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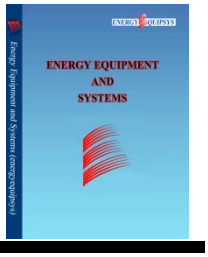

Numerical investigation of the solar activated carbon/methanol adsorption refrigeration system in Tehran's climate

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ABSTRACT

Solar adsorption refrigeration systems are used to extract heat using solar radiation based on the adsorption phenomena. In these systems, the temperature of the solar collector plays an important role in the efficiency of a system. In this study, two different models, including the lumped and the distributed ones, are investigated to predict the temperature distribution in a specific solar collector. The operating conditions are the same for both cases. Moreover, for the solar radiation as one of the boundary conditions, the data for Tehran solar irradiation is used. The results of the temperature analysis show that the distributed model predicts a less maximum collector temperature than the lumped model which clearly results in a lower system performance. In addition, it can be concluded that because of using steel as a main material for the collector and its high thermal capacitance, it takes almost 3 days for the system to reach the periodic operating conditions.

Keywords: Solar Adsorption; Activated Carbon; Methanol; Distributed Model; Lumped Model

1. Introduction

Today, energy plays a crucial role in human life, and it is the heart of economic improvement and an unavoidable prerequisite of technology enhancement in one country. In the last decades, with the rapid growth in world population, country's need to more sustainable energy resources has been dramatically increased. This rapid growth in the energy demand made governments not only to depend on fossil fuels but to try to find other alternatives. The renewable energy resource is a kind of energy which may be replaced by the environment in a short period, unlike fossil fuel. This feature makes it more attractive than a conventional one for scientists and governments and can persuade them to put more effort into, making it economically feasible to be used in industrial or domestic usage. One of these renewable sources is solar energy power, which is more available in countries near the equator. Although there are some factors like uneven distribution of this energy in the world or changes in the intensity of the solar radiation in different seasons, there is one important factor that makes it still appealing, and that is its sustainability. Scientists estimate that the sun has produced energy more than 14 billion years, and it can continue producing energy for about 5 billion years.

Iran with about 300 sunny days in more than 65% of its land and an average 4.5 up to

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5.5 kWhr/m^2 solar irradiation per day, has a great capacity to use solar energy. Scientists believe that if Iran uses its entire desert to produce energy by solar power, it produces energy even more than its annual usage so that it can be sold to other countries. One of the new ways that solar energy may be used is in the refrigeration industry. Today, an enormous amount of electricity is used to reduce temperature for different purposes so that changing these systems sources to solar energy could be an innovative idea for scientists and companies. In this way, conventional refrigeration systems can be replaced by new low power consumption solar ones. One of these promoting technologies which can be powered by solar energy is solar adsorption systems.

