CONTINUOUS ADSORPTION REFRIGERATION PERFORMANCE OF ACTIVATED CARBON–R134A PAIR FOR ICE-MAKING APPLICATION USING TRANSIENT CFD SIMULATION

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Abstract

The new system and refrigerant were introduced in heat driven adsorption refrigeration system. Adsorption refrigerator's capability to be operated by relatively low temperature heat source has drawn considerable attention. This system can be driven by utilizing waste heat and solar energy. Positive gauge operating pressure has been pursing R-134a as the most suitable refrigerant due to its saturated temperature on high pressure and other considerations including health factor, safety, and environment. The continuous system was designed to obtain higher cooling capacity. The optimization was conducted on temperature for each process undergoing in the reactor to approximate the highest possible COP (Coefficient of Performance). The cooling capacity of the system was estimated by transient simulation on CFD software. The cooling capacity acquired by employing CFD transient simulation is 18.36 W, whereas the highest possible COP which could be attained is 0.1047 for ice-making application.

Keywords: Adsorption refrigeration system, CFD simulation, Continuous, Cooling capacity, COP R-134a, Positive gauge pressure

Introduction

Until 2010, electrification ratio in Indonesia only reached 68% and it is planned to be 91% on 2019 [1]. It means there are still lot of regions in Indonesia which don't have the electricity, especially in the hard access region such as seashore and hill. This phenomenon caused the decomposing of the food source such as: fishes, fruits, and vegetables because of the inexistence of the cold storage which could work without the electricity. For the last two decades, thermally compressed adsorption refrigeration system had become a very interesting research topic due to its advantageous. The advantageous of this system are (i) no electricity required, (ii) no moving part, (iii) no lubricant required, and (iv) easier to be maintained. Examples of adsorbent-refrigerant pairs are silica gel-water [2], zeolite-water [3], activated carbon (AC)-ethanol [4], and AC-methanol [5]. All of the examples work on sub-atmospheric pressure. The sub-atmospheric pressure condition is very difficult to be maintained from the leakage, also when there is a leakage it would be very difficult to detect it on the installed system. This phenomenon will reduce the reliability and could cause a catastrophic failure. Adsorption refrigeration system utilize heat directly to operate the system. Heat can be obtained freely from solar or waste heat because this system need only relatively low temperature.

Single adsorption refrigeration system has disadvantage in the cooling capacity. This happens because the heating and cooling will take a long time. If single system is used the cooling effect will occur after both cooling and heating process. It will decrease the cooling capacity of the system because of the longer waiting time will cause larger amount of heat transferred to the evaporator. Continuous system is one of the most effective way to prevent this from happening. In the continuous system, the waiting time would only be the heating time, because the heating and cooling process are running simultaneously.

R134a is one of the most used refrigerant in the world especially Indonesia. On the atmospheric pressure its saturation temperature is very low, as low as -26^{o}C. For ice-making application the pressure would be more than atmospheric pressure. Besides its pressure, R134a has zero ODP [6], small toxicity, and small flammability characteristic [7] make this refrigerant would be sustained. From those perspectives, this research presents the performance investigation of AC-R134a continuous adsorption refrigeration system.

Working Principle of Continuous System

The schematic diagram is shown in Figure 1. Two reactors are used and featured by hot and cold water storage tanks. First of all, hot water is flowed thru HO1 to reactor 1. After the pressure at reactor 1 has reached designed condenser pressure, the valve GV RC1 is fully opened and GV C2 is little opened to prevent the sudden pressure change in condenser. The refrigerant will flow from condenser to expansion valve causing the pressure reduction. After the pressure is equal to the evaporator pressure, the refrigerant will flow to the evaporator. Since the refrigerant temperature is low, it gains heat from surrounding and evaporates to give the cooling effect. The refrigerant vapor then directly flows to the reactor 2 and it is adsorbed by activated carbon in reactor 2. Cold water is then flowed thru CO1 to the reactor 1 and hot water is flowed thru HO2 to the reactor 2. After the condenser pressure is reached in reactor 2, refrigerant is then flowed to the condenser and the flowing sequence is exactly as before. These processes are running continuously until the desired water temperature has been obtained.

