Evaporator Performance for Water Refrigerant Adsorption Cooling System

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ABSTRACT

Adsorption Cooling System gives an alternative to the commercial vapor compression refrigeration cycles due to their benefits of having a very environmentally friendly and promising energy-saving system. An adsorption cooling system consists of four main components which are the condenser, evaporator, expansion valve, and adsorption bed for the system to effectively function. One of the factors that affect the efficiency of the system is the performance of the evaporator itself as the system operates at sub-atmospheric pressure and the performance is mediocre when using conventional evaporators. Due to the low-pressure condition, hydrostatic pressure may affect the saturated temperature of the water refrigerant in a flooded type evaporator. Therefore, in this study, the performance of the evaporator was investigated based on the water height variation. The highest heat transfer coefficient and evaporation heat transfer rate are achieved when the water is set at the heat exchanger tube diameter level. Furthermore, 0.1 kg of silica gel adsorbent is used to obtain the maximum of 250 W/kg of Specific Cooling Power when the heat transfer fluid is set to 20 ºC.

Keywords: *Adsorption Cooling System; Low-Pressure Evaporator; SCP; Water Refrigerant*

Introduction

Almost 180 years ago, Faraday discovered adsorption refrigeration and since then several refrigerators have been developed for storing food and air conditioning [1]. In 1929, a commercial silica gel-sulfur dioxide adsorption

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cooling system was built and installed in a freight car refrigeration system to carry fish and meat all over the U.S. [2]. However, a short time after that in the 1930s, the compression refrigeration technology was accelerated by technology innovations such as CFC/HCFC/HFC refrigerants and compact mechanical compressors [3], and the adsorption cooling system was forgotten for several decades. Despite environmental issues that are widely advocated such as global warming and ozone depletion for which this refrigerant is highly responsible, most of the refrigerant-and air-conditioning industries are still using mechanical compressor-based refrigerant technology due to its high COP and high refrigerant effect today. Fortunately, scientist had focused on global warming and its effects in Kyoto Protocol 1997 [4]. Since that, more and more research are concentrated on the development of a more sustainable and environmentally friendly adsorption refrigeration technology.

Two main reasons why adsorption was chosen to replace the conventional air-conditioning system are energy shortages and climate change caused by depletion [5]. In 1992, at the Earth Summit (Rio de Janeiro), it was discussed how to reduce fossil fuels whilst in the Montreal Protocol in 1987, the protection of the ozone layer and substances that are responsible for its depreciation was discussed [6]. Adsorption refrigeration and heat pump technology are one way to solve it because they could meet the needs since it requires little electricity, and the refrigerants for this technology are the substances of water, ammonia, alcohol, and so on which are green refrigerants with zero ODP (Ozone depletion potential) and zero GWP (Greenhouse warming potential) [7]. Thermal energy which has the potential to be utilized by solar energy and waste heat are examples of energy sources that can be used to drive the adsorption heat pump technology [8, 9]. The choice of appropriate environmentally friendly refrigerant is that for an adsorption cooling system is how we can deal with the global warming and energy crisis issues.

Despite the benefits, the adsorption cooling system isn’t widely marketed due to its low Coefficient of Performance (COP) and low Specific Cooling Power (SCP) relative to traditional refrigeration technologies. Although some companies have begun to develop commercially viable adsorption chillers/heat pumps, they are still unable to replace existing vapor compression units [10]. Moreover, the available adsorption system is too heavy and bulky making it not suitable for at-home installation or portability. This is due to poor heat and mass transfer characteristics between the adsorbent and its natural refrigerant. To overcome these problems, researchers are rigorously searching for new working pairs namely activated carbon-water/ethanol/methanol, zeolite-water/ethanol, silica gel-water/methanol, and the recent one which gained a lot of attention; the Metal-Organic Framework (MOF) [11]–[14]. MOFs provide improved equilibrium properties such as high water uptake and well-located uptake step [15]. However, even though all these working pairs show promising performance based on isotherm and kinetic studies but still the working viability of all these pairs in the heat exchanger is infancy [16]. This is due to the use of an off-shelf-heat exchanger that is not optimized for adsorption cooling system applications [17, 18]. Until today, there is no conclusive evidence yet on what type of heat exchanger namely the adsorber bed, evaporator, and condenser is proper for an adsorption cooling system.