In 1986, Pons and Guilleminot [1] started working on the concept of using the adsorption process to make the refrigeration effect and made an experiment on zeolite/water and activated carbon/methanol to produce ice. After Pons and Guilleminot [1], lots of experiments were performed based on the system designed by them. In 1997, in order to study the long-term performance reliability of a solar-powered carbon/methanol ice maker, an investigation of thermal decomposition of methanol on the alloy surface under solid adsorption refrigeration conditions had been carried out by Hu, and it was proved that the decomposition products (unwanted gases) might be one of the main reasons for the diminishing performance of the solar ice maker [2]. In 2001, Li et al. [3] conducted an experimental study on the dynamic performance of the solar adsorption system. In this research, A flat-plate solid-adsorption refrigeration ice maker was built for demonstration purposes. The working pair consists of methanol used as the refrigerant and activated carbon as the adsorption medium. In 2003, Buchter et al. [4] did another experiment on solar adsorption system with 2 m^2 tube base-collector in Burkina-Faso and found COP of the system about 0.9 to 0.13. In 2000, Leite and Daguenet [5] did a numerical analysis of the system. Their analysis was focused on the numerical analysis of heat and mass transfer for solar adsorption system with a tubular collector covered by Transparent Insolation Material (TMI). In 2004, Anyanwu et al. [6] analyzed a solid adsorption system with methanol and activated carbon in a tabular tube. In their analysis, they have used the finite difference method to solve the equations for the system. Also, they used a distributed model for the tabular collector, and the results of the numerical analysis were acceptable and could represent the temperature distribution in the system correctly. Li and Wang [7] worked on the flat plate collector in 2003, and they used the distributed model for the heating process to model the system and compared the result with an experiment in China. El Fadar et al. [8] started doing an analysis on continuous adsorption refrigeration system with parabolic trough solar collector, which suggested a numerical study of a continuous adsorption refrigeration system consisting of two adsorbent beds and powered by parabolic trough solar collector (PTC). Activated carbon as an adsorbent and ammonia as a refrigerant are selected. In 2007, El-Sharkawy et al. [9] conducted an experiment to investigate the possibility of using carbon-ethanol for refrigeration purposes. In this research, Adsorption equilibrium uptake of ethanol onto a highly porous activated carbon-based adsorbent, namely Maxsorb III, has been experimentally investigated using a thermogravimetric analyzer (TGA) unit over adsorption temperatures ranging from 20 to 60°C. In 2011, Hassan et al. [10] tried to simulate the tabular collector again by analyzing a different part of the collector step by step. In their analysis, they have focused on one pipe and used the energy balance combined with energy equations for carbon and pipe with a Dubinin-Astakhov equation to find the temperature distribution. In their model, they have used the distributed model to find the temperature change in the system.

In this article, we are going to model a flat plate collector with both lumped and distributed methods in the condition of Tehran radiation. Our goal here is to find which method is more acceptable to be used to model the system. For using the lumped method, we are using a simpler model, so dealing with this model will be much easier,

and if we could find an acceptable result this model can be used for other purposes like optimization of the system. On the other hand, a distributed model is more complicated and takes much more time to be done, but there is a possibility to get a better result from this model. At the end of this article, the temperature distribution for these two models will be compared and the possible reasons for any differences will be discussed.

2. Background

2.1. Adsorption Process

Adsorption is a fundamental process that has been known for a long time and was used in different processes such as purification. Adsorption is a solid sorption process in which the binding force between liquid molecules and a solid medium comes from the electrostatic origin from dispersion-repulsion force (Van der Waals forces). The energy released in this process is called isosteric heat, and it depends on the nature of the adsorbent-adsorbate pairs [1]. The concentration of the adsorbate, Temperature, and Pressure are the three parameters that are usually used to describe an adsorption process.

There are different equations that are typically used to make a connection between these three critical parameters mentioned above. Dubinin-Astakhov is one of the most famous equations which is generally used to describe the adsorption equilibrium in microporous materials with a poly-modal distribution of pores size, such as activated carbon-methanol pair, which is in the following form [11]:

$$a = W_0 \rho_l \exp\left\{-D\left[T\ln\left(\frac{P_s}{P}\right)\right]^n\right\} \quad (1)$$

where the constant W_0 is the maximum adsorption capacity, n and D are constants related to the adsorbate-adsorbent pairs, ρ_l is the adsorbate density and P_s is the saturation pressure corresponding to the adsorbent temperature? Critoph et al. [15] utilized a simplified D-A equation as:

$$x = x_0 \exp\left\{-K\left[\frac{T}{T_s} - 1\right]^n\right\} \quad (2)$$

where x_0 is the concentration in the temperature equal to the saturation temperature, and K is the constant parameter. The constant parameters in Eq. (2) are suggested by Wang et al. [11], as shown in Table 1.

2.2. Solar Adsorption Cycle

The idea behind the working of this system is based on the adsorption process. In this system, instead of using a conventional refrigeration system with a compressor that needs electricity, a thermal power system with a solar energy source will be utilized. The processes which take place in the system can be described as follow:

- Isosteric heating (1-2)

In this process, the bed and the methanol trapped in its micro-pores are heated by solar energy. The process is done while the collector is isolated from the other parts of the system by closing the valve "a" and “c” in Fig. 1, so the absorbed energy leads to an increment of the bed pressure.

