

The analysis of the adsorption cooling subsystem used in a MCCHP system with Stirling engine like prime mover

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Abstract— The paper presents an analysis of the cooling subsystem used in a trigeneration system with Stirling engine like prime mover. The advantages and disadvantages of the adsorption cooling are presented, related to absorption cooling system. The schematic thermal diagram of the trigeneration system is presented. Because the low efficiency of the Stirling engine, a thermally activated cooling subsystem is used. A theoretical thermodynamic analysis of the adsorption cooling system is presented. The influence of the operating conditions on performance of the adsorption cooling is presented.

Keywords— thermally activated chiller, adsorption cooling, Stirling engine, trigeneration, thermodynamic analysis

I. INTRODUCTION

TRIGENERATION can be considered as a special case of the application of cogeneration systems where a fraction of the shaft work or residual heat is used for running a refrigeration system. Although the basic theories and technologies for the power generation, heat exchange, and absorption refrigeration are not new, combining them together is a quite new idea. The concept of trigeneration comes to use is only at the mid-1990s. Some investigations have been conducted by a number of researchers, which showed an encouraging effect on raising the energy efficiency and reducing greenhouse gases emissions. The results from the investigations show that trigeneration have the advantages over single electricity generations and cogenerations (Combined heat and power): the total energy efficiency is higher; the emissions of CO₂ and the other waste gases are lower; and it has more choices for useful energy outputs, i.e., electricity, heat and cooling/refrigeration. The results show that trigeneration has both of the economic and environmental merits.

Trigeneration systems tend to become a good solution for energetic needs for a building, especially if the general grid is difficult to be accessed. In our university a project for a guest house with a trigeneration system is developed. The prime mover is a Stirling engine with pellets. Because the electrical efficiency of a Stirling engine with solid fuels is very low (about 20 %), we decided to use a thermally activated chiller like cooling system. Maximum thermal loads of the building

are calculated. All the components system are commercially available.

II. TRIGENERATION SYSTEM PRESENTATION

In figure 1 a schematic diagram of the system is presented. The paper refers only to thermal loads. The Stirling engine and the central heating boiler are activated by pellets burning. To supply the total heating load of the building in the cold period, the system contains a central heating boiler which use pellets like combustible too. The system contains some solar collectors, because in Galaţi area the solar energy have a good potential and the insulation is maximum when the cooling load of the building is maximum. Because the return cooling circuit of the Stirling engine must be less than 40°C and the water in the buffer must have at least 65°C for a good efficiency of the adsorber cooling chiller, there is a supplementary air cooler in the cooling circuit of the Stirling engine (component 8 in Fig.1). In the warm period the heating load is necessary to obtain the domestic hot water and the hot water which represents the heat source to activate the adsorption cooling system. In the cold period, the heating load is necessary to obtain the domestic hot water and to supply the heat load of the building. The trigeneration system structure contains a buffer with two coils. That thermal buffering has a dramatic effect on the behaviour of the trigeneration device performance. The device efficiency is improved, while on/off cycling is significantly reduced.

The cooling component is an adsorption chiller. It is environmentally friendly because it employ natural refrigerant. In addition, the adsorption chiller can enhance the efficiency of energy system if it is driven by waste heat or by renewable energy. Because of the increased attention to the ozon layer depletion and the global warming, the adsorption refrigeration has been intensively studied for the last time. The adsorbent-adsorbate pair for air conditioning purpose are zeolite-water, activated carbon-ammonia, silicagel-water. Silicagel-water is suitable and useful pair for most applications under 100°C. In our project we will use an adsorption chiller produced by Sortech, having a cooling capacity of 15 kW.

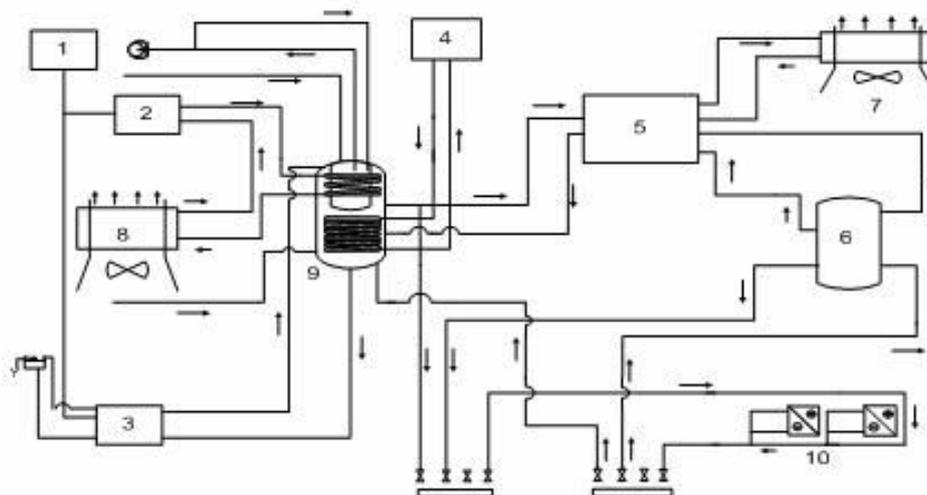


Figure 1. Schematic drawing of the trigeneration system.