Background

Generally, adsorption cooling has two working processes, namely adsorption-refrigeration and desorption-condensation. During the process of adsorption-refrigeration, the adsorption heat releases cooling air to the heat sink and pressurizes inside, the adsorber decreases to a level lower than the evaporating pressure. The refrigerant evaporates and is absorbed by the adsorbent under the function of pressure difference and the evaporation process provides the refrigerant output. During this process, an evaporator is used to allow the refrigerant to evaporate from liquid to gaseous while running the heat adsorption process [19].

In this experiment, an adsorber, condenser, evaporator, and expansion valve are used as the main system components for it to run as a complete adsorption cooling system. Silica gel is used together with water as an adsorbent-refrigerant working pair due to its environmental-friendly characteristics, low-cost material, and ease of operation [20]. Moreover, the water-silica gel pair is also chosen due to its promising adsorption uptake rate and the good of increasing adsorption capacity [21]–[23]. Besides that, a silica gel is used over the adsorbent is due to its benefit on the regeneration temperature, which is about 85 ℃, making it ideal for solar energy and low-temperature waste heat sources [24]. Furthermore, when a multistage setup system is used, it also might go as low as 50 ℃ [25].

Water is well known as the heat transfer fluid and refrigerant due to its properties which have higher heat capacity [26]. Extensive studies of water evaporation have been studied in the literature but the scope is for atmospheric pressure conditions and data on the vacuum condition is still limited [27, 28]. Previously in our study, a low pressure flooded type evaporator performance was also evaluated but the focus was on the optimization of adsorption/desorption cycle time and the effects were measured based on evaporator cooling power and SCP [29]. This current research continues by using a function of water level inside the evaporator during the adsorption process in order to investigate the performance of the evaporator. The copper tube in the evaporator was immersed in a pool of refrigerant as shown in Figure 1. For a given liquid height, there must be a hydrostatic pressure influence that increases the saturation temperature or boiling point [30]. Water is evaporated in a temperature range between 4 °C and 20 ℃, which corresponds to pressures between 0.81 to 2.34 kPa [31]. For an evaporator operating at 2.34 kPa (20

°C), the hydrostatic pressure of water increases the saturation temperature to 25 °C at the depth bottom of the copper tube (9 mm diameter) which clearly will affect the cooling generation of the adsorption chiller. Therefore, it is necessary to find an optimum water height in this kind of evaporator design. There are three different levels of water height in the evaporator that were studied in this experiment which the tube is fully immersed, transition and the water height are lower than the tube diameter. Figure 1 illustrates the schematic~~s~~ diagram of the water level height that influences the performance of the system, where h_{water} is varied at three different water heights that represent the fully immersed zone, the transition zone, and lower than the tube diameter zone. The water height is set to 2 cm above the tube diameter for the fully immersed zone and is referred to as $h_{water120}$. For the transition zone, the water height is set at 80% of the tube diameter (D_{tube}) and is referred to as $h_{water80}$. Finally, h_{water0} represents the lower zone and the water height is set to 0 cm below the tube diameter.

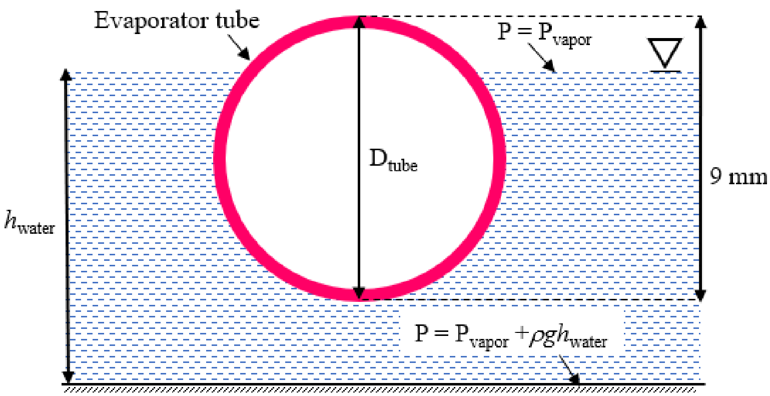

Figure 1: Schematic diagram of the immersed evaporator with a function of water level height