- Isobaric heating (2-3)

As the bed pressure reaches the desired one, valves "a" and "b" will be opened while valve "c" is closed, so the methanol can flow into the condenser. During the process, concentration is not constant anymore and decreases as time goes by.

Table 1. Constant parameter of the simplified D-A equation [11]

Activated Carbon Type	T_s (K)	x_0	K	n
18#AC	298.1	0.238	13.30	1.33
YKAC	288.3	0.284	10.21	1.39
Eshland AC	295.5	0.266	11.57	1.41
ACF0	290.9	0.400	17.19	1.66

- Isobaric cooling (3-4)

In this process, due to a decrease in solar radiation, the collector is cooled by the ambient temperature or the water, so the pressure decreases until it drops down to the evaporator pressure.

- Isosteric Cooling (4-1)

As the pressure of the system drops to the evaporator pressure, valve "c" is opened to connect the evaporator to the collector. Since the pressure of the collector has been dropped, the methanol in the evaporator chamber absorbs energy from the water and will be evaporated and adsorbed on the activated carbon in the bed.

2.3. Thermodynamic Design

Since the valves can control the process and consequently, the pressure and the temperature of the system, the system performance strongly depends on the valves opening time. As this temperature and pressure will control the concentration of the methanol and also the concentration of the methanol is related to the mass of activated carbon, it is necessary to find a proper mass for methanol and activated carbon and also the pressure that we will have during the cycle. To start analyzing, we assume different valve opening time for a system and will find other parameters based on the temperature at end of process (1-2). We will continue our calculation as stated in Fig. 2.

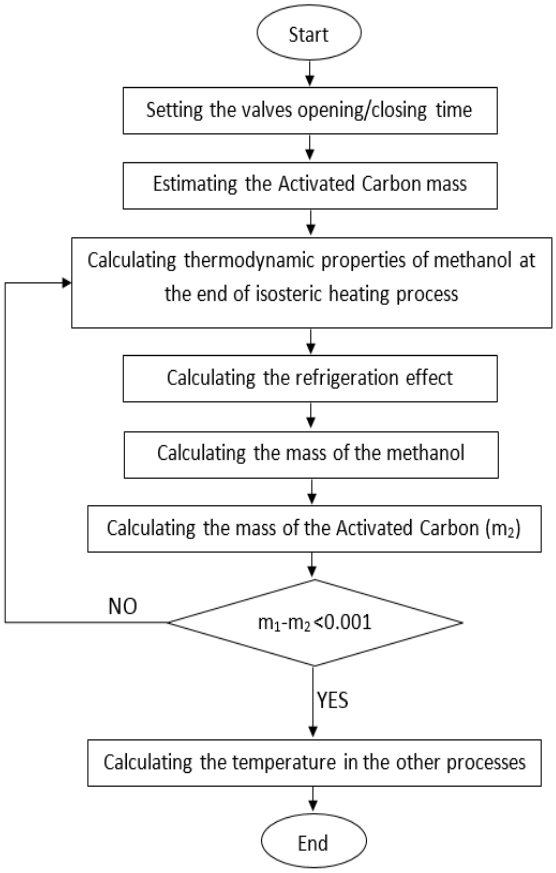

Fig. 2. Flowchart represents the procedure to find the mass of the activated carbon/methanol pair

