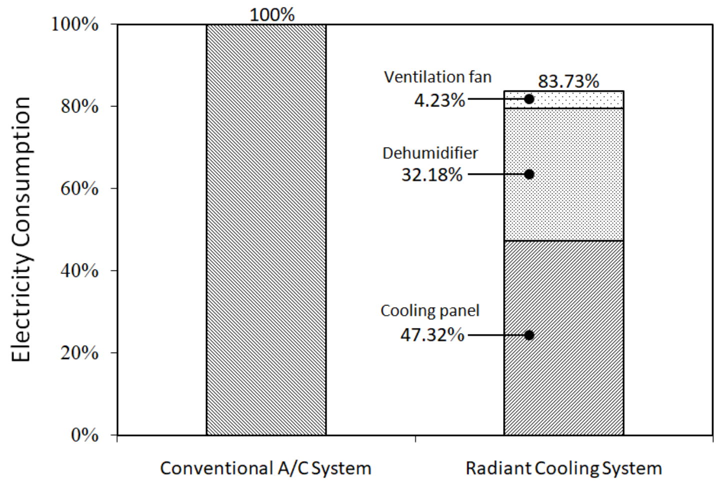


**Fig. 11.** Comparison of electrical consumption for air conditioning system

**Table 1**
Result of energy consumption measurements for the air conditioning system

| | Without cooling panel | With only cooling panel | With cooling panel and dehumidifier | With cooling panel and dehumidifier and ventilation fan |
|---|---|---|---|---|
| Exterior air temperature (°C) | 26.0 to 34.5 | 25.8 to 34.8 | 26.2 to 34.1 | 26.2 to 34.1 |
| Exterior relative humidity (%) | 61.4 to 83.4 | 60.7 to 83.4 | 62.7 to 82.5 | 62.7 to 82.5 |
| Interior air temperature (°C) | 28.6 to 32.5 | 26.6 to 31.3 | 26.6 to 31.9 | 25.9 to 30.1 |
| Interior relative humidity (%) | 66.3 to 77.7 | 69.8 to 88.3 | 37.3 to 69.3 | 37.7 to 42.7 |
| Radiant temperature (°C) | 27.7 to 31.2 | 25.2 to 30.6 | 25.8 to 34.8 | 25.2 to 29.0 |
| Cooling panel temperature (°C) | - | 24.0 to 29.6 | 24.6 to 29.2 | 24.6 to 29.2 |
| Interior humidity ratio ($g_w/kg_{da}$) | 19.9 | 19.8 | 10.3 | 9.3 |
| Average PMV (-) | 1.5 | 0.9 | 0.6 | -0.2 |
| Average PPD (%) | 50.1 | 21.6 | 13.1 | 6.2 |
| Energy consumption (kWh/24 h) | - | 3.36 | 5.64 | 5.94 |

## 4. Conclusions

Radiant cooling panel with the solid desiccant dehumidifier was investigated for tropical climate region. The improvement of the human thermal comfort was proposed and the performance was analysed through simulations and experimental studies. The experimental studies with the dehumidifier coupled to the radiant cooling panel confirmed the accuracy of simulations. The values of PMV for the cases of without cooling panel, with cooling panel, and cooling panel with dehumidifier are 1.5, 0.9 and 0.6, respectively. Moreover, the average moisture content of the interior air is reduced from 19.8 $g_w/kg_{da}$ to 10.3 $g_w/kg_{da}$. Furthermore, the air temperature, the relative humidity, and the PMV distribution in the experimental room are explained by the results of the CFD simulation contour plots. In the case of the ventilation fan installation in the radiant cooling panel, the PMV improved to -0.2 and the PPD was 6.2%. Finally, from this research work under hot and high humidity, the radiant cooling system with using cool water supplied from cooling tower can achieve the thermal sensation level. Moreover, the desiccant dehumidification has an extreme effect.

Only in the afternoon, there are the warm conditions. However, the thermal comfort assessment can improve with the dehumidifier and the inside ventilation fan in this interval time. The daily electric power consumption was 5.94 kWh which was lower than the conventional air conditioning system about 16.27%. In short, the radiant cooling panel with dehumidifier, it cannot only decrease the energy consumption in air conditioning system, but also develop occupant's thermal comfort.

**Acknowledgement**
This research was funded by a grant from EPPO (Energy Policy and Planning Office), Ministry of Energy of Thailand.

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