Experimental Study

A schematic diagram of the experimental setup, a photograph of the evaporator tube, and the actual adsorption chiller experimental setup built in our laboratory are shown in Figure 2. It consists of one adsorber bed, a condenser, and an evaporator. Four thermal fluid tanks were used to control the temperature of these components.

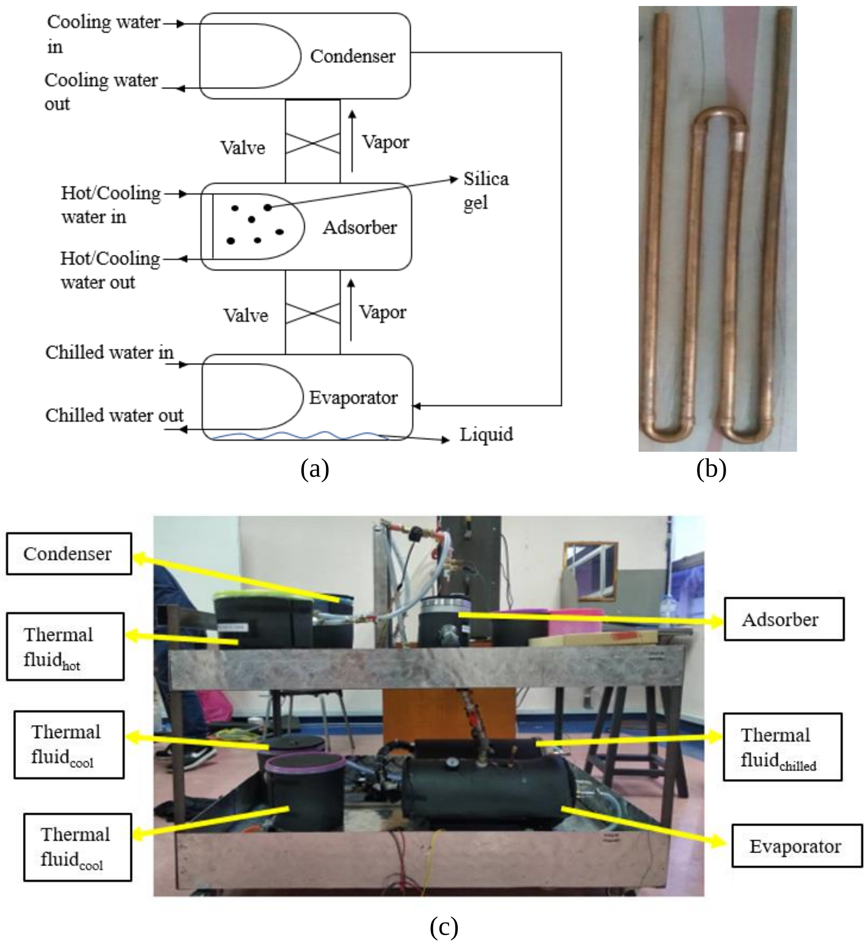

Figure 2: (a) Schematic of the experimental setup, (b) evaporator tube (c) the main components of the actual experimental setup

Further details of the test setup and heat exchanger dimensions can be found in [32]. Leak testing should be performed before the experiment to avoid equipment leaking in the experiment, which could result in inaccurate data. There were several leaking equipment detected during the leak test that involved pipe interval connections and evaporator covers. Once the leakage problem is resolved, the adsorbent, evaporator, and condenser should be emptied using a vacuum pump to remove unwanted air and water vapour trapped in adsorbents, condensers, and evaporators and all gas pipe connections.

