ADSORPTION COOLER DESIGN, MODELING, AND DYNAMICS AND PERFORMANCE ANALYSES

João M.S. Dias and Vítor A.F. Costa

Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, Campus Universitário de Santiago, 3810 -193 Aveiro, Portugal

João M.S. Dias
joaomdias@ua.pt

Abstract: *This paper presents an adsorption cooler (AC) driven by the surplus heat of a solar thermal domestic hot water system to provide cooling to residential buildings. A cylindrical tube adsorber using granular silica gel as adsorbent and water as adsorbate is considered. The AC is modelled using a two-dimensional distributed parameter model that was implemented in previous adsorption heating and cooling studies. The performance coefficients of the resultant thermally driven colling system are obtained for a broad range of working conditions. The thermally driven AC has a coefficient of performance (COP) of 0.5 and a specific cooling power (SCP) of 44 W.kg^{-1}, considering condenser, evaporator, and regeneration temperatures of 15 ^{o}C, 18 ^{o}C, and 70 ^{o}C, respectively. Moreover, results show that the AC can be used for refrigeration purposes at temperatures as low as 2 ^{o}C, and that it can also operate during hotter days under temperatures of 42 ^{o}C.*

Keywords: adsorption cooler, thermally driven cooling, solar heat surplus, air cooling, refrigeration

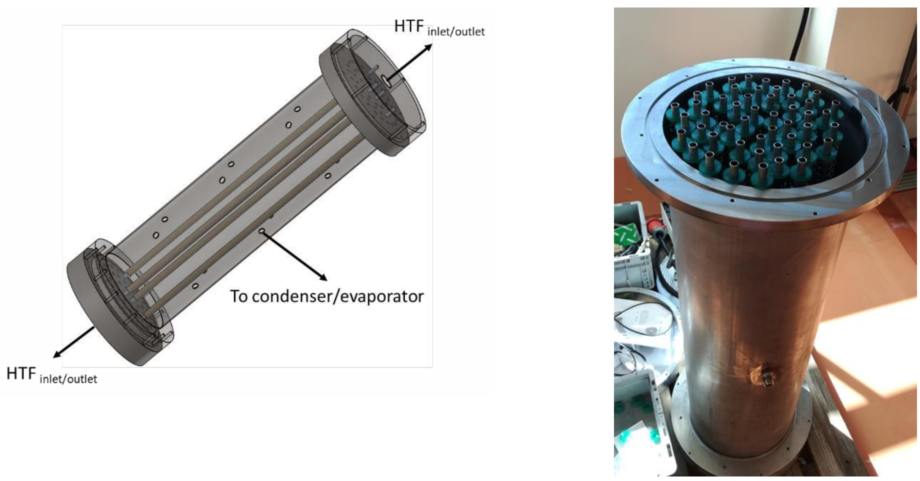
1. INTRODUCTION

Heating and cooling stood as the biggest energy end-use sector in Europe, accounting for 51 % of the EU's total energy consumption in 2019, approximately 75 % being obtained from burning fossil fuels [1]. During recent years, most focus is being addressed to include renewables in the energy sector and increase its share. However, considering residential and industrial buildings and processes, the heating and cooling sector is more harmful to the environment than the energy sector itself. More efforts must be made to diminish the negative impacts of thermal energy needs and move towards the achievement of the key energy goals set for the following decade, through the introduction of new technologies and the improvement of those that are already available. Given that adsorption cooling (AC) can be driven by renewable energy sources and waste heat, this technology can play a significant role towards the achievement of these goals. Unlike common vapor compression refrigerators and coolers, AC can work with zero global warming potential (GWP) refrigerants like water, which is environmentally friendly, abundant in nature, and causes no harm in case of leakages. The low COP is usually pointed out as a major disadvantage of AC technologies. However, ACs are directly driven by thermal energy, meaning that no energy is lost to produce electricity and compensate the heat to work energy conversion efficiency. Due to that, a fairy comparison criterion is required than just compare the numerical values of the adsorption and vapor compression systems' COPs. Moreover, when using thermal energy that is freely obtained, the coefficient of performance (COP) loses its importance. Developing systems that can use waste heat to regenerate AC lead to the elimination of their major disadvantage, that is its low COP. It is common that the need for cooling occurs when excess heat is available, as solar heat, ambient heat, waste heat from machines operation and industrial processes. Using the surplus of thermal energy, it is possible to thermally drive the ACs. Unlike conventional refrigerators and coolers that require electricity to function, ACs can work with the excess thermal energy, resorting just to tiny batteries to power its control electronics and drive small circulation pumps.

