Temperatures limitation of adsorptive solar powered ice maker using AC35-methanol pair

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Abstract. A numerical evaluation of temperatures limits of solar adsorption refrigeration machine cycle using the AC35-methanol pair is presented in this paper. The cold production was better for lower adsorption temperatures and higher temperatures of evaporating and generating. For each 1 kg of adsorbent, 1 kg of ice can be produced for temperatures of generating from 40°C to 100°C according to solar irradiance and ambient temperature. The considered lower adsorption temperature is 10°C, which can allow to produce 9 kg of ice for higher temperatures of generating up to 130°C, this needs 680 kJ of solar irradiance for surface area of 1 m² of solar collector. The considered higher evaporating temperature is 10°C, which can allow to produce 3.5 kg of ice for higher temperatures of generating up to 144°C, this needs 622 kJ of solar irradiance for surface area of 1 m² of solar collector.

1. Introduction
Energy needs have become more important in the world. The isolated regions require at least the storage of medical and food products. The solar energy can be an alternative to cold production by installing solar adsorption chillers. The efficiency of these machines is still further than the conventional refrigeration machines. The refrigerant circulation in adsorption refrigeration machines requires a valve for closing and opening the passage of the fluid flow, depending on the process of thermodynamic cycle of the machine (Fig.1). The transition from one process to another is dependent on the temperature and pressure reached by the adsorbent-adsorbate pair and this pressure variation is due to variation in temperature, which is due to the heating or cooling isosteric of the pair. The two processes, desorption and adsorption, of the refrigerant are at constant pressure with a temperature variation. Then, the knowledge of the state of this physical parameter (temperature) during the thermodynamic cycle of the adsorption refrigeration machine allows to determine the cycle process in progress, which gives the suitable moment to open or close the valve of refrigerant, but the choice of temperature is also dependent on the performance of the machine. Critoph [1] proved analytically that the COP (cycle performance coefficient) is based on the four temperatures of the thermodynamic cycle of the machine (see fig.1: Tₐ, T₁, T₂ and T₃). Douss et al. [2] studied experimentally the variation of COP for AC35-methanol pair according to evaporating temperature Tₑ and adsorption temperature Tₑ. Critoph [3] studied experimentally the variation of COP for 208C-R32 and 208C-ammonia pairs according to generating temperature Tₑ. Teng et al. [4] gave analytical relations for temperature at start of generation Tₛ¹ and temperature at start of adsorption Tₛ² as a function of the evaporating temperature Tₑ, the adsorption temperature Tₐ, the generating temperature Tₑ and the adsorbed mass rate. Liu et al. [5] studied numerically the variation of COP for Zeolite 13X -water pair according to the condensing temperature Tₑ, the evaporating temperature Tₑ, the generating
temperature \( T_g \) and the adsorption temperature \( T_a \). Cherrad and Benchabane [6] have proposed a numerical model to control the evaporating temperature of refrigerant for solar adsorption cooling machine. We see clearly through these literature assignments that the performance and the operation of the adsorption refrigeration machine depend on the temperatures of the thermodynamic cycle. Recently, Cherrad et al. [7] have developed a transient numerical model for determining the operating temperatures and its corresponding times of the solar adsorption refrigeration cycle, where the solar irradiance received and the amount of produced cold have been considered in the study, but the evaluation of limits of temperatures according to theses parameters has not been addressed by the authors. In this work we will study numerically the evaluation of the temperatures limits of the thermodynamic cycle of adsorption refrigeration machine using the AC35-methanol pair according to the solar irradiance, ambient temperature and the cold production amount.