Before running the experiments, the heating, cooling, and chilled thermal fluid to the adsorbent bed, condenser and evaporator were set as shown in Table 1. The liquid refrigerant water is evaporated in the evaporator using a chilled water supply. When pressure and temperatures inside the evaporator become constant, the control valves between the adsorber beds and the evaporator were opened and the evaporator pressure was then set by the adsorption rate of the adsorber beds. The adsorber is depressurized first using cooling water during the pre-cooling process. The evaporated water is adsorbed by the adsorbent and the heat desorption generated is removed by the cooling water. The adsorption process is ended by shutting the valve between the evaporator and the adsorber bed. The process continues with pressurization pre-heating where hot water is circulated through the adsorber. The valve will be opened to allow the desorption process to take place and the required heat input is taken from the hot water source. The refrigerant desorbed from the adsorbent will be cooled and condensed in the condenser by cooling water. Finally, the condensed refrigerant will be accumulated in the refrigerant receiver tank and a valve is used to control the refrigerant supply into the evaporator. The experiments were repeated based on the h_{water} variation at three different chilled water temperatures.

Table 1: Experimental conditions

Parameters	**Values**
Working pairs	Silica gel/water
Mass of adsorbent bed	0.1 kg
Heat source water temperature	75 ℃
Cooling water temperature	30 ℃
Evaporator inlet water temperature	10 ℃, 15 ℃, 20 ℃
Heat source flow rate	2 L/min – 3 L/min
Chilled water flow rate	3 L/min – 4 L/min
Pre-heating/Pre-cooling	1 minutes
Desorption/Adsorption time	14 minutes
Condenser water flow rate	3 L/min – 4 L/min

Data analysis

The chilled water inlet temperature and outlet temperatures, T_{in} and T_{out} were used to calculate the heat accumulated during adsorption, Q_{eva} [J] as follows:

$$Q_{eva} = \sum_{t=0}^{t=ads,end} \dot{m}c(T_{\text{in}} - T_{\text{out}})\,\Delta t \tag{1}$$

where, $\dot{m}$[kg/s] represents the mass flow rate and c[J/kg·K] is represents the specific heat capacity.

The total evaporation rate, $\dot{Q}_{eva}$ [W] is calculated by averaging the heat accumulated in Equation (1):

$$\dot{Q}_{eva} = \frac{Q_{eva}}{t_{ads}} \quad [W] \tag{2}$$

where t_{ads} [s] is the cycle time during pre-cooling and adsorption time.

The SCP [W/kg], specific cooling power is defined based on the accumulating of the cooling performance to adsorbent mass ratio during the pre-cooling and adsorption time as in this study, the experiments were carried out based on one-bed operation. The equation was calculated as follows:

$$\mathrm{SCP} = \frac{\dot{Q}_{eva}}{m_{ads}} \tag{3}$$

$m_{ads}[kg]$ represent the mass of the adsorbent which is a silica gel.

The logarithmic mean temperature difference between the chilled water circuit and the refrigerant is given by:

$$\mathrm{LMTD} = \frac{T_{in,} - T_{out}}{ln\,\frac{T_{in} - T_{sat}}{T_{out} - T_{sat}}} \tag{4}$$

with T_{sat} the refrigerant saturation temperature. The overall evaporator heat transfer conductance UA can also be expressed as:

$$\mathrm{UA} = \frac{\dot{Q}_{eva}}{LMTD} \tag{5}$$

with A is the actual outer surface area of the tube. All the equations above (1) to (5) are taken from the previous study [29].

Results and Discussion

Pressure and temperature profile

Figure 3 presented the operating temperature and pressure of the evaporator during adsorption time at a constant chilled inlet water temperature of 20 °C. During pre-heating and desorption, hot water which a temperature is at 75 ℃ is supplied at the entrance of the adsorber and the connecting valve between the adsorber and evaporator is shut closed. It can be seen from the figure that the thermocouples of chilled water temperature have the same reading at the beginning as the temperatures had reached the equilibrium state during desorption. After the desorption process had finished, the hot water pump is shut and cooling water temperature at 30 °C is supplied to the evaporator to start the pre-cooling process. The valve connecting the adsorber to the condenser is also closed. During this process, the temperature of the adsorber is reduced to allow the adsorption process. After opening the control valve between evaporator and adsorber, heat is then transferred from the chilled water to the liquid refrigerant, therefore the outlet temperature of the chilled water at the evaporator has dropped and then the evaporated refrigerant is transferred to the adsorber to be adsorbed by the adsorbent (silica gel). As shown in Figure 3(b), the evaporator pressure decreases as the evaporation process begins and remains constant until the process is completed (the valve between the evaporator and the adsorber is closed).