This work presents a thermally driven cooling system that uses the heat surplus obtained from solar thermal panels during warm seasons to drive an AC for space cooling. In this study an adsorber that has been used in previous works is filled with granular silica gel. The AC is modelled using a two-dimensional distributed parameter model that has been used validated in previous adsorption heating and cooling works [2–4], which is here adapted to the granular adsorbent. Several simulations are carried out to analyse the impact of the evaporator, condenser, and regeneration temperatures, as well as the cycle time, on the AC's performance. It is to be noted that the same base adsorption system that is being used for cooling in summer can be used for heating purposes in winter, yet requiring any other heat source, which can also be a renewable heat source.

2. DESIGN

The core of any AC is the adsorber, which can be designed in several configurations. There are a bunch of review papers available in the literature that analyse the different adsorber configurations and adsorbent packing techniques [5]. The most common designs are shell packing, plate-finned, tube, finned tube, fin plate, flat pipe, spiral plate, coated tube and coated plates [6]. Coatings have been considered as the most promising packing technique due to its inherent high heat transfer coefficients and compact sizes. However, it is more difficult to build real scale prototypes using adsorbent coatings and the manufacturing costs are much higher than solutions with granular adsorbent materials. This work considers a cylindrical tube adsorber configuration using a granular adsorbent. Silica gel-water are selected as the adsorbent-adsorbate working pair, given that its regeneration can be made at temperatures that can be provided by solar thermal panels, and its properties are well studied and widely reported in the literature. Granular silica gel RD2060 produced by Fuji Silysia Chemical LTD is considered in this study. The adsorber consists of fifty individual metal tubes packed with silica gel on their outer surfaces. The tubes are enclosed in a vacuum chamber that is alternatively opened to the evaporator or to the condenser, allowing water vapour exchanges. The energy exchanges required to drive the adsorption/regeneration processes are carried out through a heat transfer fluid (HTF) that is circulated inside the tubes. The adsorber and its schematic are depicted in Figure 1.



a) b)

Figure 1. a) Adsorber schematic; b) Adsorber with fifty tubes covered with silica gel.

3. MODELING

Several different physical models have been used to model adsorption heat pumps and refrigerators. An extensive review can be found in reference [7]. Three types of models are normally considered: thermodynamic models, lumped parameter models, and distributed parameter models. To accurately simulate an adsorption device, considering all the dynamics, distributed parameter models are mandatory. Reference [3] presents an extensive analysis to physical models for an AHP, comparing different types of models and considering several dimensions. It is concluded that a 2D distributed parameter model must be used to accurately simulate an AHP system based on the cylindrical tube design. Therefore, the 2D distributed parameter model is used to describe the AC dynamics and estimate its performance throughout this work.

