

Effect of Operating Temperatures and Working Pairs on Performance of Solar Adsorption Cooling System



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ABSTRACT

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Renewable energies including solar energy requirements for refrigeration and air conditioning are increasingly gaining interest due to the refrigerants friendly to the environment. However, it was found that these technologies have some limitations like the low performance and their high cost. This paper proposes a comparative study of a solar adsorption refrigeration machine. The study consists in determining the influence of thermodynamic parameters of operation on the performance of the system. This is based on a thermodynamic model using different types of adsorbent / adsorbate pairs. The main parameters considered in this study are: temperature of generation, evaporation, maximum heating temperature, condensation pressure as well as the type of the pair used: activated carbon / methanol and zeolite / water. Simulations for different thermodynamic parameters show that the COP is very sensitive to the generation and evaporation temperatures as well as the maximum heating temperature, on the other hand it was slightly influenced by the condensation pressure. The results obtained have shown that the AC / methanol pair is more profitable than the zeolite / water pair.

1. INTRODUCTION

Solar (solar photovoltaic, solar thermal), hydropower, wind, biomass and geothermal energy are inexhaustible flows compared to "stock energies" from fossil fuel deposits in the process of becoming rare: oil, coal, natural gas [1]. The conversion of solar energy into cooling has become one of the major applications and consists of two major types which are photovoltaic and thermal cooling, this has several methods of which gas sorption is the dominant one in air conditioning and solar refrigeration [2].

Absorption [3-6] is the main technology while adsorption [7, 8] is the second main technology of thermal cooling; this made it receiving a great deal of interest due to their refrigeration capacities in comparison with photovoltaic systems [9, 10] which are offered for low-capacity air conditioning applications and our work deals with solar adsorption refrigeration systems in its basic cycle. This technology is mainly used for ice making, air conditioning and refrigeration. The main advantages of adsorption system are: ability to work with wide range of driving temperatures, noiseless, non-corrosive, and environmentally friendly refrigerants [11-13]. However, several factors have been discovered and appear to be disadvantages for this type of refrigeration such as intermittent solar energy, low coefficient of performance compared to those with vapor compression cycle, high cost of adsorber chillers, poor heat transfer performance, the size of this type of technology and long adsorption/desorption time, hence the need to improve performance of solar adsorption cooling taking into account the cost factor.

Due to their high cost, energetic systems powered by solar

energy and solar adsorption cooling systems precisely, modelisation and numerical simulation presents reliable solution to study, test, evaluate and improve this type of systems. thus, for this purpose several researches work for simulation have been proposed and developed in which consist in testing the influence of numerous parameters that can be geometric, thermodynamic or temporal variables, in the hope of solving the technical, economic, environmental problems, and achieve high performance and low cost [13]. An experimental platform was carried out by Najah et al combining an internal combustion gas engine with adsorption machine and developed a simulation model confronted with experimental measurements [14]. They found that the outlet temperature of the collector increases with increasing the solar radiation. The COP and cooling power of the chiller achieved was 0.62 and 5.64 KW. the thermal conductivity of adsorbent, the flow rate and the inlet temperature of the heat transfer fluid were simulated and analyzed by Xu [15]. Douss and Meunier [16] studied the effect of operating temperatures on the coefficient of performance of active carbon -methanol system. The results showed that The COP was seen to be very sensitive to the evaporating and adsorbing temperatures. A numerical simulation for adsorption solar cooling system with activated carbon -methanol pair was carried out by Leite et al. [17]. The effect of TIM cover system was studied and found that is 40% more efficient then the single cover with COP reached 0.13 and corresponds to 7-10 kg/day of ice production. Ambarita and Kawai [18] tested experimentally the type and amounts of adsorbents filled in a solar adsorption refrigeration system using activated ammonia AA and activated carbon AC. The results showed that a higher COP of 0.074 was been found with utilizing of adsorbent of 100% AC. Brites et al. [19]