1. Pellet box; 2. Stirling engine; 3. Hot water boiler; 4. Solar panels; 5. Adsorption chiller;
6. Cold water tank; 7. Air cooler; 8. Air cooler; 9. Thermal buffer; 10. Fancoils.

III. ADSORPTION COOLING SYSTEMS

A. Comparative Analysis of Thermally Activated Chillers

Because Stirling engine has a poor electrical efficiency, in a micro combined cooling-heating-power system (mCCHP) it is necessary to use a thermally activated chiller.

Silica-gel-water adsorption systems, LiBr-water absorption systems are major thermally activated air conditioning systems under consideration. Compared to the vapor compression refrigeration cycle, they have the advantage of being able to be driven by industrial waste heat and other low grade heat such as solar energy, and they also use environmentally friendly refrigerants like water. The major drawbacks associated with heat activated cooling systems are their low COP and low specific cooling power (SCP). However, the recent rise in oil and gas prices and the increasing availability of industrial waste heat and inexpensive flat plate solar collectors is making these systems more and more competitive when compared to conventional vapor compression refrigeration systems.

Both thermally activated cooling system has advantages and disadvantages.

Although extensive experimental and simulation work has been done to analyze each thermally activated system individually or to compare its performance with that of the vapor compression system, few attempts have been made to compare their relative quantitative and qualitative performances. The reason behind this is the distinctive nature of all these systems, which makes it relatively difficult to compare their performance. The distinction is mainly in the type of sorbent, i.e. generally a solid in adsorption and a liquid in absorption systems, and the type of sorption process – chemisorption in absorption systems and physisorption in

adsorption systems

Lithium-bromide technology has more experience from different sources and a good number of installations. But due to its basic Li-Br chemistry in general it has gained a much less than positive perception by operators, with many bad experience stories of crystallization available within the marketplace. Alternatively, with the stated advantages of silicagel adsorption, facilities will enjoy significant operating and energy cost advantages - causing silicagel adsorption to eclipse Li-Br absorption as the preferred method for reliable low temperature waste heat waste recovery.

Thermally driven absorption chillers have been effective, but have been burdened with significant maintenance and upkeep. Absorption chiller systems often depend on a corrosive solution of lithium bromide salt that tends to corrode the internal copper tubing and steel shell of the unit. Additionally, absorption chillers produce hydrogen gas as a by-product, requiring an expensive palladium cell inside the chiller unit to remove the hydrogen. The lithium bromide solution in absorption chillers also has phase state challenges and has a tendency to solidify within the system while operating. If the regeneration temperature becomes too hot or too cold, or the conditions change too rapidly for the system to adapt, the liquid salt will solidify and crystallize inside the chiller unit. Many installations of absorption units require a dedicated caretaker to maintain.

Conversely, adsorption chillers use municipal water as the refrigerant and solid silica gel as the desiccant. There are no CFCs or freons, no lithium bromide, and no ammonia. Not using these chemicals equates to no potential for hazardous material leaks, no aggressive corrosion, no chemical testing required, and no damage to upper-level atmospheric ozone. An adsorption chiller significantly reduces the maintenance and

upkeep costs by substituting the corrosive salt desiccant with a benign silica gel. Reliability and machine availability are significantly improved. Adsorption chillers have very few moving parts and do not require the maintenance and attention that the absorption chiller systems require. The heat extracted from the chilled water and the heat consumed from the hot water is directed into a cooling water system used to dissipate this energy. This heat dissipation may occur in a water system; water heat exchanger, a dry water tower or an evaporative

(wet) water tower.

Very little electric power is consumed running the chiller, generally about the same amount of electricity as a handful of old-fashioned incandescent light bulbs. The electric power used drives the internal process computer, a PLC (programmable logic controller), and the intermittent running of a fractional horsepower vacuum pump.

In Table 1 a comparison adsorption chiller versus absorption chiller is presented.