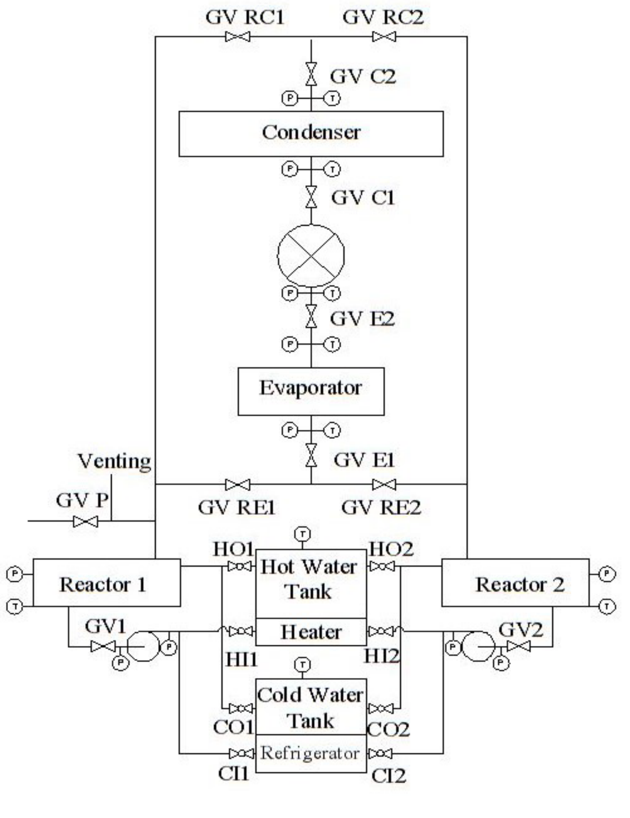

Figure 1. Schematic diagram of the total system.

Mathematical Modeling

There are several mathematical models used in this study. Firstly, isotherm adsorption which is the process occurs in the reactor. The refrigerant will be adsorbed and released by the AC in the reactor. The adsorption and desorption process is utilized to produce a flow in the system. Secondly, isosteric process which also occurs in the reactor. This process would replace the function of compressor to increase the pressure of the refrigerant. The reactor is heated to increase the pressure of refrigerant. The heating process that increase the temperature of the reactor and refrigerant can be estimated using finite different method. Meanwhile in the evaporator and condenser which are treated as heat exchanger, heat exchanger calculation can be employed.

Convection heat transfer coefficient is required to calculate temperature transient by finite difference method and heat exchange of the process. Nusselt number estimation can be empowered to determine convection heat transfer coefficient. Finally, the performance of the system can be assessed by using coefficient of performance (COP). COP is defined as the heat absorbed by evaporator compared to heat required in isosteric process.

Isotherm Adsorption

Dubinin-Astakhov (D-A) model, which is expressed by Equation (1), is used to estimate the equilibrium uptake of AC-R134a on the mass basis.

$$\frac{C}{C_0} = \exp\left(-D\left(T.\ln\frac{p_s}{p}\right)^n\right) \qquad (1)$$

The numerical values of c_o, n and $D$are evaluated experimentally by Saha et al. [8], which are found to be 0.926 kg/kg, 1.8, and 3 × 10^{-6} J/mole respectively.

Isosteric Process

The pressure will increase when the reactor is heated. The increasing of the temperature follows Equation (2).

$$\ln\frac{p_1}{p_2} = \frac{\Delta H_{ads}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad (2)$$

ΔH_{ads} can be found by using Equation (3), also can be estimated by using graph which is defined by Saha et al. [9].

$$\Delta H_{ads} = h_{fg} + E\left[\left\{\ln\left(\frac{x_0}{x^*}\right)\right\}^{\frac{1}{n}} + a\left(\frac{T}{T_c}\right)^b\right] \qquad (3)$$

The numerical values of E, a and $b$are evaluated by El-Sharkawy et al. [10], which are found to be 82.9 kJ/kg, 1.81, and 6.21, respectively.