To model the AC adsorber, the energy and mass balance equations, respectively equations (1) and (2), are applied to the cylindrical tube geometry.

$$\frac{\partial(\rho C_p T_s)}{\partial t} + \nabla(\rho_v C_{p,v} T_s u) - \nabla(k_s \nabla T_s) - \rho_s(1-\varepsilon)\Delta H_{ads}\frac{\partial X}{\partial t} = 0 \tag{1}$$

$$\varepsilon\frac{\partial \rho_v}{\partial t} + \nabla(\rho_v u) + \rho_s(1-\varepsilon)\frac{\partial X}{\partial t} = 0 \tag{2}$$

where

$$\rho C_p = \varepsilon \rho_v C_{p,v} + \rho_s (1-\varepsilon)(C_s + X C_{p,a}) \tag{3}$$

and

$$\varepsilon = \varepsilon_{bed} + (1-\varepsilon_{bed})\varepsilon_p \tag{4}$$

The momentum balance is expressed by Darcy's Law.

$$u = -\frac{k_D}{\mu}\nabla P \tag{5}$$

The adsorbent bed permeability is obtained by the Blake-Kozeny model [8].

$$k_D = \frac{d_p^2 \varepsilon_{bed}^3}{150(1-\varepsilon_{bed})^2} \tag{6}$$

To obtain the adsorbate uptake, the linear driving force (LDF) model is applied [9].

$$\frac{dX}{dt} = K_{LDF}(X_{eq} - X) \tag{7}$$

The K_{LDF} coefficient being evaluated as:

$$K_{LDF} = \frac{15 D_{ef0} e^{-\frac{E_a}{R' T_s}}}{R_p^2} \tag{8}$$

The equilibrium adsorbate content in the adsorbent for the silica gel-water pair is calculated as:

$$X_{eq} = \frac{Pk_0 e^{\frac{\Delta H_{ads}}{R'T_s}}}{\left[1 + \left(\frac{Pk_0}{q_m} e^{\frac{\Delta H_{ads}}{R'T_s}}\right)^{t_{SG}}\right]^{\frac{1}{t_{SG}}}} \tag{9}$$

The following assumptions are considered:

- The adsorbent bed is homogenous.
- The evaporator and the condenser are considered ideal heat exchangers with uniform pressures.
- Adsorbate vapor phase behaves as an ideal gas and the adsorbed phase is in the liquid state.
- Specific heats of the adsorbate vapor and liquid phases are constants.
- Adsorbate vapor around the adsorbent is considered to be saturated vapor.
- Thermophysical properties of solid materials do not change with temperature.
- Temperature, adsorbent content, and pressure in the adsorbent bed do not vary along the angular direction.

More details on the modeling of the HTF and the metal tube, as well as the initial and boundary conditions can be found in references [2–4].

4. THERMALLY DRIVEN COOLING PERFORMANCE AND DYNAMICS

A heat surplus on domestic hot water storage tanks frequently exists when it is necessary to cool down households. This work proposes to use the heat surplus produced by domestic solar thermal panels, used with the main purpose of providing domestic hot water, to drive an AC that can remove heat from a residential building. A basic scheme of such a system is represented in Figure 2. The ideal thermodynamic cycle of the AC is presented in Figure 3.

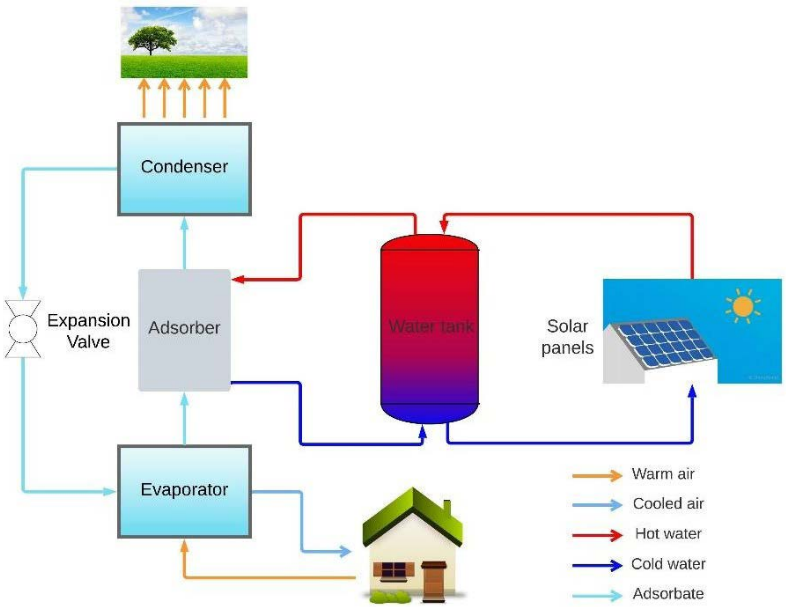


Figure 2. Schematic of an AC driven by solar thermal heat used to remove heat from a residential building.