Table 1. Adsorption chiller vs absorption chiller

	Adsorption Chiller	Absorption Chiller
Refrigerant	water	water
Adsorbent/Absorbent	silicagel	lithium-bromide
Vacuum Pump	Yes (but operates 1 hour out of every 40)	Yes
Refrigerant Pump (Water)	Runs only when chiller unloads	Continuous
Absorbent Pump	not applicable /notrequired	Magnetic, continuous operation required
Automatic Valves	Butterfly Valves (simpler operation)	3 Way Control Valves
COP	0.7	0.7
Cooling Tower Size	Heat of rejection equals Cooling	Capacity plus amount of heat input
Corrosion	None	Strong
Crystallization	None	Yes! 1. On low temperature cooling water 2. On air leakage into the machine 3. On power loss/ failure of dilution Malfunction 4. On failure of a pressure-reducing valve
Warm up (Start)	0 to 7 minutes after long stop	Loss of Heat source - 30 min.
Dilution Cycle (Stop)	Not applicable	Yes 15 min.
Inhibitor	None required	Inhibitor with heavy metal
Chiller Life Expectancy	More than 30 years	7 to 9 years
Frequency of replacement of adsorbent or absorbent	Not necessary	Every 4 to 5 years
Heat Exchanger replacement	Not applicable	Should be considered due to corrosion
Required Hot Water Temperature	Operates down to 50°C (but no problem if temperature goes below this)	Shut down at 82.5°C or need back up heater to avoid crystallization
Input Condition of Cooling	Fluctuation is no problem. The lower the temperature, the higher the refrigeration capacity	Must be stable. Need 3 way-control valve to control between 25°C to 30°C.
Chilled capacity control	Built-in 7 step unloading	Need 3 way-control valve to bypass return water extra cost
Chilled Water Temp.	3°C is available as standard	88°C normal/ 5°C for experimental
Maintenance	Very minor service every 3 years 1. Vacuum pump oil level 2. Butterfly Valves Seat	Expect continuous service tasks & monitoring 1. Liquid analysis (replacement indication) 2. Pumps 3. Controls 4. Back Up Boiler 5. Air Leakage 6. Li-Br exchange 7. Heat exchanger replacement (corrosion)
Complexity	Simple - understandable mechanical operation of common valves and vacuum pump. Refrigerant is only tap water, so pipe or valve work is easy and without hazards.	Complex - Chemical operation which typical facility mechanics do not easily understand the chemical phenomena and its problems and required corrections.

Adsorption cooling technology is relatively new, clean and which can use heat sources of low heat potential. An adsorption cooling system is similar to the cooling system with mechanical vapor compression, except that the energy needed

by the compression process is provided by heat instead of mechanical work. Unlike the classic mechanical compression cooling, which requires a mechanical compressor, the adsorption cooling system uses a static thermally activated

sorbent layer. In this way the compression energy requirement drops to 90% over the energy needed to drive the mechanical compressor. The basic operating cycle of an adsorption cooling system consists of four thermodynamic transformations. A thermodynamic cycle of a basic adsorption cooling system on an isoster of an adsorbent-adsorbate pair is presented in Fig.2 [3]. An isoster of an adsorbent-adsorbate pair indicates the change of the constant amount of adsorbate pressure with respect to temperature. This thermodynamic process is a pressurisation at constant volume.

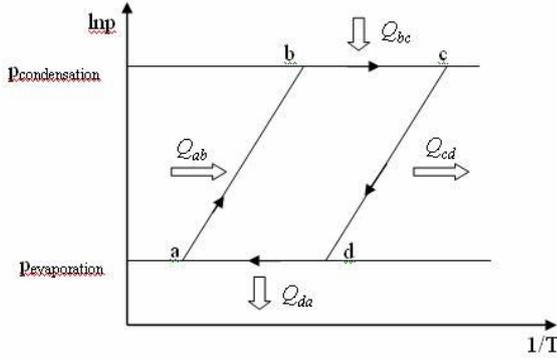


Figure 2. Thermodynamic cycle for the adsorption cooling system

The main steps of the cycle are:

- Isosteric heating a-b, during which the adsorber is isolated both from the evaporator and condenser. This is a pressurisation process at constant volume. The pressure inside the adsorber increases until reaching the condensation pressure by taking heat from an external source. This is a sensible heating process. The temperature bed is increased from T_a (which is the coolant temperature) to T_b (which is the condensing temperature):

$$Q_{ab} = \int_{T_a}^{T_b} (m_s c_{ps} + m_s c_{prw} C_b^d + m_{b,m} c_{pb,m}) dt \quad (1)$$

