COBEM-2017-1980
THERMOSYPHON APPLIED AS THERMAL RESERVOIR TO CHEMISORPTION CHILLERS

Marcos Vinício Oro
Federal University of Santa Catarina, Mechanical Engineering Department, Laboratory of Combustion and Thermal Systems Engineering - LabCET, Florianópolis, SC, Brazil
oro@labcet.ufsc.br

Rogério Gomes de Oliveira
Federal University of Santa Catarina, Department of Energy and Sustainability, Laboratory of Applied Thermal Science, LABCITEA, Araranguá, SC, Brazil
rogerio.oliveira@ufsc.br

Edson Bazzo
Federal University of Santa Catarina, Mechanical Engineering Department, Laboratory of Combustion and Thermal Systems Engineering - LabCET, Florianópolis, SC, Brazil
e.bazzo@ufsc.br

Abstract. *Waste heat from a device or a process can be used to produce cooling power when integrated with sorption refrigeration systems. Hence, we analyzed through numeric simulation the thermal energy integration between a chemisorption chiller and a generic waste heat source by a two-phase closed thermosyphon, which acted as thermal reservoir to reduce temperature drop in the chiller heating fluid and also heat fluctuations delivered by the waste heat device or process. The chiller mathematical model assumed that ammonia was the refrigerant and NaBr impregnated in expanded graphite was the adsorbent, and it was validated by experimental results. Water was considered as working fluid for the thermosyphon. Three levels in the flow rate of the heat transfer fluid (water at 70 °C) between the waste heat source and the thermosyphon were simulated: 5, 10 and 20 L/min. The system reached cooling powers of about 300 W and coefficient of performance of about 0.30. A power interruption of 5 min from the waste heat was also simulated, wherein the thermosyphon was able to provide the required heat for heating the chiller during the desorption stage, keeping in operation the system.*

Keywords: *heat recovery, refrigeration, sorption, thermosyphon, waste heat.*

1. INTRODUCTION

Sorption refrigeration has become popular in recent years for utilizing waste heat as the driving force, and can be divided into refrigeration by absorption and refrigeration by adsorption. This work is focused on adsorption systems with chemical sorbent (chemisorption); hence, absorption ones are not addressed.

An adsorption refrigeration system consists of at least one adsorbent bed (reactor), an adsorbate (refrigerant), a heat source, a heat sink, an evaporator, and a condenser. This system operates in a cyclic and semi-intermittent manner, in which the reactor goes through four distinct stages to complete a cycle, which are cooling, adsorption, heating and desorption.

Several studies have been performed concerting the use of waste heat to drive adsorption refrigeration systems from different sources as engine of fishing boats (Lu *et al*., 2007) or automobiles (Sharafian and Bahrami, 2014), and fuel cells (Oh *et al*., 2013). The use of solar collectors also have been considered to drive these devices (de Oliveira, 2011).

To our best knowledge, there is no research that took into account the mismatch between the use of a steady stated thermal source and the transient heat consumption by the adsorption chiller. Therefore, we analyzed the utilization of a thermal reservoir between a generic heat source and the adsorption chiller to guarantee the match between the steady state heat supplied and the transient heat consumption. Another benefit of the utilization of a thermal reservoir is the damping of the temperature variation of the heat transfer fluid which flows in a closed loop between the heat source and the adsorption chiller.

2. MATERIALS AND METHODS

A numerical model was used to simulate the integration between a thermal reservoir, a heat source and the adsorption chiller. The chiller had NaBr impregnated in expanded graphite as sorbent and ammonia as refrigerant. The thermal reservoir was a two-phase closed thermosyphon filled with water.

The scheme of the proposed system is shown in Fig. 1. Waste heat from a heat source is delivered to the thermosyphon, which heats reactor 1. When the pressure of the reactor 1 reaches the condenser pressure, ammonia is desorbed and goes to the condenser. At the same time reactor 2 is been cooled by a heat sink. When the pressure inside the reactor 2 reaches the evaporator pressure, the refrigerant evaporates in evaporator, producing cooling power, as it is adsorbed in reactor 2. After a predetermined time, the reactors switch their operation modes.