developed a numerical study to determine the influence of the design parameters on the overall performance of a solar adsorption refrigerator using flat plate collector and silica gel-water pair. The main parameters in this study were the mass of silica-gel, the number of metallic fins in the silica-gel bed, the orientation of the solar collector (azimuth angle). The influence of collector area and cycle time on performance of a single-stage, two-bed adsorption chiller is studied by Kumar et al. They used dynamic model with silica gel / water in two different days in summer and winter to study the performances. They found that both daily average and cyclic average COP increase with increase in solar collector area and the same thing for the cycle time [20]. Cherrad [21] studied the effect of heating time of the adsorber/collector on the performance of a solar adsorption refrigerator. They developed a numerical model to predict the amounts of heat transfer in the adsorber/collector. The shorter heating time corresponds to higher efficiencies of adsorber/collector and the maximum COP reached was 0.11. Fernandes et al. [22] presented a state of the art of different operating pairs and technologies with a basic cycle for solar adsorption refrigeration system. Chekirou et al. [23] evaluated the performance of an adsorption cooling system powered by solar energy with activated carbon-methanol as a working pair and using a numerical model. They discussed the effect of the collector surface area and the operating temperatures. The performance described in this study was solar and thermal coefficient of performance. The results showed that both coefficients of performance decrease with the increase of solar collector area, and strongly depends on the operating temperatures considered [23]. The effect of solar collector area and its configuration, solar total irradiation on system's performance was studied by Chekirou et al. [24]. They concluded that both the COP and cooling capacity decrease when solar collector area is increased while the utilization of TIM for collector insulation shows best results then the double and single glazed configurations. Furthermore, COP also increase when the total solar irradiance is increased. Chua et al. [25] developed a transient model for tow bed silica gel adsorption chiller. He discussed the effect of switching and cycle time on the chiller performance. The results showed that a maximal COP of 0.56 can be attend by a chosen 450 s a cycle time. Moreover, a 11% increase in COP can be achieved by a 0.4% reducing in maximal cooling capacity. Tubreoumya et al. [26] used a dynamic modelling for simulation of an adsorption solar refrigeration system with silica gel -water as working pair. They analyzed the influence of the adsorbate/adsorbent working pairs, the solar flux, the ambient temperature on the adsorption and desorption process. Liu et al. [27] evaluated experimentally the effect of adsorption time on the performance of solar adsorption cooling system using silica gel -water as working pair, in which the results showed that the optimal COP was 0.258 for an adsorption time of 45 min. In addition, a comparison between two working pairs: silica gel to the SAPO-34 zeolite was made. Ji et al. [28] designed, analyzed and optimized a large-diameter aluminum-alloy finned-tube adsorbent bed collector for enhancing the heat transfer and reducing the uneven temperature distribution in the collector/adsorber. The adsorbent bed efficiency was improved between 31.64% and 42.7%, the maximum COP was 0.122 and maximum daily ice-making can achieve 6.5 kg. The choice of the adsorbent / adsorbate pairs appeared essential and decisive on the performance of the system [21, 27, 29].

From literatures above, it can be found that a good

improvement of technical problem of solar adsorption cooling systems can be brought. Hence, high cooling capacity, coefficient of performance and adsorption chiller temperature can be achieved by a good analyzing of the influence of all type of parameters theoretically, then approve it experimentally in manufactures.

In view of this, a thermodynamic model is proposed to evaluate the solar adsorption cooling system based on the typical basic cycle. The method proposes a study of the influence of thermodynamic cycle parameters and the working pair at the same time on the coefficient of performance.

In this paper, thermodynamic results were presented to see the effect of coefficient of performance as a function of the pressure and temperature operating parameters and compared for two pairs chosen AC / methanol and Zeolite / water and that for a solar refrigeration system at conventional adsorption.

2. SYSTEM DESCRIPTION AND WORKING PRINCIPAL

The studied system is a solar adsorption refrigerator in its simplest form, the schematic diagram of which is shown in Figure 1. It has been shown in detail about the various components of a solar adsorption refrigeration system as well as the working principle in Ref. [30]. A solar adsorption refrigerator based on the basic adsorption refrigeration cycle does not require any mechanical or electrical energy, just thermal energy, and it operates intermittently according to the daily cycle [8].