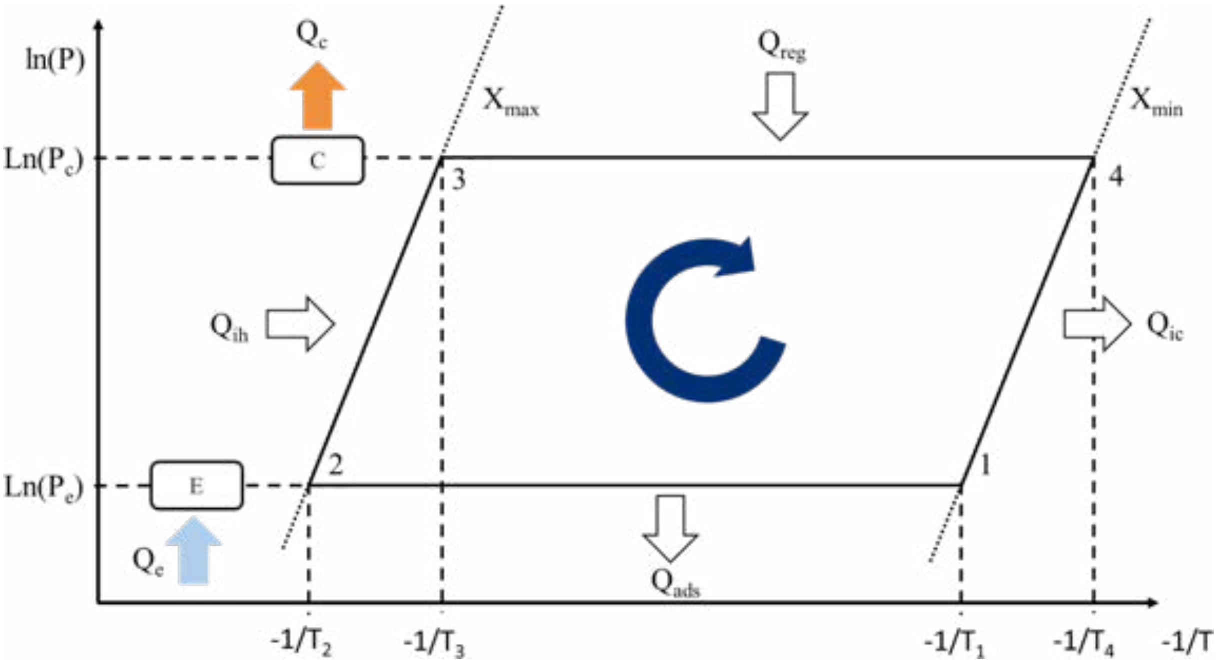


Figure 3. Ideal thermodynamic cycle of the AC.

The performance of an AC is defined by its cooling COP and specific cooling power (SCP), which can be obtained using equations (10) and (11), respectively. Details on how to obtain the isosteric heat (Q_{ih}), regeneration heat (Q_{reg}), and the heat withdrawn by the evaporator (Q_e) can be obtained from Reference [4].