2. Description of intermittent cycle of solar adsorption refrigeration machine

The basic thermodynamic cycle of the adsorption refrigeration consists of four processes which are shown in fig.1. In the first process A-B, the adsorbent is heated by solar energy up to the condensing pressure \( P_c \) (refrigerant saturation pressure at \( T_c \)) required to activate the desorption of refrigerant (state B). During the process B-C, the addition of the heat supplied from the solar energy allows the desorbing of the refrigerant vapor and its condensing in an air condenser. In state C, when the adsorbent reaches its maximum temperature, solar radiation begins to be decreased. The collector is separated from the condenser by closing the valve and its temperature decreases. The cooling of adsorbent induces the pressure drop (process C-D). Meanwhile the liquid refrigerant is transferred to the evaporator. When the pressure reaches the value of evaporating pressure \( P_e \) (refrigerant saturation pressure at \( T_e \)) at the evaporating temperature \( T_e \), the collector is connected to the evaporator at state D (the valve is opened). The adsorbent continues to decrease in its temperature and adsorbs the liquid refrigerant, which evaporates and extracts the heat from the evaporator (process D-A) generating the cooling process within the cold chamber. The described cycle is intermittent because the evaporation-cooling process is done only during the night. Critoph [1] defined the various temperatures of the thermodynamic cycle of the adsorption refrigeration in a Clapeyron diagram as follows: \( T_{s2} \): temperature at start of adsorption [\( \text{°C} \) or K], \( T_a \): temperature at end of adsorption [\( \text{°C} \) or K], \( T_e \): evaporating temperature [\( \text{°C} \) or K], \( T_c \): condensing temperature [\( \text{°C} \) or K], \( T_{s1} \): temperature at start of generation [\( \text{°C} \) or K] and \( T_g \): temperature at end of generation [\( \text{°C} \) or K]. We define \( m_{\text{max}} \) and \( m_{\text{min}} \), respectively, by the maximal adsorbed mass and the minimal adsorbed mass of the adsorbate. The adsorbed amount of mass is calculated by Dubinin-Astakov equation presented below. In the Clapeyron diagram the logarithm of the pressure is a function of the temperature inverse:

\[
\ln(P) = A \left( \frac{1}{T} \right) + B
\]  

(1)

A and B are coefficients which will be calculated by interpolation of experimental data given by Bejan and Kraus [8]. Calculating of the pressures of Clapeyron diagram is necessary for the numerical simulation of thermodynamic cycle.

Figure 1. Ideal thermodynamic cycle of the adsorption refrigeration in a Clapeyron diagram.
3. Dubinin-Astakhov equation (D-A)

Dubinin and Astakov proposed a state equation for the adsorbed mass as a function of the adsorbent pressure and temperature:

\[ m(T, P) = W_0 \rho \exp \left\{ -D \ln \left( \frac{P(T)}{P_c} \right)^n \right\} \]  

(2)

where: \( m \): adsorbed mass [kg of adsorbate/kg of adsorbent], \( W_0 \): maximum adsorbed volume [m3 of adsorbate/kg of adsorbent], \( \rho \): density of the adsorbate in the liquid state [kg/m3], \( D \): coefficient characterizing the adsorbent-adsorbate pair, \( T \): temperature of the adsorbent-adsorbate pair [K], \( P_c \): saturation pressure of the adsorbate [Pa], \( P \): equilibrium pressure of adsorbent-adsorbate pair [Pa] and \( n \): parameter of adjustment of the D-A equation.

The values of \( W_0 \), \( n \) and \( D \) are given by Critoph [1] depending on the kind of the adsorbent and the adsorbate. According to the Clapeyron diagram (fig. 1), we can report that [9]:

\[ m(T_a, P_e) = m(T_a, P_e) = m_{\text{max}} \]  

(3)

\[ m(T_c, P_e) = m(T_c, P_e) = m_{\text{min}} \]  

(4)

where:

\[ P_e = P_e(T_e) \]  

(5)

\[ P_c = P_c(T_c) \]  

(6)

4. Performance of solar adsorption refrigeration cycle

The formulation for calculating the performance coefficient of an adsorption refrigeration machine is given as follows:

\[ \text{COP} = \frac{Q_f}{Q_{\text{AC}}} \]  

(7)

\( Q_{\text{AC}} \) is the useful daily global irradiance received by the collector [10] from the state A to the state C of the thermodynamic cycle shown in fig. 1. This heat can be calculated by the following formula:

\[ Q_{\text{AC}} = \eta \cdot S \cdot G \]  

(8)

where, \( \eta \) is the collector efficiency, \( G \) is the daily global solar irradiance [J/m²] and \( S \) is the collector area [m²]. The extracted heat \( Q_f \) by the evaporator for cold production is estimated as follows [11]:

\[ Q_f = m_d(m_{\text{max}} - m_{\text{min}}) \int_{T_e}^{T_c} L(T_e) - \int_{T_e}^{T_c} C_p(T) dT \]  

(9)

where: \( m_d \): adsorbed mass [kg], \( L \): Latent heat of the adsorbate [J/kg] and \( C_p \): Heat capacity of the adsorbate in liquid state [J/(kg.K)].