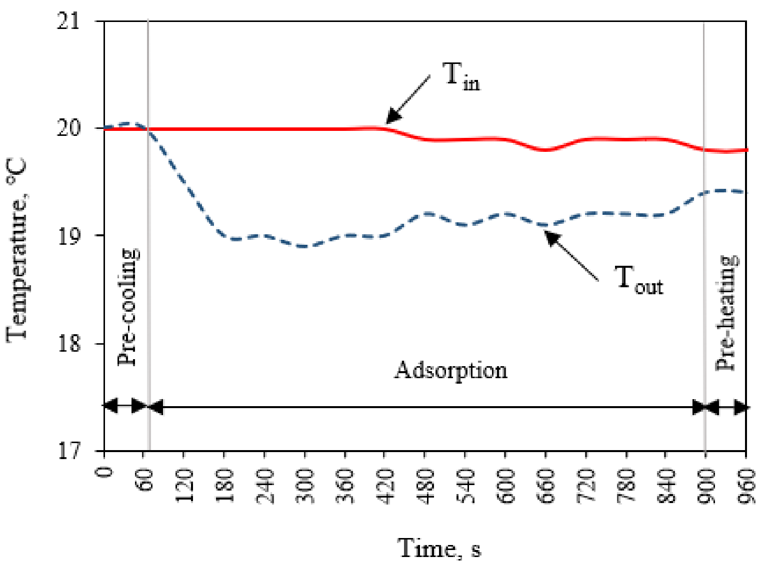

Figure 3(a): The behaviour of evaporator temperature at the chilled water inlet temperature of 20 °C vs. time

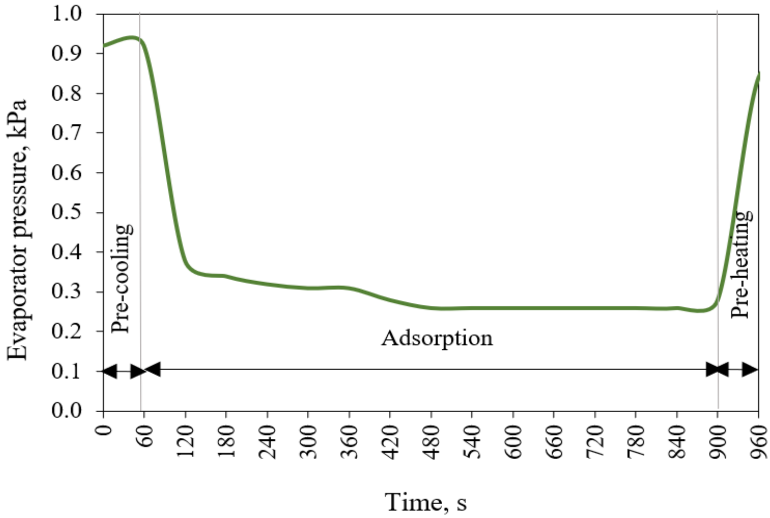

Figure 3(b): The behaviour of evaporator pressure at the chilled water inlet temperature of 20 ºC vs. time