$$\mathrm{COP} \quad = \frac{Q_e}{Q_{ih} + Q_{reg}} \tag{10}$$

$$\mathrm{SCP} = \frac{Q_e}{m_s \tau_{cyc}} \tag{11}$$

Table 1 contains the main parameters used in the simulations, which were selected aiming to describe the use of the adsorber described in this work to remove heat from a resident building, according to Figure 2. The selected temperatures correspond to a warm summer day in the region of Aveiro, Portugal. The condenser is outside, at an ambient temperature of 30 °C. The evaporator temperature is set to 15 °C, which may be considerably low for space cooling but takes into account that the air will increase its temperature during the path from the evaporator to the home division that is being cooled (approximately 3 °C temperature increase is considered during that path). The regeneration temperature corresponds to the typical temperature inside a domestic hot water reservoir heated by solar thermal collectors. Net water at 18 °C is used to remove heat from the adsorber during adsorption. For the application considered in this work, the performance of the AC is characterized by a COP of 0.5 and a SCP of 44 W kg^{-1}. The performance coefficients may be lower than those of conventional coolers, but it should be highlighted that the energy used to drive the AC is surplus energy that would otherwise be wasted. Furthermore, the total cooling power of the system can be improved by increasing the mass of adsorbent material in the adsorber, or by using two or more adsorbers in parallel (one being regenerated when the other is adsorbing water).

Table 1. Reference parameters used in to calculate the COP and SHP.

Parameter	Value	Unit
C_s	921	$J.kg^{-1} K^{-1}$
$d_{in,tube}$	0.01	m
$h_{m\rightarrow s}$	30	$W.m^{-2} K^{-1}$
k_s	0.198	$W.m^{-1} K^{-1}$
L_{tube}	1	m
m_s	5.35	kg
t_{ads}	600	s
T_c	30	^oC
T_e	15	^oC
$T_{f,ads}$	18	^oC
$T_{f,reg}$	70	^oC
VHTF	0.05	$M s^{-1}$
ρ_s	2027	$Kg m^{-3}$
σs	0.002	m

The performance of the AC was obtained for several working conditions and control parameters, aiming to investigate its behavior under different working conditions. A segregated approach was considered, varying one parameter at a time and assuming the reference values for the remaining parameters. The analysis includes the evaporator, condenser, and regeneration temperatures, as well as the cycle time, which is considered a control parameter. Figure 4 shows the evolution of the performance coefficients for different evaporator and condenser temperatures. As expected, the performance of the AC improves for higher evaporator temperatures and lower condenser temperatures. Lower evaporator temperatures and higher condenser temperatures deteriorate the performance of the AC. Notwithstanding the loss of performance, the system can work in very hot days with a COP of 0.31 and a SCP of 26 W kg^{-1}, corresponding to condenser temperatures as high as 42 ^oC. Moreover, the thermally driven cooling system can be used for refrigeration purposes at temperatures as low as 2 ^oC, to which corresponds a COP of 0.25 and a SCP of 18 W kg^{-1}.

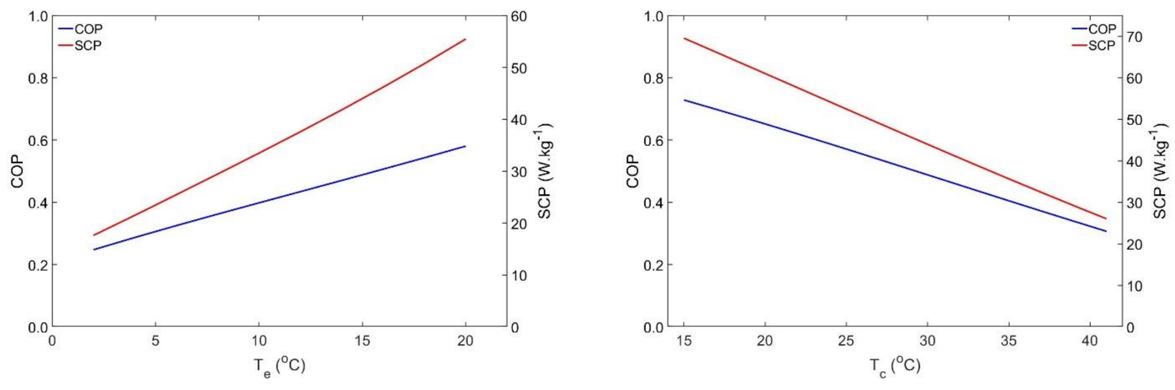


Figure 4. COP and SCP variation with the evaporator (on the left) and condenser (on the right) temperatures.