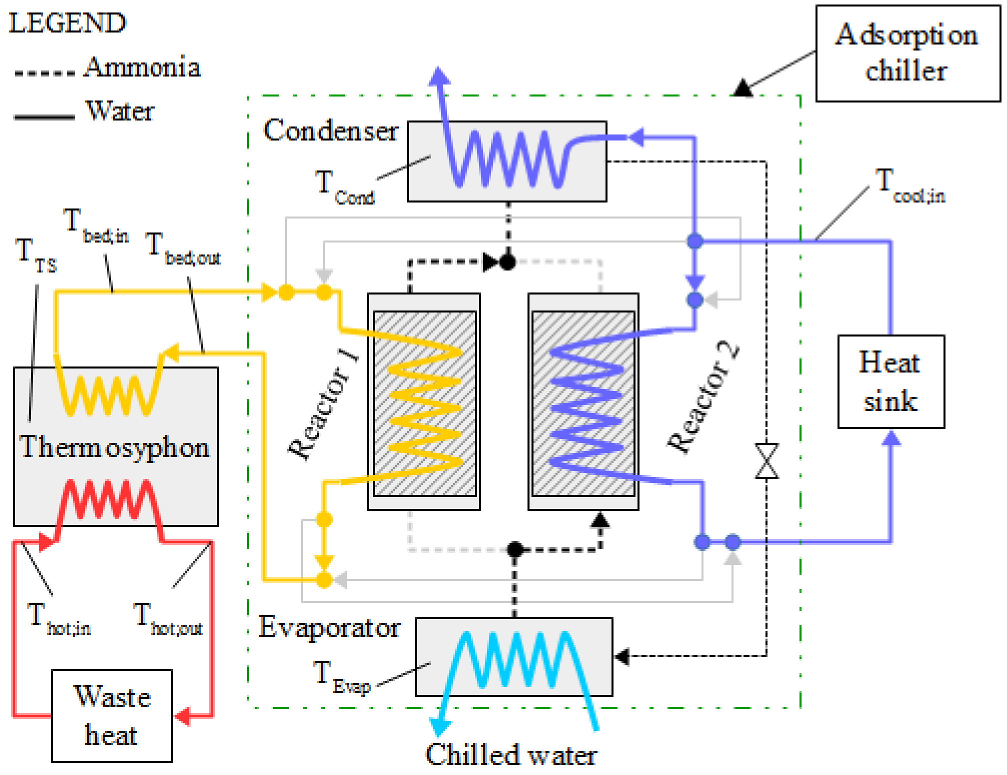

Figure 1: System schematic representation.

The thermosyphon is composed of a cylinder with two coils inside, one receiving the waste heat and other delivering the heat to the adsorption chiller. Thermosyphon features are presented in Tab. 1.

Table 1. Thermosyphon features.

Internal diameter [m]	Net volume [m³]	Water mass [kg]	Coil outer diameter [mm]	Coil thickness [m]	Coil length [m]
0.20	0.015	10	15	1	2

Each reactor of the chiller is a shell and tube heat exchanger, where the adsorbent bed is placed around the tubes and the heating/cooling fluid flows inside the tubes to supply/remove heat from the adsorbent. Annular fins were used along the tubes. Expanded graphite impregnated with NaBr was used as adsorbent and ammonia as refrigerant. The reactor dimensions are presented in Tab. 2, where $d_{o;shell}$ is the outer diameter of the shell, $d_{i;shell}$ the inner diameter of the shell, L_{bed} is the bed length, $d_{o;bed}$ the bed outer diameter, $d_{i;bed}$ the bed inner diameter, $d_{i;tube}$ the tube inner diameter, δ_{bed} the distance between two fins, δ_{fin} the fin thickness, and n_{bed} the number of beds contained in each reactor.

Table 2. Adsorbent reactor dimensions.