Evaporation heat transfer rate and evaporator heat transfer coefficient

Each test was performed with chilled water temperatures of 10 °C, 15 °C, and 20 °C under the operating conditions listed in Table 1 to evaluate the performance of the evaporator tube with three different refrigerant heights. The heat transfer coefficients of the evaporator are shown in Figure 4. When the heat exchanger tube was set fully immersed, $h_{water120}$, the heat transfer coefficient is about 100 W/m^2·K at the temperature of the chilled water set to 20 ℃. The value is slightly lower than when the water refrigerant was set at $h_{water80}$ due to the pressure gradient effect between the liquid-vapor surface and the bottom of the evaporator. At this condition, the hydrostatic pressure increases the liquid pool refrigerant saturation temperature at the bottom of the evaporator, hence limiting the evaporation process as the temperature difference between the heat transfer fluid inside the tube and the water refrigerant outside the tube decreases [31]. As the water refrigerant height is reduced at the tube diameter level, the hydrostatic pressure is also reduced, hence the heat transfer coefficient increases from 100 W/m^2·K to 150 W/m^2·K. However, as the water refrigerant is furtherly reduced, the heat exchanger tube fails to maintain the heat transfer rate and the heat transfer coefficient is drop to 38 W/m^2·K. This is due to the heat transfer being limited by natural convection only and no capillary action wetting the free surface as the tube surface is plain and uncoated. The water loses contact with the tube resulting in a sharp decrease in the heat transfer process and breakdown of the evaporation process [33].

The effect of chilled water temperature as the heat transfer fluid on the evaporator performance is shown in Figure 5. As the temperature of the chilled water is increased, the total evaporation heat transfer rate is also increased resulting in the highest total evaporation rate at all water height levels. This is due to the increment of heat applied towards the water refrigerant, encouraging the process of phase change from liquid to vapor [34]. As the liquid changes to vapor, the more the temperature of the heat transfer fluid drops, the more cooling is generated. From the figure also, it was shown that the maximum evaporation heat transfer rate or cooling generation by the system is around 25 W. One of the reasons for the low-value heat transfer rate generated is due to the amount of silica gel in the adsorber bed which is only 0.1 kg, as this is the preliminarily test for the current experimental setup. By increasing the amount of the silica gel embedded in the adsorber; a higher cooling capacity can be achieved in the future study.