The basic cycle process of adsorption solar refrigeration systems is as follows:

- 1-2: Isosteric heating
- 2-3: Isobaric heating
- 3-4: Isosteric cooling
- 4-1: Isobaric cooling

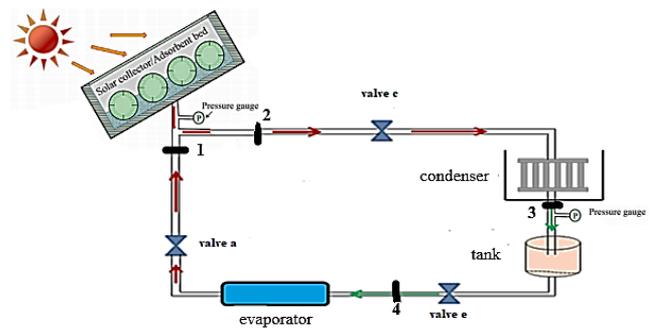


Figure 1. Schematic diagram of the solar adsorption refrigeration system

The cycle begins at point 1 (Figure 2), when the system is at the adsorption temperature T_a and at a low pressure P_e (evaporation pressure), but the concentration of the refrigerant is maximum X_{max} . The adsorber receives a quantity of thermal heat Q_{d1} which increases the pressure and temperature along the isosteric line 1-2 (at constant concentration). At point 2, the heating continues and by increasing the temperature and desorption begins, the generation of steam occurs receiving a quantity of heat Q_{d2} the pressure remains constant along the isobar line 2-3 while the concentration decreases to X_{min} . the vapor generated is liquefied by the condenser following the isosteric line 3-4 releasing a quantity of heat Q_{cd} at a constant

concentration X_{\min} and at a condensing temperature T_c . During transformation 4–1, the condensed refrigerant following the isosteric line 3–4 releasing a quantity of heat Q_{cd} at a constant concentration X_{\min} and at a condensing temperature T_c . During transformation 4–1, the condensed refrigerant flows into the evaporator and the pressure decreases to the evaporating pressure P_e and the adsorption phase occurs by absorbing a quantity of heat Q_{ev} bringing the vapor back to liquid and producing the effect of cold. The evaporated refrigerant flows to the adsorber to be adsorbed and accumulated causing its concentration to increase to X_{\max} at point 1 and is cooled to the adsorption temperature T_a and the cycle begins again.

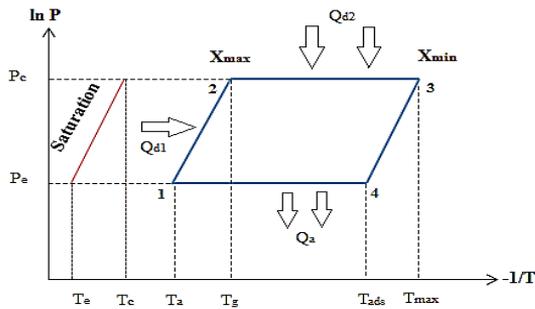


Figure 2. Theoretical cycle of the adsorption solar refrigeration system (Clapeyron diagram)

3. THERMODYNAMIC STUDY

The refrigeration capacity, the heating capacity and the coefficient of performance are given by Lu et al. [31] in the Eqns. (1) to (3).

$$Q_e = \dot{m}_{ch} c_w (T_{ch,i} - T_{ch,o}) \quad (1)$$

$$Q_h = \dot{m}_h c_w (T_{h,i} - T_{h,o}) \quad (2)$$

$$COP = \frac{\dot{m}_{ch} c_w (T_{ch,i} - T_{ch,o})}{\dot{m}_h c_w (T_{h,i} - T_{h,o})} \quad (3)$$

For constant physical properties of fluids, the mass enthalpy is defined:

$$\Delta h = cp(\Delta T) \quad (4)$$

The expression of the quantity of heat exchanged in this case by the adsorber, the condenser and the evaporator are expressed as follows:

3.1 Adsorber / condenser

According to the theoretical thermodynamic cycle of adsorption solar refrigeration systems, the generation of vapor from the liquid state of the working fluid occurs in two different phases.