- Isobaric desorption b-c, during which the adsorber is connected to the condenser, allowing the refrigerant vapor to flow from the adsorber to the condenser, where condenses while the heating process continues. This is a desorption-condensation process at constant pressure. The condensation heat is absorbed by the cooling fluid. The heat transferred by heat source partly increase the temperature of adsorbate-adsorbent pair, partly causes the desorption process.

$$Q_{bc} = \int_{T_b}^{T_c} (m_s c_{ps} + m_s c_{prw} C_b^d + m_{b,m} c_{pb,m}) dt + \int_b^c m \Delta H_d dx \quad (2)$$

-Isosteric cooling c-d, during which the adsorber is isolated

both from the evaporator and condenser. This is a depressurization process at constant volume. The pressure inside the adsorber decreases until reaching the evaporation pressure. The temperature bed is decreased from T_c (which is the maximum temperature of the cycle) to T_d . The amount of heat which must be evacuated from the adsorbent bed is obtained from the equation:

$$Q_{cd} = \int_{T_c}^{T_d} (m_s c_{ps} + m_s c_{prw} C_b^a + m_{b,m} c_{pb,m}) dt \quad (3)$$

- Isobaric adsorption d-a, during which the adsorber is connected to the evaporator and isolated from the condenser. This is an adsorption-evaporation process at constant pressure. During the adsorption process, heat is released due to heat of adsorption. This generated heat is removed from the adsorbent bed to and the temperature will decrease T_a , which is the coolant temperature:

$$Q_{da} = \int_{T_d}^{T_a} (m_s c_{ps} + m_s c_{prw} C_b^a + m_{b,m} c_{pb,m}) dt + \int_d^a m \Delta H_a dx \quad (4)$$

The heat of evaporation, which causes cooling effect, is obtained from the relation:

$$Q_{evaporation} = Q_e = m(C_b^a - C_b^d) \Delta H_v + \int_{T_{cond}}^{T_{evap}} m(C_b^a - C_b^d) c_{p,w} dT \quad (5)$$

The heat of condensation is obtained from the relation:

$$Q_{condensation} = Q_c = m(C_b^a - C_b^d) \Delta H_v \quad (6)$$

The cooling effect occurs during the isobaric adsorption process d-a, when the refrigerant (chilled water) is evaporated from the silicagel bed. The system has the advantage of adsorbent material stored in the adsorber being able to soak a relatively large amount of refrigerant vapor at a low temperature and pressure.

The heating power consumed by the adsorption chiller, Q_h , is given by :

$$Q_h = \frac{\int_0^{\tau_{cycle}} \dot{m}_{hw} (T_{hw,in} - T_{hw,out}) dt}{\tau_{cycle}} \quad (7)$$

where τ_{cycle} is the refrigeration cycle period of the adsorption chiller.

The cooling capacity of the adsorption chiller, Q_c , is given by:

$$Q_c = \frac{\int_0^{\tau_{cycle}} \dot{m}_{chw} (T_{chw,in} - T_{chw,out}) dt}{\tau_{cycle}} \quad (8)$$

The specific cooling capacity, SCC, is defined as the cooling capacity per unit mass of the adsorbent:

$$SCC = \frac{Q_c}{m_s N} \quad (9)$$

where m_s is silicagel mass and N is number of adsorbent beds.

The COP of the cooling cycle is:

$$COP_{ref} = \frac{Q_e}{Q_{ab} + Q_{bc}} = \frac{Q_c}{Q_h} \quad (10)$$

The cooling effect may be varied by adjusting the temperature of the heat source.

In the above equations, the signification of the terms is:

m_s - adsorbent mass, kg;

c_{ps} - specific heat of the adsorbent, J/kgK;

c_{prw} - specific heat of the liquid refrigeration fluid, J/kgK;

C_b^d - water content of the adsorption bed in desorption process, kg/kg;

C_b^a - water content of the adsorption bed in adsorption process, kg/kg;

\dot{m}_h - hot water mass flow, kg/s;

c_{pw} - specific heat of the hot water, J/kgK;

T_h - hot water temperature, K;

ΔH_{ev} - latent heat of the cooling fluid, J/kg;

ΔH_{ad} - adsorption heat, J/kg.

B. Adsorption Cooling System Improvement

B.1. Multibed Adsorption Cooling

If there is one adsorbent bed, the cooling effect is not continuous. A first step in improving this adsorption cooling process is to obtain a continuous cooling by using minimum two adsorbent beds. These two adsorbent beds alternately execute the adsorption process. Before the adsorbent beds

change the processes, the switching process is usually carried out to make the pressure in the adsorbent beds closer to the connection targets. During the switching process, sensible heating and cooling of the adsorbent beds are carried out [10]. The continuous adsorption cooling cycle is presented in Fig.3 and Fig.4.