Finite Difference Method

The explicit finite difference method for transient conduction on a cylinder can be expressed by Equation (4). When convection exist, Equation (5) is used.

$$T_{r,n}^{p+1} = Fo\left[2T_{r-1,n}^{p} + T_{r,n-1}^{p} + T_{r,n+1}^{p} + 2BiT_\infty\right] + [1 - 4Fo - 2BiFo]T_{r,n}^{p} \qquad (4)$$

$$T_{r,n}^{p+1} = Fo\left[T_{r-1,n}^{p} + T_{r+1,n}^{p} + T_{r,n-1}^{p} + T_{r,n+1}^{p} + \frac{\Delta r}{2r}\left(T_{r,n+1}^{p} - T_{r,n-1}^{p}\right)\right] + [1 - 4Fo]T_{r,n}^{p} \qquad (5)$$

Heat Exchanger Calculation

Calculation of heat exchanger is based on logarithmic mean temperature difference method. For designing the heat exchanger, Equation (6) and Equation (7) are used.

$$\frac{d}{dt}(\delta m)c\Delta T = F \cdot U \cdot A \cdot \Delta T_{lm} \quad (6)$$

$$\frac{1}{U} = \frac{1}{\bar{h}_i}\left(\frac{d}{d_i}\right) + \frac{\ln(\frac{d_o}{d_i})}{2k} d_o + \frac{1}{\bar{h}_o} \quad (7)$$

Condenser and evaporator have two regions, phase change region and temperature change region. Both of them have the same calculation method but different convection heat transfer coefficient calculation. The left side on Equation (6) represents heat transfer from the heat exchanger, and the right side represents the ability of the apparatus to transfer heat.

Convection Heat Transfer Coefficient

Convection heat transfer coefficient is different for different mode. Equation (8) is used for convection on external flow on cylinder. Equation (9) is used for convection on internal flow on cylinder. Equation (10) is used for condensation process. Equation (11) is used for turbulent concentric tube convection [11].

$$Nu_D = CRe^m Pr^{\frac{1}{3}} \quad (8)$$

$$Nu_D = 4.36 \quad (9)$$

$$Nu_D = 0.555\left(\frac{g\rho_l(\rho_l - \rho_v)d^3 h'_{fg}}{\mu_l(T_{sat} - T_s)k_l}\right)^{\frac{1}{4}} \quad (10)$$

$$Nu_D = C_o Re^P Pr^{1/3}\left(\frac{\mu}{\mu_w}\right) \quad (11)$$

$$P = 1.0138e^{-0.067a} \quad (12)$$

$$C_o = \frac{0.003a^{1.86}}{0.063a^3 - 0.674a^2 + 2.225a - 1.117} \quad (13)$$

$$a = \frac{d_o}{d_i} \quad (14)$$

Performance Calculation

There are two parameters for defining performance of the system. First cooling capacity (q) in Equation (15), and second is Coefficient of Performance (COP) in Equation (16).

$$q = \frac{d}{dt}(\delta m)\left[h_g(p_{eva}) - h_l(p_{cond})\right] = \frac{\delta m}{\Delta t}\bigg|_{des}\left[h_g(p_{eva}) - h_l(p_{cond})\right] \quad (15)$$

$$COP = \frac{Q_{eva}}{Q_{gen}} \quad (16)$$

$$Q_{eva} = \delta m\left[h_g(p_{eva}) - h_l(p_{cond})\right] \quad (17)$$

$$Q_{gen} = Q_{1-2} + Q_{2-3} \quad (18)$$

$$Q_{1-2} = \left(mc_p\big|_{AC} + mc_p\big|_r\right)(T_2 - T_1) \quad (19)$$

$$Q_{2-3} = \left(mc_p\big|_{AC} + \overline{m}c_p\big|_r\right)(T_3 - T_2) + \delta m\, \Delta H_{ads} \quad (20)$$

Computational Fluid Dynamic Modeling

Computational Fluid Dynamics (CFD) was employed to estimate the time for heating the reactor. This time would be used to calculate the heat required by the system to operate. The CFD modeling then is modeled as a transient conduction. The properties empowered in this CFD modeling are listed in Table 1. The reactor is modeled as concentric tubes. The outer tube is defined as steel, whereas the inner tube is defined as AC. The simulation is considered finish if the inner face has reached the desired temperature. The time needed to reach the aforementioned temperature is recorded.