3.1.1 Isosteric heating

The adsorber receives a quantity of solar energy necessary for heating the adsorbent / adsorbate pair Q_{d1} expressed by:

$$Q_{d1} = \dot{m}_d (h_2 - h_1) \quad (5)$$

3.1.2 Isobaric heating

In this phase begins the generation of steam (desorption), the required energy Q_{d2} is:

$$Q_{d2} = \dot{m}_c (h_3 - h_2) \quad (6)$$

3.2 Evaporator

During the evaporation phase, the refrigerant which is the adsorbate in the case of the adsorption refrigeration system, passes from the liquid state to the vapor state by absorbing a quantity of heat from the medium to be cooled Q_{ev} corresponds to:

$$Q_e = \dot{m}_e (h_1 - h_4) \quad (7)$$

3.3 System performance equation

The expression of the COP will be defined as follows:

$$COP = \frac{Q_e}{Q_g} \quad (8)$$

Within our case Q_g is given by:

$$Q_g = Q_{d1} + Q_{d2} \quad (9)$$

By replacing (1) and (2) in (5):

$$Q_g = \dot{m}_d (h_2 - h_1) + \dot{m}_c (h_3 - h_2) \quad (10)$$

The final expression of the coefficient of performance becomes:

$$COP = \frac{\dot{m}_e (h_1 - h_4)}{\dot{m}_d (h_2 - h_1) + \dot{m}_c (h_3 - h_2)} \quad (11)$$

4. WORKING CONSTRAINTS

4.1 Hypotheses

In order to have an agreement between the chosen model and the considered unit, certain assumptions were imposed.

We consider that there is no heat loss to the outside environment.

- All the liquid present in the adsorber is evaporated (desorption) as well as the condensate stored in the container is assumed to be completely evaporated (adsorption).
- The flow rate of the fluid in each phase is assumed to be constant.
- The opening and closing of each valve are done at the end of each phase.

4.2 Operating parameters

Condensation and evaporation pressure: literature shows that condensation takes place at a pressure of 145 mbar to 216 mbar, while adsorption takes place at a pressure of 90 mbar to 160 mbar [18, 24].

Our work consists in varying the pressure value in this interval to see the effect of condensing pressure on the COP

and that for the two couples chosen.

Temperatures: the operating temperatures were chosen such that they are close to those found in the experimental units seen in the literature [14, 16].

The objective of this study is to investigate the COP variation as a function of operating temperatures and pressure as well as a comparative profitability study between the two pairs chosen: AC / methanol and zeolite / water.

4.3 Data table

The data required for the calculation software are presented in the Table 1 below:

Table 1. Calculation data

Symbol	Parameter	Value
\dot{m}_c	Mass flow rate of condensate	3.7 m ³ /h [14]
\dot{m}_d	Desorption phase mass flow	1.6 m ³ /h [14]
\dot{m}_e	Evaporation phase mass flow	2 m ³ /h [14]
P_c	Condensing pressure	0.21676 bar [24]
P_e	Evaporation pressure	0.02872 bar [24]
T_a	Adsorption temperature	16°C [16]
T_e	Evaporating temperature	-5°C [16]
T_g	Generation temperature	61°C [16]
T_{max}	Maximum heating temperature	82°C [16]

5. RESULTS AND INTERPRETATION

To facilitate the analysis of the effect of varying the operating parameters of different components of the solar adsorption refrigeration system on performance, a thermodynamic model was presented. Numerical analysis consists of obtaining the appropriate configurations and therefore making the improvements to the COP.

The simulations were conducted by using the EES (Engineering Equation Solver) software and certified by the laboratory of Telemen university. The method of solving the system equations which describes the thermodynamic cycle and the model is purely numerical and based on the residue method approved by the calculation software which mean that the number of equations must equal to the number of variables and takes into consideration the thermodynamic adsorption cycle presented by the pressure and temperature parameters at each point of the diagram (Figure 2) and from there the quantities of heat exchanged can be determined and represented as a function of the mass enthalpy at this point. by knowing the thermodynamic parameters at each point of the cycle and the diagram (Figures 1 and 2), the software can determine the associated amount of heat then use it in the thermodynamic equations describing the performance of the system. And by varying each time the thermodynamic parameters of the cycle and even the working pair, we conduct to the results obtained.

In this study, we respectively discuss the effect of: (1) the maximum temperature T_{max} (2) the evaporation temperature T_e (3) the generation temperature T_g (4) the condensing pressure P_c as well as the choice of the couple adsorbent / adsorbate on the COP. Calculation data is shown in Table 1.

5.1 Model validation

The values of the coefficient of performance COP as a function of the maximum temperature reached during the

heating of the adsorption bed for the AC / methanol couple and those calculated by Douss & Meunier [16] are presented in Table 2. The figure shows a reasonable agreement between the results although the COP shows a slight difference, which can be a consequence of not taking into account the thermal losses present in each phase and the difference between the operating conditions taken in each model.