As is seen in Fig.4, the adsorbent bed 1, which support the desorption process, is cooled down by the cooling water. In the mean time, the adsorbent bed 2, which support the adsorption process, is heated up by the hot water [8].

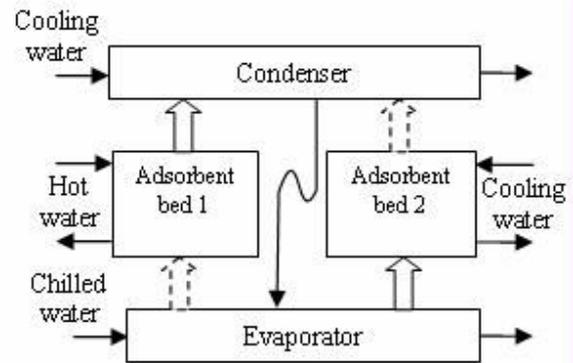


Figure 3. Adsorbent bed 1 in desorption process, adsorbent bed 2 in adsorption process

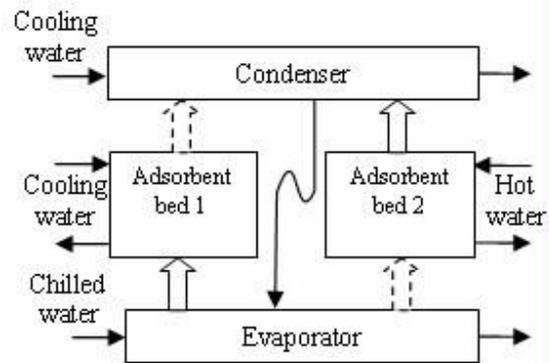


Figure 4. The switching process

So, there is no cooling effect during the switching process. Therefore, the excess switching time reduces the average cooling capacity of the cycle. The time chart of the adsorption chiller operation is presented in figure 5 [5].

Mode	M1	M2	M3	M4
Adsorbent bed 1	desorption	Switching (cooling)	adsorption	Switching (heating)
Adsorbent bed 2	adsorption	Switching (heating)	desorption	Switching (cooling)

Figure 5. The time chart allocation of the adsorption chiller operation

The cycle consists in four operational modes. The adsorption time is formed of the time length of the modes M1

and M3, while the switching time is formed by the time length of the modes M2 and M4. The sum of the time lengths of the four operational modes can be called the cycle time. The adsorption time affects the cooling performances of the chiller, because in this time the cooling effect is obtained [6].

. B.2. Uniform Temperature Adsorber Process

These systems consist of two or more adsorbers, operating with the same refrigerant, a single evaporator and a single condenser. A general view of the uniform temperature adsorber cycle is shown in Fig. 6. In this system, one of the adsorbers is preheated with rejection heat of another adsorber which is under the cooling process. The transfer of heat between the adsorbers is performed by a heat transfer fluid. The process continues until both adsorbers reach to the same temperature (e and f). After this period of heat recovery, one adsorber is heated by the external heat source (ec) while the other one is cooled by the external heat sink (fa) [12]. Although each adsorber follows exactly the same cycle as the basic adsorption heat pump cycle, the heat which is supplied to the total system decreases. This type of advanced cycle results in enhancement of the COP up to 50% [3]. Dous and Meunier [11] have proposed and made another alternative adsorption cycle. The proposed adsorption cycle consists of two cycles, a zeolite–water cycle for high temperature stage and an active carbon–methanol cycle for low-temperature stage. The heat which should be transferred to the active carbon–methanol cycle for isosteric heating and isobaric desorption processes is completely obtained from the zeolite–water cycle. The driving energy for zeolite–water cycle is supplied from an external heat source. The experimental COP for cooling was found as 1.06.