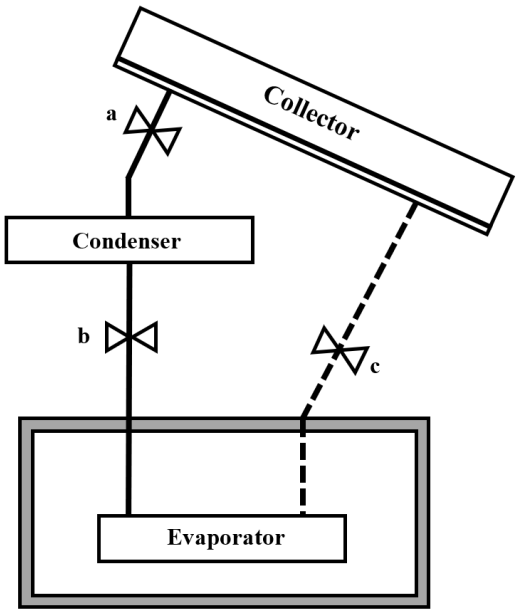

Fig. 1 Schematic of the solar adsorption refrigeration system

We assume that the valve is opened at 11:30 AM (end of the first process). If the valve is opened later, this late opening time may result in having a pressure higher than the atmospheric pressure, so the system has to operate both under and above atmospheric pressure, which is not acceptable from a mechanical design point of view. Also, 30 kg Activated carbon is assumed to be needed to make 8 kg ice with -5°C temperature from 8 kg water with a temperature around 20°C, as an estimation to start the loop. After 4 iterations, the exact amount of the activated carbon and the methanol will be found as 16.34 kg activate carbon and 4.9 kg methanol to run the process, respectively. It is also important to mention that the pressure and the temperature will be related to each other by Dubinin-Astakhov equation. Based on a research work performed by Butcher et al. [4], about two-third of the total methanol circulates in the cycle, which is about 3.3 kg.

3. Numerical Modeling

3.1. Lumped Model

To have a rough estimate of a temperature change in the system, lumped analysis can be used in this system. It should be mentioned that this method is not always for a rough estimate and the accuracy of this method strongly depends on the system characteristic and specially Biot number. In this method, it is assumed that there is no temperature gradient in the collector, including the activated carbon bed and the adsorbed methanol. As a result, the isosteric process can be written as [13]:

$$\left(MC_p\right)_e \frac{\partial T}{\partial t} = A_s S_s - U_l A_s (T - T_{amb}) \tag{3}$$

The term on the left side of the equation is the energy change, and the right side of the equation demonstrates the net solar energy which is absorbed by the collector. In this equation, $\left(MC_p\right)_e$ is the equivalent thermal capacitance of the collector, A_s is the area of the collector, S_s is the solar radiation and U_l is total heat loss coefficient of the collector. In the research which was done by Agarwal and Larson [14] the heat transfer coefficient was described as:

$$U = \left[\frac{N}{\left(\frac{C}{T_p}\right)\left(\frac{T_p - T_a}{N + f}\right)^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma\left(T_p + T_a\right)\left(T_p^2 + T_a^2\right)}{\left[\varepsilon_p + 0.05N\left(1 - \varepsilon_p\right)\right]^{-1} + \left[\frac{2N + f + 1}{\varepsilon_g}\right] - N} \tag{4}$$

where:

$$f = (1 - 0.04h_w + 0.005h_w^2)(1 + 0.091N)$$

$$C = 250[1 - 0.0044(s - 90)]$$

$$h_w = 5.7 + 3.8V_w$$

where σ is the Boltzmann constant, T_p is the collector plate temperature, T_a is the ambient temperature, N is the number of the layers of the glass covers, and ε_g , ε_p are the emissivity of the glass cover and the heat adsorbing plate, respectively, and V_w is the wind velocity.

Since the collector contains activated carbon, methanol, and a structure, the effective heat capacity should be considered for the system and may be calculated as:

$$\left(MC_p\right)_e = M_a C_{pa} + xM_a C_{pl} + M_m C_{pm} \tag{5}$$

where C_{pa}, C_{pl} and C_{pm} are the specific heat capacity of the activated carbon, methanol, and the structure respectively, and x is the adsorption quantity which can be calculated using the simplified Dubinin-Astakhov equation. Substituting Eq. (2) in (3), the lumped equation can be described as:

$$A_s U_l T + \left[\frac{-M_a H_{st}\left(-\frac{Kn}{T_s}\right)x_0}{\left(\frac{T}{T_s} - 1\right)^{n-1} e^{-k\left(\frac{T}{T_s} - 1\right)^n}} + \left(MC_p\right)_e\right]\frac{\partial T}{\partial t} = A_s(S_s + U_l T_{amb}) \tag{6}$$

3.2. Distributed Model

To find a better temperature distribution in the system, a distributed model for a flat plate collector can be used as shown in Fig. 3. In this model, the temperature is the function of both the time and the height of the activated

carbon layer in the collector. For more simplification, the temperature change in x direction is neglected.