Table 1. Properties Used in CFD Modeling

Property	Value	Unit	Property	Value	Unit
k_{AC}	0.36	W/m·K	$c_{p,ST}$	490	J/kg·K
ρ_{AC}	2000	kg/m^3	α_{ST}	1.58×10^{-05}	m^2/s
$c_{p,AC}$	930	J/kg·K	h	1000	W/m^2·K
α_{AC}	1.94×10^{-07}	m^2/s	r_{ST}	6	mm
k_{AC}	60.5	W/m·K	r_{AC}	12	mm
ρ_{ST}	7800	kg/m^3	L	110	mm

Result and Discussion

Iteration was done for different condition of temperature to get the highest possible COP. As shown in Figure 2 iteration was done for different condenser temperature, while evaporator temperature is held constant to be -7^{o}C and desorption temperature also held constant to be 85^{o}C. Figure 2 confirms that COP will decrease linearly if the temperature increase. This phenomenon caused by the releasing temperature in the reactor. High the condenser temperature is also pressure inside. The temperature needed in the isosteric heating will be also higher and it will decrease the mass flow from the reactor.

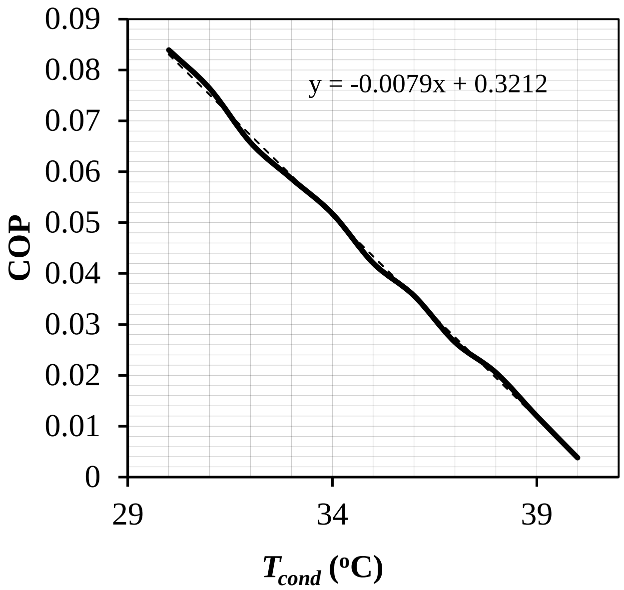

Figure 2. Graph of iteration for condenser temperature

As shown in Figure 3, iteration was done for different desorption temperature, while evaporator temperature is held constant to be -7°C and condenser temperature is also held constant to be 31°C. From Figure 3, it can be known that COP is increasing and follows a quadratic function if the temperature is increasing. It happens because when the desorption temperature is higher, so the amount of refrigerant released from the reactor is larger, and the capacity will be higher. The maximum COP is 0.206 when the temperature is 118°C.