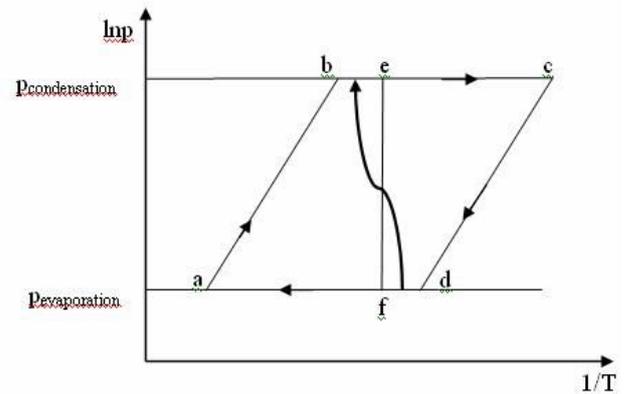


Figure 6. Thermodynamic cycle for the adsorption cooling system

. B.3. Thermal Wave Process

The system is composed of two or more adsorbers, a condenser and an evaporator. The working principle of a thermal wave process is shown in Fig. 7. The cycle consists of two adsorbers which are called as adsorber 1 and 2. A heat transfer fluid is circulated between the two adsorbers. While adsorber 1 is under cooling, the adsorber 2 is under heating process and vice versa. For the case shown in Fig. 6, the heat which is recovered from the adsorbent 1 is transferred to the heat transfer fluid. The heating of fluid is continued to desorption temperature by a heating system and then it is fed to adsorber 2 for the isobaric desorption process. After leaving of heat transfer fluid from adsorber 2, it is cooled by a cooler to be fed into the adsorber 1. Hence, the heat transfer fluid completes a cycle in the system. A reversible pump is used to change flow direction of heat transfer fluid for the reverse process, when the adsorber 2 is under cooling and adsorber 1 is under heating stage [3].

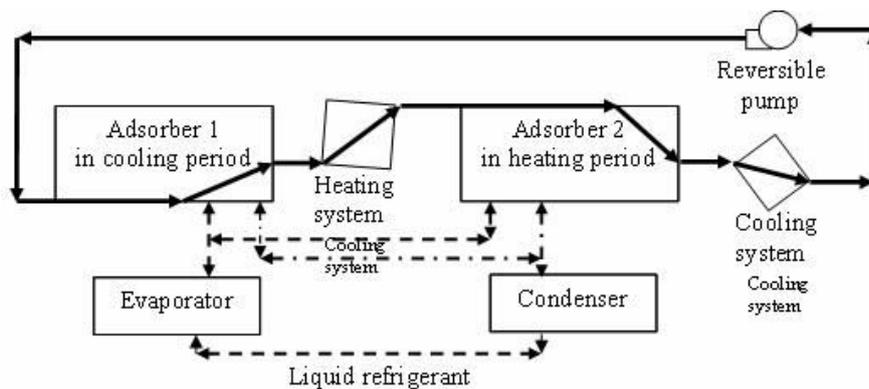


Figure 7. Working principle of an adsorption system with wave process

IV. THE INFLUENCE OF OPERATION CONDITIONS ON ADSORPTION CHILLER PERFORMANCE

To evaluate the adsorption chiller performances, we consider the characteristics of adsorption chiller manufactured by german company Sortech, with a nominal cooling capacity

of 15 kW.

The main variable have an major importance in performance characteristics of the adsorption chiller are considered: mass flow rate of working fluid, hot water temperature which activates the adsorption chiller and time adsorption cycle. When the mass flow rate of refrigerant is varied, the NTU of

adsorbent bed is changed, so the UA value of adsorbent beds kept constant. In figure 8 optimum half cycle time with the variation of mass flow rate is presented. The optimum switching time is about 10 % of the half time cycle for an optimum solution. When the mass flow rate will increase, the optimum half time cycle will decrease, because a higher mass flow rate produce a higher cooling capacity of the adsorption chiller. If the hot water temperature is increased, the cooling capacity will increase.

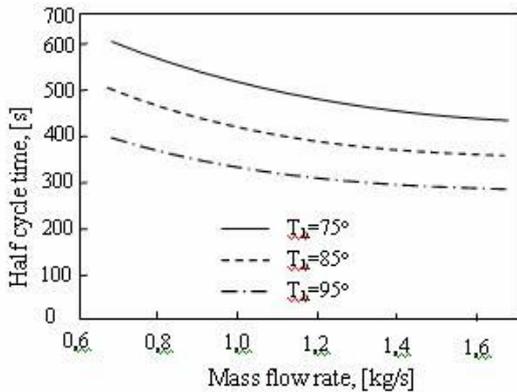


Figure 8. The influence of the mass flow rate on the optimum half cycle time

In figure 9 are presented the variations of SCC and COP in function mass flow rate, for different values for hot water temperature.

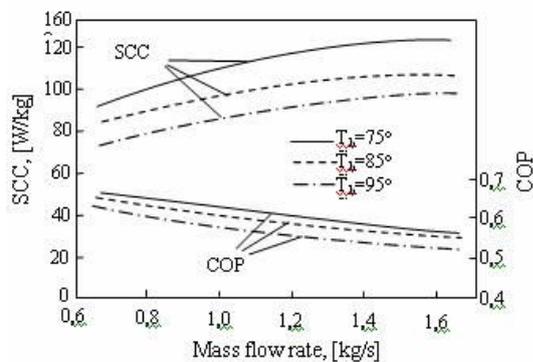


Figure 9. The influence of the mass flow rate on the SCC and COP

We can see that the SCC will increase when the mass flow rate and hot water temperature will increase, because of the increased cooling capacity of adsorption chiller. In the same time, COP will decrease, because of shorter half cycle time at the larger mass flow rate [7].