$d_{o;shell}$ [m]	$d_{i;shell}$ [m]	L_{bed} [m]	$d_{o;bed}$ [m]	$d_{i;bed}$ [m]	$d_{i;tube}$ [m]	δ_{bed} [m]	δ_{fin} [m]	n_{bed} [-]
0.210	0.195	0.500	0.037	0.017	0.015	3.0E-3	5.0E-4	19

The thermophysical properties and the parameters for the reaction between ammonia and the compound adsorbent used in the simulation can be found in Vieira *et al.* (2016) for the expanded graphite mass fraction in the compound adsorbent of 0.35.

The Biot number was estimated somewhat about 0.1 inside the adsorbent, so it is reasonable considering a lumped formulation. Therefore, the governing equation of the adsorbent bed temperature, T_{bed}, inside the reactor is

$$C(x)\frac{dT_{bed}}{dt} = 5.25 N_{NaBr}\,\Delta H_r\,\frac{dx}{dt} + \frac{q}{V_{bed}\,n_{bed}} \tag{1}$$

where the first term on the right side represents the heat released or absorbed during the adsorption or desorption stages, respectively, whereas the second term represents the heat exchanged between the bed and the working fluid per unit of bed volume. N_{NaBr} is the number of moles of salt per m³ of composite sorbent, V_{bed} the bed volume, ΔH_r the reaction enthalpy and dx/dt the conversion rate of the chemical reaction, which is presented in Vieira *et al.* (2016). On the left side, C(x) represents the volumetric heat capacity of the bed, which takes into account metal parts, sodium bromide, expanded graphite and ammonia.

The cooling power (*CP*) delivered from the adsorption chiller is

$$CP = \frac{\sum_{i=1}^{i_{cool}} \left[\dot{m}_{NH3}\,\Delta t\left[h_{lv;NH3} - c_p\left(T_{cond} - T_{evap}\right)\right]\right]_i}{t_{cool}} \tag{2}$$

where $\dot{m}_{NH3}$ is the mass flow rate of ammonia, $h_{lv;NH3}$ is the enthalpy of vaporization, T_{cond} is the saturation temperature of ammonia evaluated at the condenser pressure, T_{evap} is the saturation temperature of ammonia evaluated at the evaporator pressure, and t_{cool} is the length of time since the beginning of the cooling stage. Also, Δt represents the time step considered in the analysis for $i = 1$ to i_{cool}.

The corresponding coefficient of performance (COP) is calculated as

$$COP = \frac{CP}{q_{in}} \tag{3}$$

where q_{in} is the heating power delivered to the reactor during the desorption stage, calculated as

$$q_{in} = \frac{\sum_{i=1}^{i_{heat}} \left[\dot{m}\,c_p\left(T_{R;in} - T_{R;out}\right)\Delta t\right]_i}{t_{heat}} \tag{4}$$

where $\dot{m}$ is the mass flow rate of the heating/cooling fluid thought the reactor, c_p is the specific heat capacity, t_{heat} is the length of time since the beginning of the heating stage. Again, Δt represents the time step considered in the analysis for $i = 1$ to i_{heat}.

It was considered a waste heat delivered from an ideal heat source, which is able to deliver a hot water with constant temperature ($T_{hot;in}$).

Heat transfer coefficients were estimated from correlation available in the literature (Carey, 1992; Collier and Thome, 1996; Incropera *et al.*, 2007; Shah and Sekulić, 2003). The simulation was performed with MatLab® environment. The thermophysical properties of the compound adsorbent used in the model where taken from Vieira *et al.* (2016), as well as the kinetic and equilibrium parameters for the reaction between ammonia and the compound adsorbent, for the expanded graphite mass fraction in the compound adsorbent of 0.35. The following temperatures were assumed constant: $T_{hot;in}$ = 70 °C, $T_{cool;in}$ = 27 °C, T_{Cond} = 30 °C, and T_{Evap} = 10 °C, as location in Fig. 1. The flow rate of the heating/cooling fluid was 10 L/min. The flow rate of the heat transfer fluid between the waste heat source and the thermosyphon was considered in three levels: 5, 10 and 20 L/min.