Figure 5 (left) depicts the influence of the regeneration temperature and the cycle time (right) on the AC's performance. It is noticeable that variations on the regeneration temperature affects the SCP more severely than the COP, given that higher regeneration temperatures lead to faster heat exchange between the HTF and the adsorbent material. Identifying the optimal cycle time is one of the most important parameters in every adsorption system, being its identification usually complex due to the opposite behavior of the COP and SCP. In this particular case, this opposite behavior is present for cycle times higher than 83 min, where the COP keeps increasing with the cycle time and the SCP starts to decrease. The optimal balance between the COP and the SCP must be found for each individual adsorption system, and in this case for each individual AC.

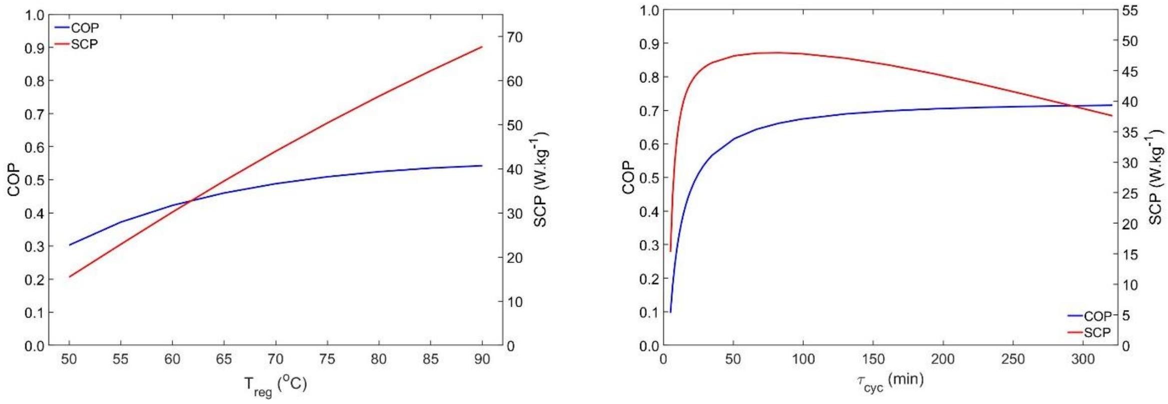


Figure 5. COP and SCP variation with the regeneration temperature (on the left) and the cycle time (on the right).

5. CONCLUSIONS

This work presents an AC driven by surplus heat from thermal solar collectors suitable for residential space cooling applications. This system can be used to provide cooling to residential buildings during the hot summer months, solely using the inherent heat surplus that is generated by solar thermal collectors during warm seasons. The AC uses silica gel-water as the working pair and is modelled by a two-dimensional distributed parameter model. The model is used to simulate the thermally driven cooling system and calculate its performance coefficients. Considering the reference parameters, corresponding to a hot summer day in the Aveiro region, the thermal cooling system has a COP of 0.5 and a total cooling power of approximately 235 W. A larger unit is required to provide cooling to households, what can be accomplished either by increasing the adsorbent mass in the adsorber or by using several adsorbers in parallel. Analysis of the thermally driven cooling system main governing parameters is carried out. Results show that despite the lower performance for lower evaporator temperatures and higher condenser temperatures, the system can accommodate evaporator temperatures as low as 2 ºC, and condenser temperatures as high as 42 ºC, demonstrating that it is still viable in hotter days. Using the heat surplus of solar thermal systems, the thermally driven cooling system can work close to its maximum COP and deliver more than half of its maximum SCP. Despite the low performance of the thermally driven cooling system, this technology is worth of further research and development, considering that the required energy to drive the system is freely obtained (clean and cheaper). The same base adsorption system can be used for cooling purposes in summer, or for heating purposes in winter.

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