In Fig.10, Fig.11 and Fig.12 are presented characteristic diagrams for an adsorption chiller with a cooling capacity of 15 kW, when the cold water is circulated through fan coils, for two values of driving temperature. The cold water inlet/outlet temperatures are: 10°C/15°C. The following diagrams are meant to help estimate the adsorption cooling system performance that is to be expected for different operating conditions (re-cooling temperature, driving temperature) [1].

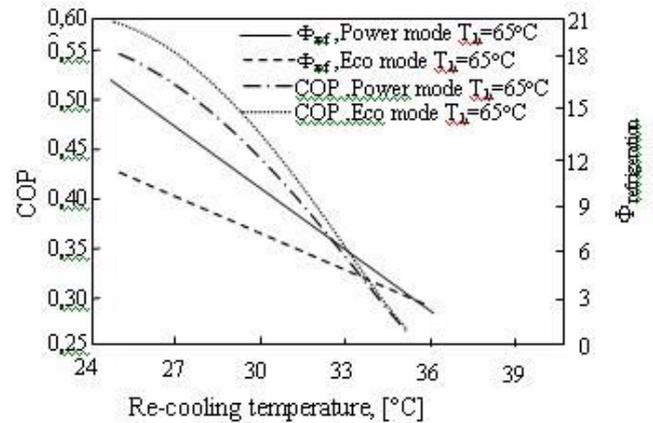


Figure 10. Characteristic diagram 1 for an adsorption cooling system

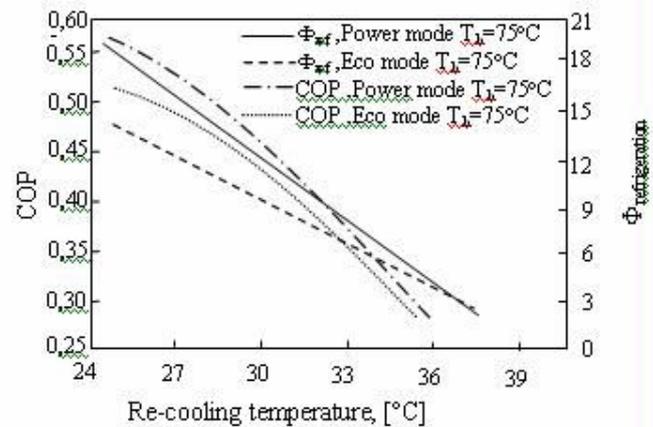


Figure 11. Characteristic diagram 2 for an adsorption cooling system

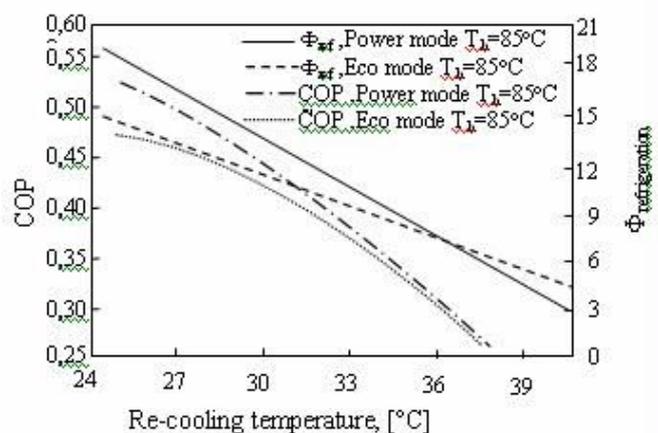


Figure 12. Characteristic diagram 3 for an adsorption cooling system

Power mode curve depicts the working point of maximum cooling power/peak cooling load at a correspondingly low COP. This performance is usually the basis for dimensioning. ECO mode curve depicts the working point of reduced

cooling power/partial cooling load at significantly increased COP. This is exactly the performance used for partial load or annual energy inspections.

V. CONCLUSION

The paper presents the adsorption cooling subsystem which is part of a trigeneration system with Stirling engine like prime mover. Adsorption cooling systems are serious alternative for vapor compression cooling systems since they do not contain any hazardous materials for environment. One of the advantages of adsorption cooling systems is operation with thermal heat source and particularly waste heat. On the other hand, adsorption chiller can be powered by solar hot water. For continuous cooling effect, an adsorption system must have minimum two adsorption beds, which work alternatively: one bed is on adsorption process, while the second bed is on desorption process. The switching time is very important to obtain good performances for adsorption cooling systems. The optimum half cycle time is shortened by the larger mass flow rate and higher hot water temperature because of increased cooling capacity. It has to be noted that the smaller the COP, the more heat input is required and the more heat has to be removed by the cooling tower. Vice versa, a high COP value is of advantage in reducing heat input for the adsorption chiller in the re-cooling cycle.