Lemmini et al. [10] considered that the evaporating temperature \( T_e \) equal to the evaporator temperature \( T_{\text{evp}} \) and gave the amount of cold production \( Q_f \) as a function of \( T_{\text{evp}} \). For making easy the comparison with the equation (9), we have simplified the equation given by Lemmini et al. [10] in the case when the desorbed mass is equal to the adsorbed mass:

\[ Q_f = m_d(m_{\text{max}} - m_{\text{min}}) \int_{T_{\text{evp}}}^{T_c} L(T_e) - m_d(m_{\text{max}} - m_{\text{min}}) \int_{T_{\text{evp}}}^{T_c} C_p(T) dT \]  

(10)

where, \( T_{\text{evp}} \) is the evaporator temperature in K and \( C_p \) is taken as a constant.

The evaporating temperature \( T_e \) cannot be considered equal to the evaporator temperature \( T_{\text{evp}} \). Douss et al. [2] noted that important differences between the evaporator temperature \( T_{\text{evp}} \) and the evaporating temperature \( T_e \) exist when the evaporating temperature is less than - 20°C, this could be avoided if the evaporator was improved. To predict the values of the evaporation temperature \( T_e \), we apply the iterative numerical process of the computation algorithm shown in fig. 3. For reasons of numerical programming, the equation (9) can be written, by applying the trapeze rule, as follows:

\[ Q_f = m_d(m_{\text{max}} - m_{\text{min}}) \left[ L(T_e) - \frac{T_c - T_e}{t_{\text{max}}} \left( C_p(T_c) + C_p(T_e) \right) \right] + \frac{i = 1}{i = \text{max} - 1} \left( C_p(T_e + i \Delta T_f) \right) \]  

(11)
\[ \Delta T_f = \frac{T_c - T_e}{I_{max}} \]  

where \( I_{max} \) is the division number of the area, under the integral curve, to elementary areas, which are necessary for the application of the trapeze rule. \( Q_f \) can be written as a function of the amount of produced ice as follows:

\[ Q_f = m_{ice} \left[ C_{pw}(T_{amb} - T_{ice}) + L_w \right] + m_{evp} \cdot C_{pevp}(T_{amb} - T_{evp}) \]

\[ + \left( V_{cc} - \frac{m_{ice}}{\rho_w} \right) \cdot \rho_{air} \cdot C_{pair}(T_{amb} - T_{cc}) \]  

where, \( m_{ice} \) is the mass of produced ice [kg], \( C_{pw} \) is the water heat capacity [J/(kg.K)], \( C_{pair} \) is the air heat capacity [J/(kg.K)], \( T_{amb} \) is the ambient temperature [K], \( T_{ice} \) is the ice temperature [K], \( L_w \) is latent heat of ice fusion at Tice [J/kg], \( m_{evp} \) is the evaporator mass [kg], \( C_{pevp} \) is the evaporator heat capacity [J/(kg.K)], \( V_{cc} \) is the volume of cold chamber [m³], \( \rho_w \) is the density of water [kg/m³] and \( \rho_{air} \) is the density of air [kg/m³]. The first, the second and the third term of the equation (13) mean respectively the extracted heat from the water, the extracted heat from the evaporator and the extracted heat from the air of the cold chamber. The term \( (V_{cc} - m_{ice}/\rho_w) \cdot \rho_{air} \cdot C_{pair} \) can be written as a function of the amount of produced ice. The term \( V_{cc} \) means the air mass in the cold chamber. The ice temperature at atmospheric pressure is equal to zero (Tice = 0°C) and the ambient temperature \( T_{amb} \) may be considered equal to the adsorption temperature \( T_a \) \((T_{amb} = T_a)\). After the thermal equilibrium, the three elements, the ice, the evaporator and the air in the cold chamber will be at the same temperature \( T_{eq} \), called thermal equilibrium temperature, which can replace the temperatures \( T_{ice}, T_{evp} \) and \( T_{cc} \). Keeping the latent heat of ice fusion in the equation (13) if \( T_{eq} \) lower or equal to \( T_{ice} \), Lemmini et al. [10] presented experimental results showing a difference between the evaporator temperature \( T_{evp} \) and the cold chamber temperature \( T_{cc} \) during the adsorption process. The energy loss from and to the outside is not considered in the equation (13) because the walls of the cold chamber are insulated (fig. 2). Critoph [1] gave:

\[ COP = \frac{T_e}{T_{d1}} = \frac{T_c}{T_{d2}} \]

where:

\[ T_{d1} = \frac{T_a + T_{s2}}{2} \] and \[ T_{d2} = \frac{T_g + T_{s1}}{2} \]

so,

\[ COP = \frac{2T_e}{T_a + T_{s2}} = \frac{2T_c}{T_g + T_{s1}} \]  