The energy equation for this model can be described as [11]:

$$(\rho C_p)_e \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial y^2} + \rho_{so} H_{st} \frac{dx}{dt} \quad (7)$$

where $(\rho C_p)_e$ is the total heat capacitance, T is the temperature of the system, k is the thermal conductivity of the adsorbent, x is the concentration of the adsorbate and H_{st} is the enthalpy of evaporation. The total heat capacity is:

$$(\rho C_p)_e = \varepsilon_a \rho_{gas} C_{pg} + (1-\varepsilon_0)\rho_{so} C_{ps} + (\varepsilon_0 - \varepsilon_a)\rho_l C_{pl} \quad (8)$$

For the first process, the methanol concentration is constant, so Eq. (7) is simplified to:

$$(\rho C_p)_e \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial y^2} \quad (9)$$

For the initial condition, the temperature is equal to ambient temperature. Also, for the boundary condition, it is assumed that the bottom of the collector is well insulated. For the upper surface, solar radiation energy can be assumed as an incoming heat flux for the system.

For the isobaric processes, when the valve will be opened, the system will encounter a change in the concentration of the methanol. For the incompressible fluid flow in a porous media, the process is described by Darcy's law [11]:

$$\vec{V}_{gas} = -\frac{k_p}{\mu}\left(\frac{\partial P_{gas}}{\partial y} + \rho_{gas}\vec{I}\right) \quad (10)$$

where k_p is the permeability factor of the adsorbent, μ is the viscosity of the gas, and $\vec{I}$ is the unit vector parallel to the direction of gravity. As the collector thickness is small, the pressure gradient may be neglected. Also, k_p is a small constant which is about 4×10^{-11} for activated carbon; moreover, the velocity in this system is not high enough to be considered. As a result, for the second process, Eq. (7) can be written as:

$$(\rho C_p)_e \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial y^2} + \rho_{so} H_{st} \frac{dx}{dt} \quad (11)$$

4. Results and Discussion

4.1. Lumped simulation

Variation of the temperature of the collector is shown in Fig. 4. As it is clear, the system temperature distribution has 3 steps. The first one starts at 7 AM and finishes at 11:30 AM. The second process starts at 11:30 AM and finishes at 6 PM, and finally, the cooling process starts at 6 PM. Based on the results, the maximum temperature which may be obtained using a flat collector is about 356 K, which is not acceptable for the cooling system. The reason which can explain this problem in our system is that, the collector is made from iron which has high thermal conductivity. For the pressure, based on Table 2, the maximum pressure will be about 93.75 kPa. So, Fig. 5 describes the pressure change in the system.