3. RESULTS AND DISCUSSION

For a cycle time of 30 min and a flow rate of the heat transfer fluid between the waste heat source and the thermosyphon of 10 L/min, the main temperatures of the system are shown in Fig. 2a, which presents a half cycle of the system. Thermosyphon temperature (T_{TS}) drops in the beginning of reactor R1 heating, due the thermal load delivered by waste heat source is lower than the reactor heat consumption. This condition is reversed in a few minutes, and T_{TS} starts to rise. When the half cycle time is reached the desorption stage of the reactor R1 is concluded, then it is connected to the cooling fluid and goes to the adsorption stage to produce cooling power. At the same time, reactor R2 undergoes the opposite stages, first it delivers heat to the cooling fluid and produce cooling power, and after it receives heat from the thermosyphon. Under those conditions the chiller reached a COP of 0.250 and a cooling power of 279 W. As shown in Fig. 2b, from the point of view of the waste heat device, the thermosyphon attenuates the high heat consumption of the chiller, reducing the drop in $T_{hot,out}$.

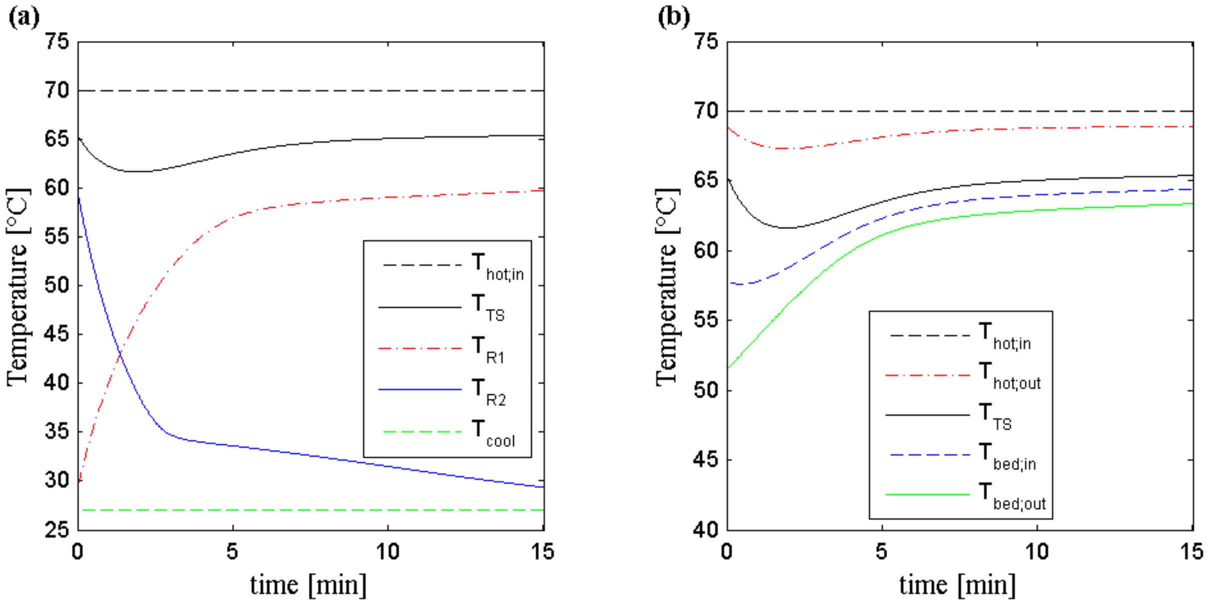

Figure 2: Temperature profiles: a) System temperatures; b) Temperatures behavior during desorption.

The system was also evaluated for cycle times in the range of 10 and 60 min, considering three levels of waste heat: water at 70 °C with 5, 10 and 20 L/min. Figure 3 shows the cooling powers and the COP reached in those cases. As can be seen, the higher the waste heat, the higher the cooling power and the COP. Another observation is the higher the waste heat, the lower the cycle time to reach the maximum cooling power. However, the COP is higher with longer cycle times. Therefore, the operating point should be defined depending on the variable to be maximized. It is also shown at high cycle times the increase in waste heat had little influence on COP.