Substituting the equations (7) and (8) into the equation (15), the necessary daily global irradiance can be estimated as follows:

\[ G = \frac{Q_f(T_a + T_{s2})}{2\eta \cdot S \cdot T_e} = \frac{Q_f(T_g + T_{s1})}{2\eta \cdot S \cdot T_c} \]

5. Numerical program algorithm

The numerical program has been developed using Fortran programming software. Two algorithms are developed, the first one is for calculating \( T_a, T_e, P_a, P_e, m_{max} \) and \( m_{min} \). The second one is for calculating \( T_{s1}, T_{s2} \) and \( G \) and it is similar to that presented by Chekirou [12] concerning the computation method of \( T_{s1} \) and \( T_{s2} \). Both will be linked to the complete calculation process. We remind that the temperatures \( T_a \) and \( T_e \) are considered as known parameters and they will be data for the numerical program. According to Critoph [1], \( T_e \) should be near to ambient temperature \( T_{amb} \) because we use an air condenser (fig. 2) and it is useful to consider \( T_a \) to be equal to \( T_e \). The error of the convergence of the numerical program is \( \varepsilon \), which will be taken as small as possible and the values of \( D, W_0, n \) are given for the AC35-methanol pair by Critoph [1].
6. Results

First, we must validate our numerical results with the experimental results given by Lemmini et al. [10]. They presented the daily global irradiance \( G \) received by the collector, the useful daily global irradiance received by the collector, the daily mean ambient air temperature \( \text{T}_{\text{amb}} \), the temperature achieved by the evaporator \( \text{T}_{\text{evp}} \), the desorbed mass, the adsorbed mass, the solar performance coefficient \( \text{COP}_{\text{sol}} \), the thermal performance coefficient \( \text{COP}_{\text{th}} \) and the collector efficiency \( \eta \) for 13 tested days. The surface \( S \) of collector studied by Lemmini et al. [10] is calculated using the dimensions given by the author, it is approximately equal to 0.5525 m\(^2\). The mass of adsorbent (AC35) is given and it is equal to 14.5 kg. In all our numerical computation, we consider the condensing temperature \( \text{T}_c \) and the adsorption temperature \( \text{T}_a \) are equal to the ambient temperature \( \text{T}_{\text{amb}} \). So, the variation of the condensing temperature is the same than the adsorption temperature. For the equation (13), we have studied the simplified case where the extracted heat from the evaporator and the extracted heat from the air of the cold chamber are neglected. Then, only the produced ice mass is considered, which will be the equivalent of the cold production amount.

**Figure 2.** Temperature of generating for 1 kg of adsorbent versus the produced ice mass for different values of evaporating temperature at \( \text{T}_a=25^\circ\text{C} \).

**Figure 3.** Temperature of generating for 1 kg of adsorbent versus the produced ice mass for different values of adsorption temperature at \( \text{T}_c=0^\circ\text{C} \).

Fig. 2 and fig.3 show clearly the limitations of the thermodynamic cycle temperatures. The generating temperature is limited even if we increase the adsorbent heating using the solar irradiance or the ice production using a good cooling process. The variation of the generating temperature versus the adsorption temperature and the evaporating temperature is also limited for a great solar irradiance...
or a great ice production. For the lower evaporating temperatures and the higher adsorption temperatures, the solar irradiance and the ice production will be lower, and this means a lower performance of the adsorption refrigeration machine. A higher performance needs a great solar irradiance for a great ice production.

7. Conclusion

The performance of the thermodynamic cycle of the adsorption refrigeration machine is based on the four temperatures, i.e. the generating temperature, the adsorption temperature, the condensing temperature and the evaporating temperature. Its limitations are as a function of the available solar irradiance and the required cold production. One kg of ice can be produced using one kg of adsorbent for an interval of generating temperature starting from 60°C to 90°C according to the evaporating temperature and from 40°C to 85°C according to the adsorption temperature. One m² of the collector (η=0.7) receiving 300 kJ of solar irradiance can heat the adsorbent for an interval of generating temperature starting from 75°C to 100°C according to the evaporating temperature and from 53°C to 97°C according to the adsorption temperature. The cold production is limited and it is not always useful to heat the adsorbent for higher generating temperature. The lower evaporating temperature leads to lower cold production. So, the decrease of the evaporating temperature is not useful for higher cold production, but this will be good for the lower adsorption temperature, in other words, the lower ambient temperatures.

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