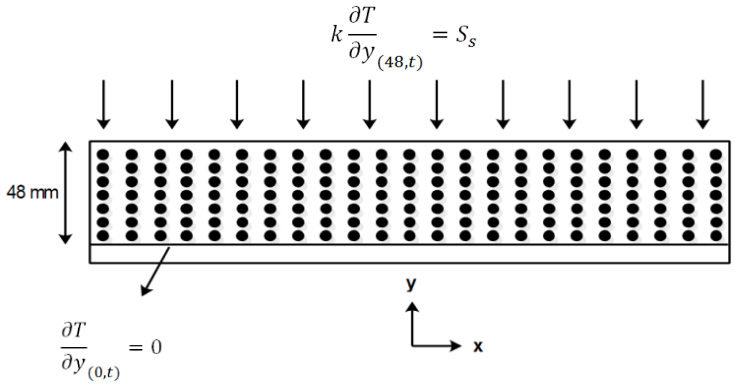

Fig. 3 Schematic of the distributed model

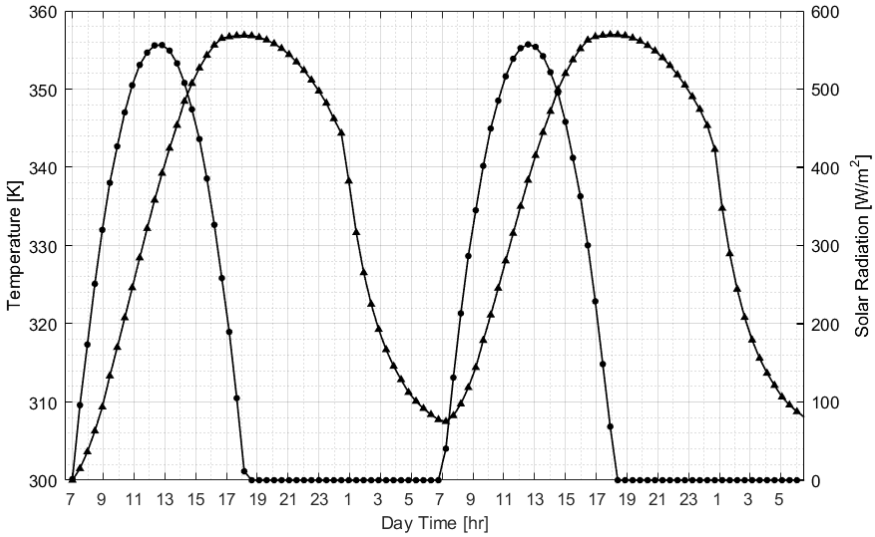

Fig. 4 Temperature distribution in the collector base on the lumped hypothesis

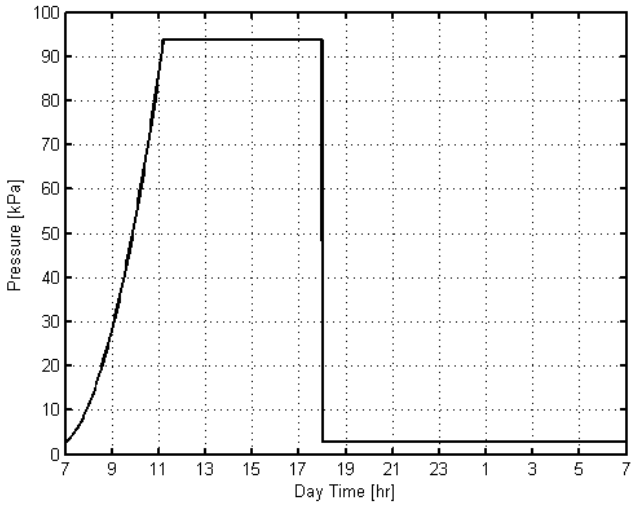

Fig. 5 A one-cycle pressure distribution of the system

As it was mentioned before, in the first process, the system experiences an increase in its pressure because the valve "a" is closed, so by evaporating methanol, the pressure of the system will increase. For the next process, by opening the valves, methanol vapor will path through the condenser and will experience the isobaric process. It should be added that in the real system, due to a sudden expansion in the time of opening the valve "a", the pressure may fluctuate, so it cannot be assumed totally constant; however, it could be assumed as a reasonable assumption.

4.2. Distributed simulation

Base on the assumption and the theory which was discussed before, the temperature distribution in the collector is plotted in Fig.6. As it is clear in Fig. 6, in the first day, the temperature increases up to 333 K; however, this temperature is not a steady-state temperature for the system. If we continue solving the equations, we will see that after 3 cycles the maximum temperature will not change anymore and will conclude that the system has reached its steady-state point. Since we have chosen the distributed method, the temperature is a function of the coordinates and will change for different points with a different position. In order to have a final temperature, the mean

temperature of the nodes in the system was used to plot this graph. It should be added that each node represents a point in the collector, so to have a mean temperature, the temperature for the nodes with a same x position and different y position has been used. Changing in the temperature for different nodes in a system for different fixed time is shown in Fig. 7.