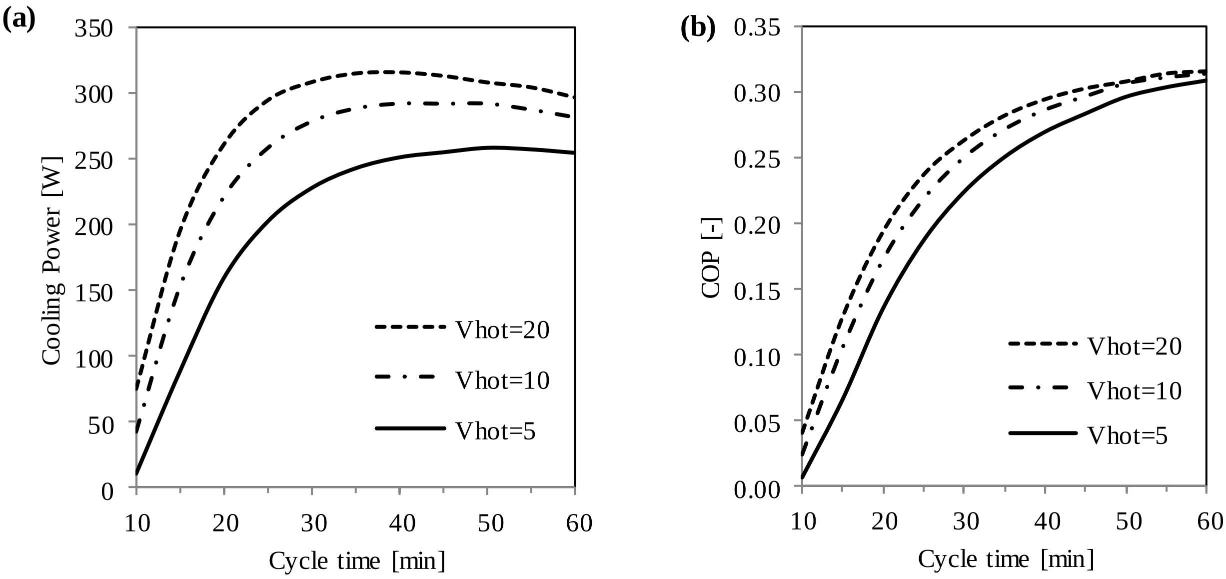

Figure 3: System behavior for different cycle times: a) Cooling powers; b) COP.

Commonly, the chiller performance is presented taking into account the adsorbent mass, i. e., a specific cooling power, which is presented in Fig. 4. Those results had similar order of another adsorption working pairs, as silica gel/water, zeolite/water and activated carbon/methanol (Wang and de Oliveira, 2006).

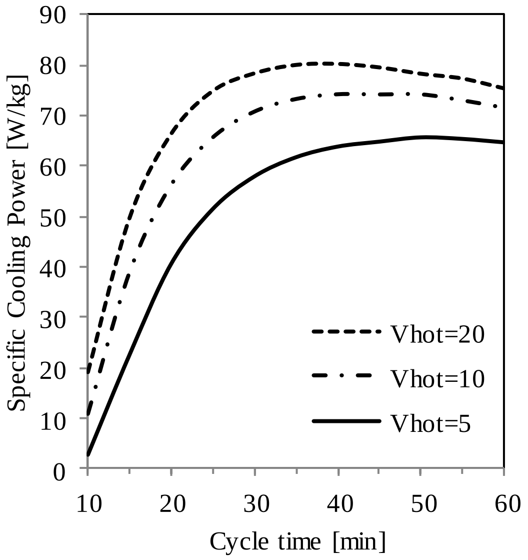

Figure 4: System temperatures behavior.

An interruption of the waste heat flow rate was simulated to assess the system behavior. Figure 5 shows temperature profiles of the system during a half cycle time of 25 min, i. e., cycle time of 50 min. The waste heat level was 10 L/min. The interruption of the waste heat starts in the tenth min and ends in the fifteenth min of every half cycle, corresponding to 20 % of the cycle time. During this period the thermosyphon was responsible for provide the required heat to the reactor, making possible the operating of the chiller, despite a little drop in the reactor temperature (T_{R1}). As expected, the interruption caused a little drop in the refrigeration performance, wherein was obtained COP = 0.299 and CP = 271.5 W. If compared with a continuous waste heat, it represents reduction of about 2 % for COP and 8 % for cooling power.