This is a preliminary analysis of the adsorption cooling subsystem. After the trigeneration system will be mounted on the building, we will make experimental measurements and we will compare with theoretical results obtained using a mathematical based on lumped parameters.

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REFERENCES

- [1] B.B. Saha, S. Koyama, J.B. Lee, K. Kuwahara, K.C.A. Alam, Y. Hamamoto, A. Akisawa, T. Kashiwagi, “Performance evaluation of a low-temperature waste heat driven multi-bed adsorption chiller”, *Int. J. Multiphase Flow* 29 (2003), pp. 1249–1263.
- [2] Di J, Wu JY, Xia ZZ, Wang RZ., “Theoretical and experimental study on characteristics of a novel silica gel–water chiller under the conditions of variable heat source temperature”, *Int J Refrig* 2007;30: pp. 515–26.
- [3] Hasan Demira, Moghtada Mobedi, Semra Ülkü, “A review on adsorption heat pump: Problems and solutions”, *Renewable and Sustainable Energy Reviews* 12 (2008), pp. 2381–2403.
- [4] Henning HM, Wiemken E., “Solar assisted air conditioning of buildings overview on technologies and state of the art”, in: *Proceedings of ISES Solar World Congress*, Gothenburg, Sweden, 2003.
- [5] K.C.A. Alam, Y.T. Kang, B.B. Saha, A. Akisawa, T. Kashiwagi, “A novel approach to determine optimum switching frequency of a conventional adsorption chiller”, *Energy* 28 (2003), pp. 1021–1037.
- [6] S. Li, J.Y. Wu., “Theoretical research of a silica gel–water adsorption chiller in a micro combined cooling, heating and power (CCHP) system”, *Applied Energy* 86 (2009), pp. 958–967
- [7] Sortech AG. *Sortech Adsorption Chiller Design Manual*.
- [8] Takahiko Miyazaki , Atsushi Akisawa, “The influence of heat exchanger parameters on the optimum cycle time of adsorption chillers”, *Applied Thermal Engineering* 29 (2009), pp. 2708–2717.
- [9] Wang DC, Xia ZZ, Wu JY, Wang RZ, Zhai H, Dou WD., “Study of a novel silica gel water adsorption chiller, Part I: design and performance prediction”, *Int J Refrig* 2005;28(7), pp. 1073–83.
- [10] Wang DC, Wu JY, Xia ZZ, Zhai H, Wang RZ, Dou WD., “Study of a novel silica gel water adsorption chiller, Part II: Experimental study”, *Int J Refrig* 2005; 28(7), pp. 1084–91.
- [11] Dous N, Meunier F., “Experimental study of cascading adsorption cycles”, *Chem Eng Sci* 1989;44, pp. 225–35.
- [12] Chahbani MH, Labidi J, Paris J., “Effect of mass transfer kinetics on the performance of adsorptive heat pump system”, *Appl Therm Eng* 2002;22, pp. 23–40.
- [13] Pospisil J., Fiedler J., “Applicability of Tri-generation Energy Production for Air-conditioning Systems in Czech Republic”, in *Proceedings of the 5th IASME/WSEAS Int. Conference on Heat Transfer, Thermal Engineering and Environment*, Athens, Greece, August 25-27, 2007.
- [14] Mancarella P, Chicco G., “Energy and CO2 emission assessment of cooling generation alternatives: a comprehensive approach based on black-box models”, in *WSEAS TRANSACTIONS ON POWER SYSTEMS* Vol.3, No.4, April 2008, pp.151-161, ISSN:1790-5060.
- [15] Alghoul, M.A., Sulaiman, M.Y., Sopian, K., “Parametric analysis of multipurpose solar adsorption system- cooling and heating”, in *Proceedings of the 3rd IASME/WSEAS International Conference on Energy & Environment*, Cambridge, UK, 2008, pp. 538-544, ISBN ~ ISSN:1790-5095 , 978-960-6766-43-5.
- [16] Haw L.C, Sopian K, Suleiman Y., “An Overview of Solar Assisted Air-Conditioning System Application in Small Office Buildings in Malaysia”, in *Proceedings of the 4th IASME / WSEAS International Conference on ENERGY & ENVIRONMENT (EE'09)*, 2009.