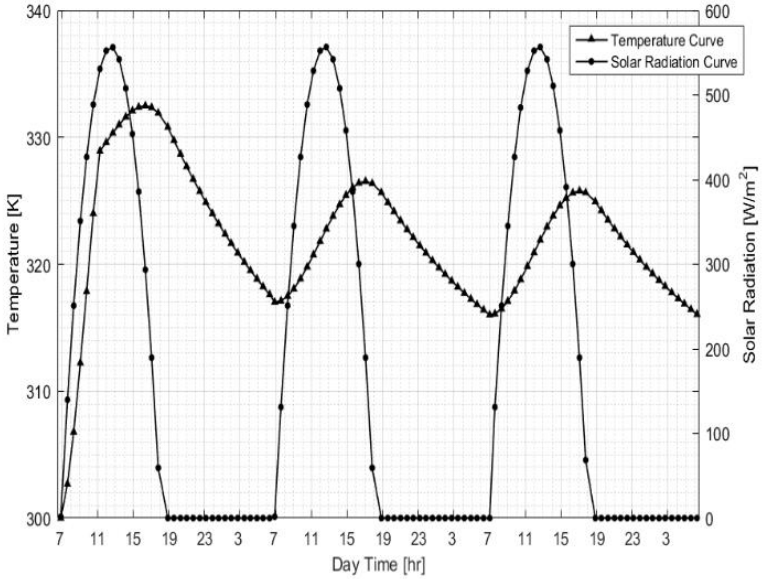

Fig. 6 Temperature distribution in a collector base on the distributed hypothesis

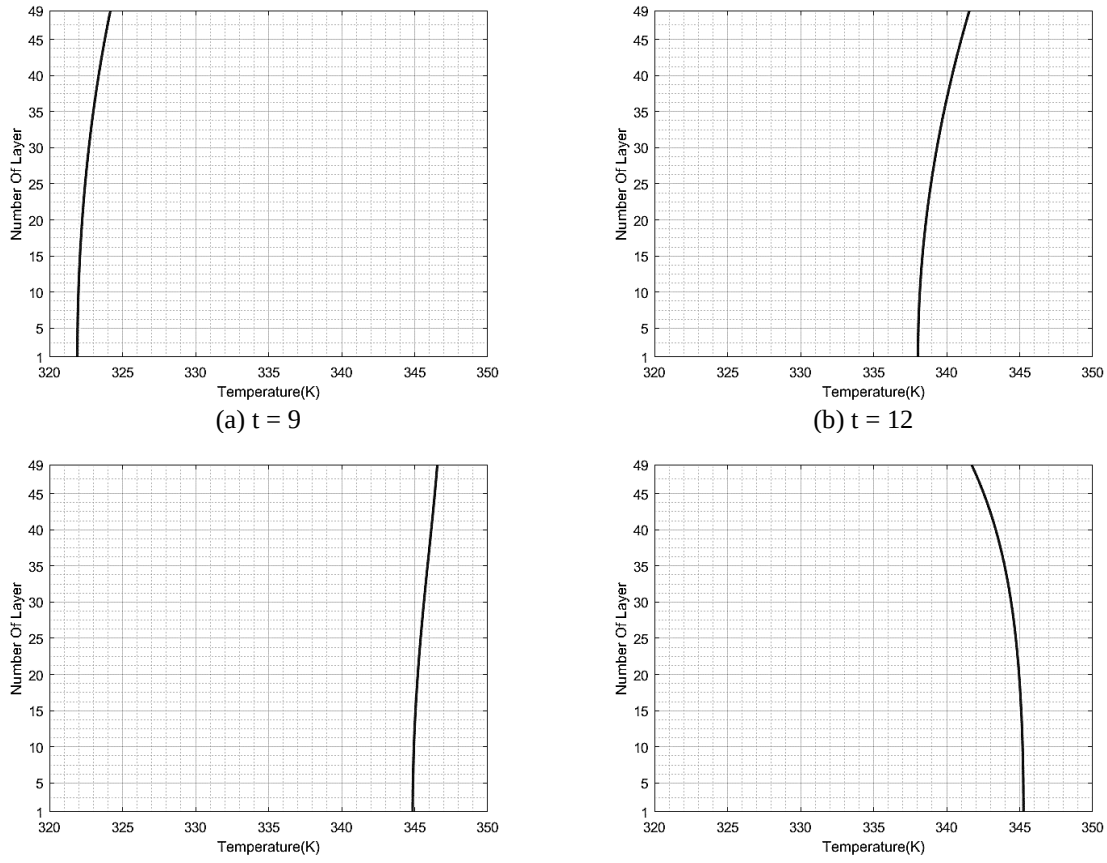

Fig. 7 Temperature distribution for a fixed time in a different layer of the collector.