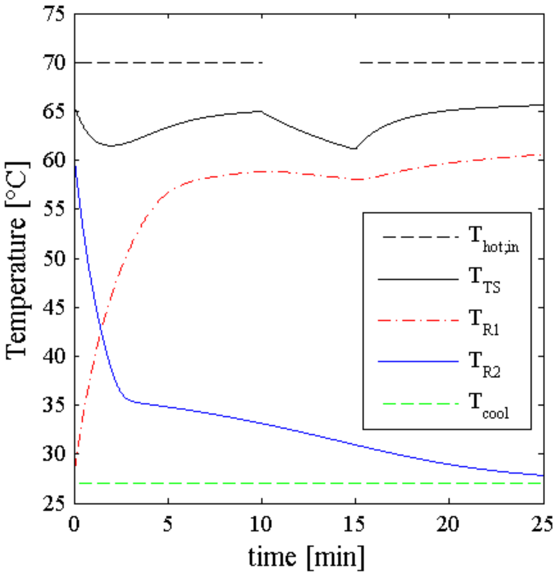

Figure 5: System temperatures behavior with a waste heat interruption.

4. CONCLUSIONS

A two-phase thermosyphon was used as thermal reservoir between a waste heat device and a chemisorption chiller. The thermosyphon was able to keep in operation the chiller without receiving heat from the waste heat device. Therefore, the use of the thermosyphon is essential when there is a transient waste heat source, even with a cyclic interruption, besides it attenuates the temperature drops due the high heat consumption in the beginning of each cycle of the chemisorption chiller.

5. ACKNOWLEDGMENTS

This work was supported by scholarship from CAPES.

6. REFERENCES

Carey, V.P., 1992. *Liquid-Vapor Phase-Change Phenomena: An Introduction to the Thermophysics of Vaporization and Condensation Processes in Heat Transfer Equipment*. Hemisphere Publishing, Washington.

Collier, J.G. and Thome, J.R., 1996. *Convective Boiling and Condensation*. Clarendon Press Oxford, New York, 3rd edition.

de Oliveira, R.G., 2011. "Solar Powered Sorption Refrigeration and Air Conditioning", in: Larsen, M.E. (Ed.), *Refrigeration: Theory, Technology and Applications*. Nova Science Publishers, New York, p. 205.

Incropera, F.P., DeWitt, D.P., Bergman, T.L. and Lavine, A.S., 2007. *Fundamentals of heat and mass transfer*. John Wiley & Sons, New York, 6th edition.

Lu, Z.S., Wang, R.Z., Li, T.X., Wang, L.W. and Chen, C.J., 2007. "Experimental investigation of a novel multifunction heat pipe solid sorption icemaker for fishing boats using CaCl2/activated carbon compound–ammonia". *International Journal of Refrigeration,* Vol. 30, p. 76.

Oh, S.T., Saha, B.B., Kariya, K., Hamamoto, Y. and Mori, H., 2013. "Fuel cell waste heat powered adsorption cooling systems". *International Journal of Air-Conditioning and Refrigeration,* Vol. 21, p. 1350010.

Shah, R.K. and Sekulić, D.P., 2003. *Fundamentals of Heat Exchanger Design*. John Wiley & Sons, New Jersey.

Sharafian, A. and Bahrami, M., 2014. "Assessment of adsorber bed designs in waste-heat driven adsorption cooling systems for vehicle air conditioning and refrigeration". *Renewable and Sustainable Energy Reviews,* Vol. 30, p. 440.

Vieira, L.W., Lima, B.C. de, Generoso, D.J. and de Oliveira, R.G., 2016. "Determination of the thermal and kinetic parameters of desorption and adsorption of ammonia in sodium bromide" (in Portuguese). In: *Anais da 6ª Conferência Internacional de Materiais e Processos para Energias Renováveis*. Porto Alegre, Brazil.

Wang, R.Z. and de Oliveira, R.G., 2006. "Adsorption refrigeration-An efficient way to make good use of waste heat and solar energy". *Progress in Energy and Combustion Science*, Vol. 32, p. 424.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.