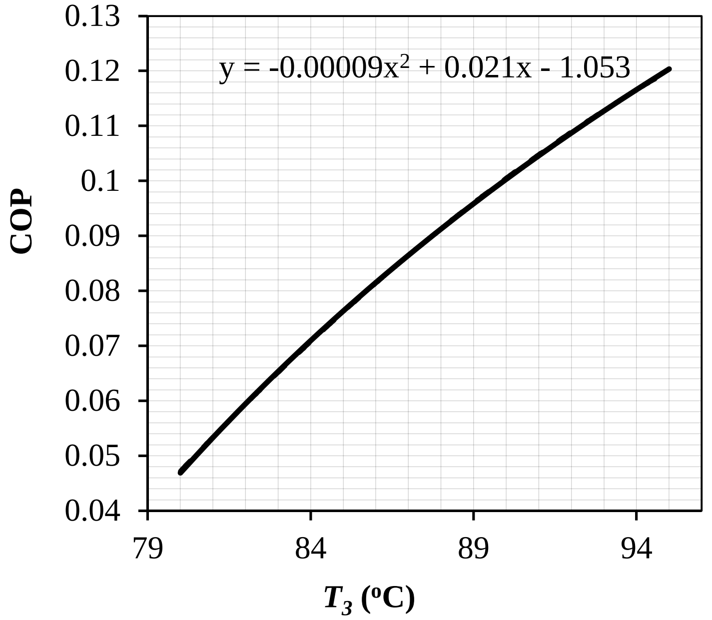

Figure 3. Graph of iteration for desorption temperature

Figure 4 shows the iteration for different evaporator temperature, while desorption and condenser temperature are held constant to be 91°C and 31°C, respectively. From Figure 4. it appears that COP is increasing and follows a quadratic function if the temperature is increasing. This is confirmed by enthalpy characteristic of the refrigerant.

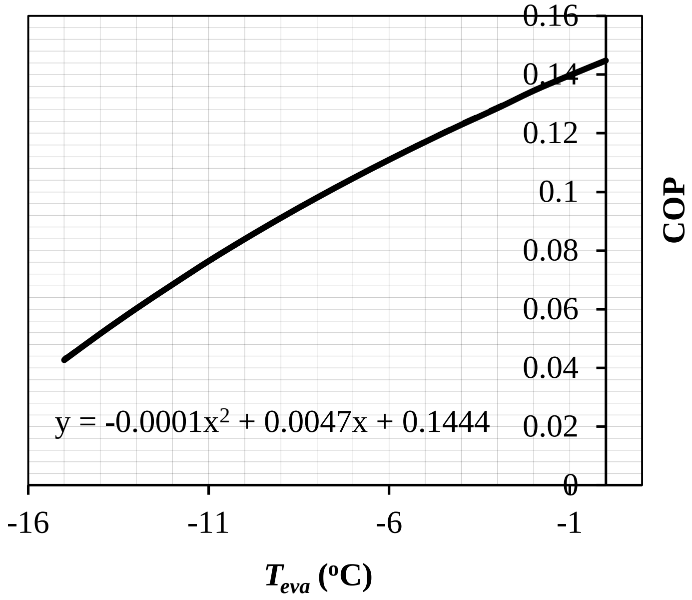

Figure 4. Graph of iteration for evaporator temperature

By deriving the equation as resulted from regression which is shown in Figure 4, the maximum COP is 0.199 when the temperature is 23.5°C. Based on the iteration the conditions taken are: (i) T condenser = 31°C, (ii) T desorption = 91°C, (iii) T evaporator = -7°C for ice-making application.

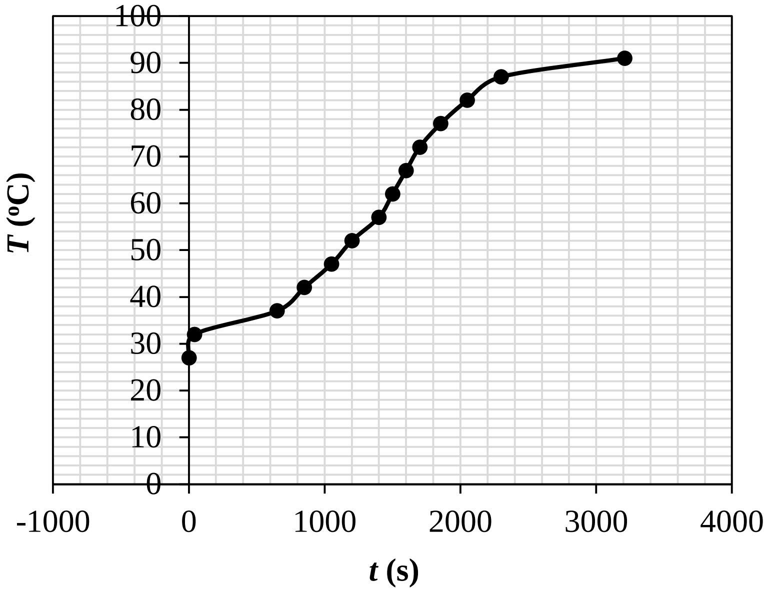

Figure 5. Graph of reactor heating temperature vs time on CFD simulation.