As it is clear, we have a change in a temperature of different layers and this difference may increase up to 10°C, so the average temperature cannot represent the exact temperature of the system. In addition, one possible reason to explain the fact that the temperature does not reach to its initial value is that the time for cooling the collector is not enough so in the next day, the initial condition will increase, and this change will continue until we reach the stable temperature for the system. This fact can be clearly recognized from Fig. 6. In this figure, the temperature difference between the first point and the last point in one cycle is significantly decreasing, so we can expect reaching stable mood for the system.

Figure 8 shows the comparison between the temperature distributions for two different methods. As it is clear, the highest temperature in different methods are different. The main reason behind this fact is that the temperate which was used to plot the distributed model is the mean temperature of the layers, so we expect having a lower temperature.

5. Conclusion

Based on what was discussed in the previous sections, it was dedicated that the pressure and the important property of the cycle need to be defined by iteration, and it cannot be fixed by the operator. Thus, a new algorithm was developed to predict the amount of activated carbon and methanol, which is needed to run the cycle. The most important limitation for the system was that, since the system is working under atmospheric pressure, for better sealing of the system, the pressure points in the cycle have to be set to be lower than ambient pressure, and this pressure was set about 93 kPa. By setting the pressure and finding the important points in the cycle, two different analyses have been done to find the temperature distribution in the collector. The first one was the lumped analysis. The maximum temperature in this approach was found to be about 356.9 K. Also, a second analysis has been done based on the distributed model. This model needed more calculation and had higher complexity than the previous model; however, it could predict the system behavior more accurately as it considers spatial temperature variation. The maximum mean temperature achieved in this model was 332 K.

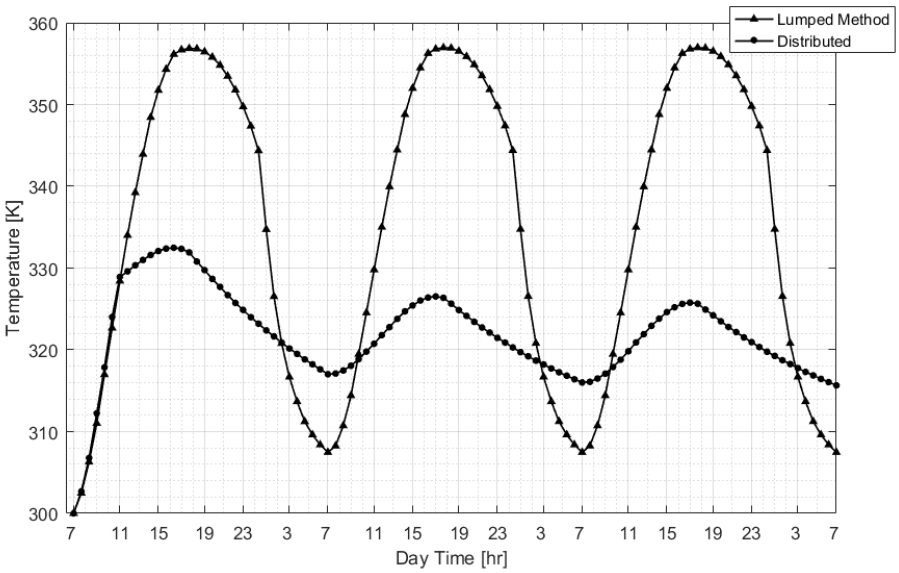

Fig. 8. Comparison of the results using the lumped and the distributed models

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