Table 2. The COP calculated by the model and by Douss & Meunier [16]

T_{max} °C	COP_{model}	$COP_{douss\&meunier}$
70	0.496	0.49
75	0.417	0.5
80	0.359	0.51
90	0.281	0.51
110	0.195	0.49
130	0.149	0.47

5.2 Effect of generation temperature

The effects of the generation temperature T_g on the coefficient of performance are shown in Figure 3. From the figure, it is noticed that the COP increases with the increase in the generation temperature and that for the two pairs used AC / methanol and zeolite / water. The reason is that the mass of the adsorbate generated is proportional at the generation temperature, in fact, increasing the generation temperature ensures better heat transfer performance at the adsorption bed level, which gives a greater amount of adsorbed mass and subsequently an increase in COP.

In addition, it is found that the change in COP as a function of the generation temperature is clearly different in the two cases of the pair type. The COP varies rapidly with the generation temperature in the case of the AC / methanol pair and reaches a maximum COP of 0.45 at $T_g = 80^\circ\text{C}$. on the other hand, in the case of the zeolite / water pair, the COP varies slowly and reaches a maximum value of around 0.15.

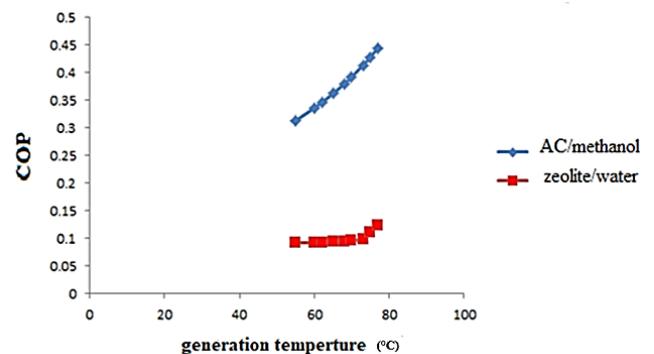


Figure 3. Effect of the generation temperature T_g and type of the pair on the COP

5.3 Effect of evaporating temperature

Figure 4 shows the effect of varying the evaporating temperature T_{ev} on the performance of the system. As can be seen in the figure, the COP decreases as the evaporating temperature increases. In addition, the COP in the case of the AC / methanol pair decreases rapidly in comparison with the zeolite / water pair. In the first case the COP reaches 0.09 at $T_{ev} = 10^\circ\text{C}$ and 0.01 in the second case for the same temperature. The results also show that the AC / methanol pair

is more profitable in comparison with the zeolite / water pair. In the first case the COP reaches its maximum value of 0.35 at $T_{ev} = -5^{\circ}\text{C}$ while in the other case the maximum value of COP is of the order of 0.1 for the same evaporation temperature.

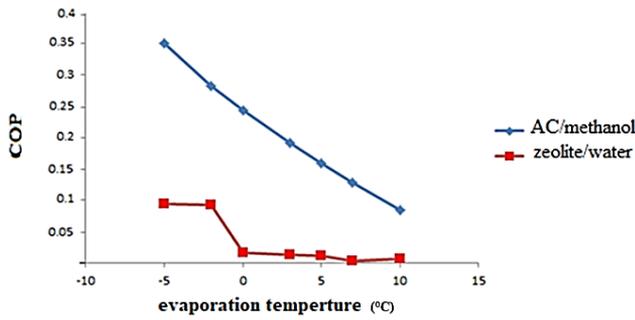


Figure 4. COP variation as a function of the evaporation temperature T_{ev} and the working pair type

5.4 Effect of the maximum temperature

A number of simulations have been carried out by varying the temperature of the maximum adsorption bed during the heating phase. Figure 5 shows the results for the two types of couples used. The figure suggests that the COP decreases when the maximum heating temperature increase. the figure also shows that the optimum COP reached is 0.49 in the case of the AC / methanol couple for a temperature of 70°C and 0.093 in the case of the zeolite / water couple. As with high heating temperatures, the COP decreases slower in the second case, reaching lower COPs.