Transient CFD simulation was done to estimate the time for heating the reactor. Time step taken on the CFD simulation is 0.1 s. Figure 5 shows the timing for heating the reactor from ambient temperature to 77°C to be 1854 s and the timing for heating the reactor from ambient temperature to 91°C is 3210 s. Based on the CFD simulation can be confirmed the desorption timing to be 1356 s. By using data presented in Table 2, performance of the system can be calculated and the result is presented in Table 3. The heating process of reactor and refrigerant before starting vapor desorption process from the AC is near two times of the process of desorption process.

Table 2. Data for Calculating Performance of the System

Properties	Value	Properties	Value
T_1 [°C]	30	$c_{p,AC}$ [kJ/kg·K]	0.93
T_{cond} [°C]	31	$c_{p,ref}$ [kJ/kg·K]	0.88
p_{cond} [bar]	7.9	T_3 [°C]	91
T_{eva} [°C]	-7	D [J/mol]	3×10^{-6}
p_{eva} [bar]	2.25	n	1.8
c_o	0.926	m_{AC} [kg]	2

The COP of the system varying from 0.05 until 0.21, depending on the conditions, are taken. Baiju [12] calculated the mean COP is 0.166 for day time operation and 0.248 for night time operation. By using this reference, it can be concluded that the result is comparable, it depends on the conditions taken. Because application has been defined for fishing boat ice-making application, so based on the possible condition and by using CFD simulation can be concluded that the highest possible COP is 0.1047 with the cooling capacity of 18.36 W.

Table 3. Performance of the System

Properties	Q_{1-2} [kJ]	Q_{2-3} [kJ]	Q_{gen}[kJ]	Q_{eva}[kJ]	q [W]	COP
Value	155.0299	82.8796	237.9096	24.8997	18.36	0.1047

Conclusions

Based on a cycle simulation model, the performance of continuous adsorption refrigeration cycles with AC-R134a pair were evaluated. CFD and finite difference methods were extensively involved in numerical calculation. Most thermodynamic characteristics were clarified from the simulation results. The system can operate by using waste heat from engine and solar system. The evaporator temperature can reach as low as -7°C with cooling capacity of 18.36 W and COP of 0.1047 for fishing boat ice-making application.

Nomenclature

Bi	Biot number		Nu	Nusselt number	
c_p	specific heat	kJ/kg×K	p	pressure	bar
c_o	maximum absorptivity	kg/kg	Pr	Prandtl number	
D	characteristic adsorption	J/mol	Q	heat	kJ
d	diameter	m	q	cooling capacity	W
F	correction factor		R	gas constant	J/kg×K
Fo	Fourier number		r	radius of reactor	m
g	gravity acceleration	m/s2	Re	*Reynolds number*	
h	specific enthalpy	*kJ/kg*	s	specific entropy	kJ/kg·K
h'	corrected enthalpy	kJ/kg	T	temperature	°C
$\bar{h}$	heat transfer coefficient	W/m2×K	t	time	s
k	thermal conductivity	W/m·K	U	overall coefficient	W/m2×K
L	length of reactor	m	α	thermal diffusivity	m^2/s
m	mass	kg	ρ	density	kg/m^3
n	constant		μ	viscosity	Pa/s
			Δ	difference	

Subscript

1	initial state before heating process	i	inner
2	state when pressure of reactor the same as condenser	l	liquid
3	state when heating process finished	gen	generator
AC	activated carbon	l	liquid

ads	adsorption	*lm*	logarithmic mean
cond	condenser	*o*	outer
D	basis of diameter	*ref*	refrigerant
des	desorption	*sat*	saturation
eva	evaporator	*ST*	steel
fg	phase change	*v*	vapor
g	gas	*w*	wall
		∞	surrounding

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