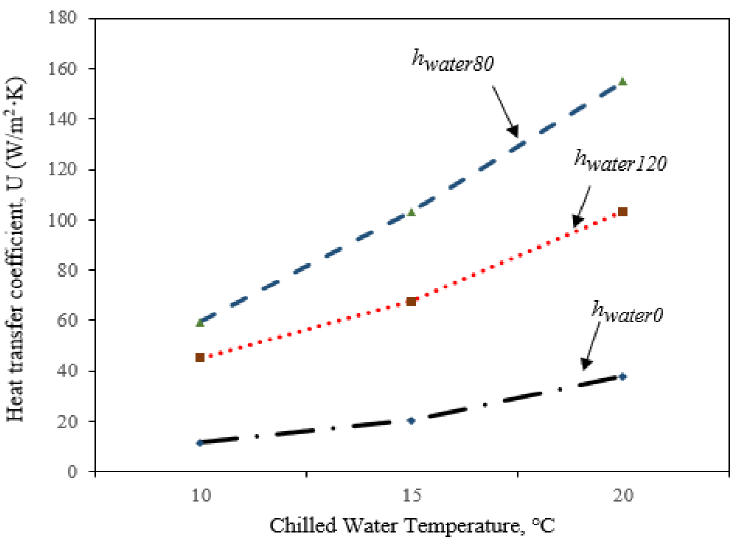

Figure 4: Coefficient of performance

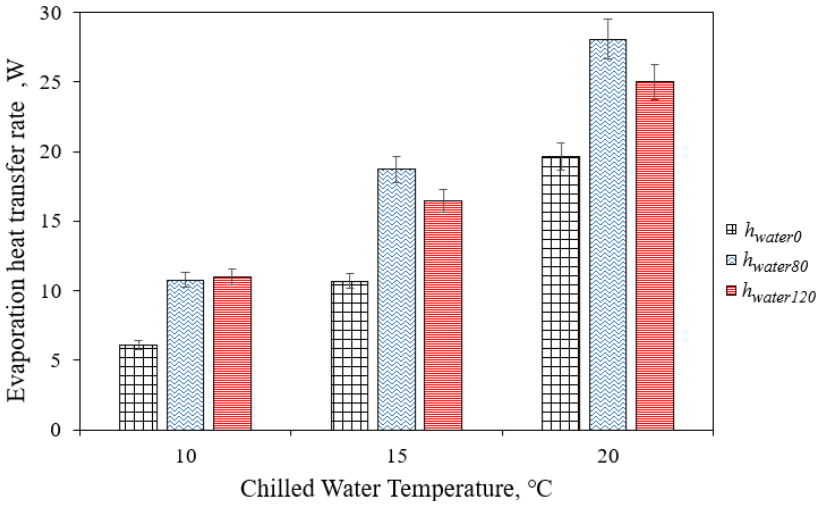

Figure 5: Total heat evaporation

The graph in Figure 6 shows the performance of the evaporator incorporated with the adsorber bed as a complete adsorption cooling set. The highest Specific Cooling Power (SCP) is obtained when the outer surface area of the heat exchanger tube is at least 80% immersed in the refrigerant, i.e., $h_{water80}$. Averagely, when the chilled water temperature is set to 15 °C and 20 °C, 10% improvement of the SCP is provided when the tube is set at $h_{water80}$ versus when the refrigerant water is set at $h_{water120}$. Refrigerant water set below the tube level should be avoided as the SCP amount will drop by 80% with the temperature of the chilled water at 15 °C and 20 °C. It can be noted that the system cooling capacity increases with the rise in chilled water intake temperature as a consequence of the increased heat input, the thermal performance of the system is also increased [35]. Another factor that needs to get attention in order to increase the SCP is the adsorbent inside the adsorber bed itself. If the adsorbent uptake is high and the amount of adsorbent in mass is higher, more vapor can be adsorbed as the adsorption which helps to encourage more water vapor to be converted from liquid to gas.

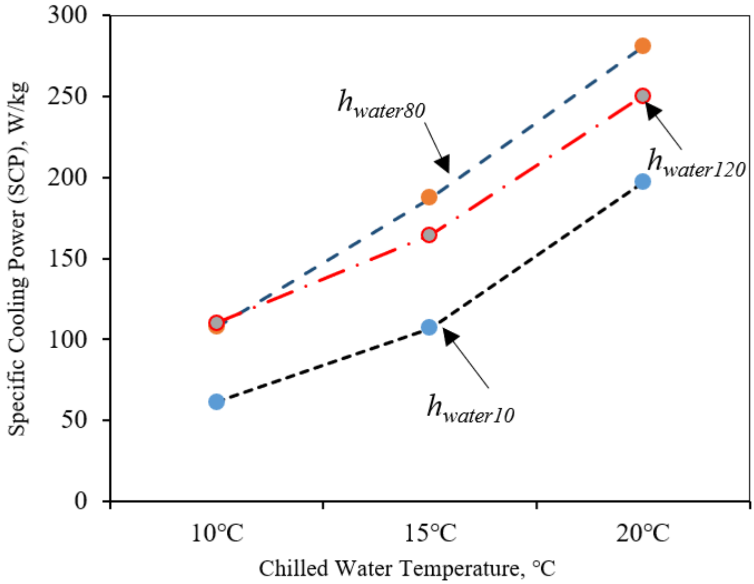

Figure 6: Specific cooling power

Conclusion

Low operating pressure with the plain tube was tested to do a preliminary study of the evaporator investigation for adsorption cooling system application. The heat exchanger that was used in the evaporator was a copper tube that was in contact with the water as the refrigerant. The effects of three different heights of water refrigerant were evaluated on the heat transfer coefficient, evaporator heat transfer rate, and also the Specific Cooling Power (SCP). In a conclusion, the optimum height of water refrigerant was identified, which is the water level must be controlled around the tube diameter height. At this water height level, maximum heat transfer coefficient, evaporator heat transfer rate, and SCP are achieved at their maximum values at all chilled water temperatures as the water is continuously provided for the evaporation process. The study also shows that a higher chilled water temperature will give a higher performance value as a higher chilled water temperature circulated in the tube will create a larger temperature difference with the water refrigerant outside the tube.

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