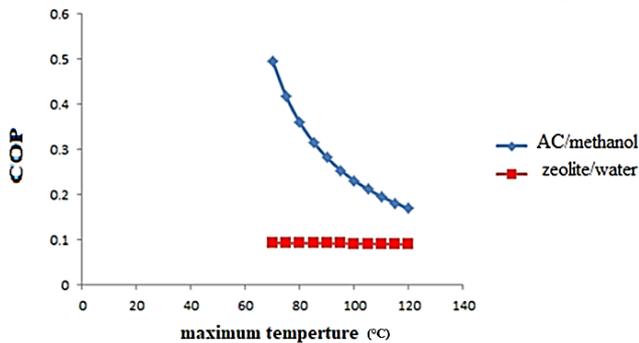


Figure 5. Variation of COP with maximum temperature T_g and the working pair type

5.5 Effect of condensing pressure

Figure 6 shows the variation in the effect of condensing pressure on the coefficient of performance. The results showed that the COP is slightly affected by the variation of the condensing pressure between 100 mbar and 270 mbar. This corresponds to a maximum COP of 0.346 in the case of the AC / methanol pair and 0.0972 in the case of the zeolite / water pair. Another thing can be seen in the figure is the influence of adsorbent / adsorbate pair type. This is present in this study with the use of the zeolite / water and AC / methanol pair, the latter seems to be the most favourable given the high values of COP given in each simulation under such imposed operating conditions of pressure and temperature and with this type of system and these components illustrated above. In addition, the profitability of the adsorbent / adsorbate couple can be

affected by the components of the solar adsorption system used and the operating conditions and the incident solar flux.

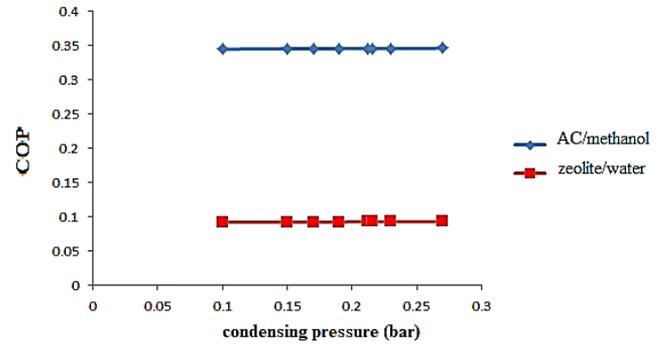


Figure 6. Effect of condensing pressure P_c and the working pair type on the COP

6. CONCLUSIONS

The effects of variations in the operating parameters of a refrigeration system based on AC / methanol and zeolite / water pairs is studied using a thermodynamic equilibrium model describing the amount of heat exchanged in each component of the solar adsorption refrigeration system.

The following conclusions can be drawn:

- The performance of the system in terms of COP varies almost linearly with the generation temperature T_g . The coefficient of performance increases remarkably if T_g is increased.
- The COP decreases with the increase in the evaporating temperature T_e for fixed operating parameters. A similar effect is observed when the maximum heating temperature T_{max} is increased.
- The condensation pressure does not present a determining factor in this study because the COP is slightly affected by its evolution and it is observed that the two pairs used AC / methanol and zeolite / water give the same variation while the effect was different. which appears in a COP of 0.346 in the case of the AC / methanol couple and 0.0972 in the other case.
- This study has shown that a solar adsorption refrigeration machine operating with the AC / methanol pair is more profitable than a machine operating with the zeolite / water pair, which justifies the wide use and commercialization of this pair in this field in the face of other.

This study evaluated the direction of variation of COP as a function of the operating parameters with a comparison between the two pairs used in this adsorption solar refrigeration system and their effects on performance, which leads to an improved system with a COP comparable to values reported in the literature. These results are therefore useful for further research into performance improvements in this area and with this type of systems.

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NOMENCLATURE

CP	specific heat, J. kg ⁻¹ . K ⁻¹
COP	coefficient of performance
h	specific enthalpy, kJ.kg ⁻¹
\dot{m}	mass flow rate, kg.s ⁻¹
P	Pressure, bar
Q	heat, kW
T	temperature, °C
X	concentration, kg adsorbate/kg adsorbent

Subscripts

a	adsorption
c	condensation
Ch	adsorber
i	In
e	evaporation
g	generation
min	minimum
max	maximum
o	out
w	water