CNR – ITAE

ISTITUTO DI TECNOLOGIE AVANZATE PER L'ENERGIA

"NICOLA GIORDANO"

SHORT TERM MOBILITY PROGRAM 2016

JUNE 6^{th} 2016 - JUNE 27^{th} 2016

"Development of evaporators for adsorption chillers"

Host Institution

Fraunhofer, Instituts für Solare Energie systeme, ISE

Freiburg (Germany)

Dr Alessio Sapienza

July 2016

1 INTRODUTION

Adsorption heat transformers (AHTs) represent nowdays an interesting alternative to traditional energy consuming technologies, for different applications (e.g. thermal energy storage, refrigeration, ice making, HVAC) both for stationary and mobile end-users, because they can be driven by low-grade thermal energy, their quasi-zero electricity consumption, and low-GWP/ODP refrigerants/working fluids employed [1,2,3].

Despite their interesting features, adsorption based systems present still crucial limitations, to be overcome in order to allow their broader diffusion, related to the overall machine efficiency as well as to the power density.

During last years, several efforts have been done to do an intelligent design of adsorption machines taking into account both thermodynamic and dynamic aspects. Several studies were carried out on the thermodynamic optimization of the system (new adsorbent pairs, advanced cycles, etc) while only recently the studies have been addressed to improve the dynamic features of the adsorption machines. Dynamic performance of adsorbers (adsorbent material integrated into heat exchangers) were studied in [4,5,6,7] demonstrating that the optimization of kinetics aspects can lead to a considerable increasing in volumetric cooling power VCP. On the other hand, very few studies were focused on the other two main components of an adsorption cooling machine [8,9], the evaporator and the condenser.

Evaporator/condenser are crucial components because they should be able to:

• maintain the steam pressure for the adsorption/desorption process. As the adsorption process depends directly on the pressure level, an insufficient evaporator can drastically limit the performance of an adsorption heat pump or chiller;

• should be able to follow the sorption kinetics that could be very fast in particular in the first instants of adsorption/desorption step;

In particular, for HVAC applications (e.g. heating/cooling and dehumidification) water is mainly employed as refrigerant since its high latent heat, friendly environmental features.

Due to the low saturation vapor pressure of water, the evaporation process needs to take place at sub-atmospheric pressure conditions which implicates fundamentally different evaporation and boiling characteristics compared to elevated pressures. Apart from some basic research activities investigating low pressure evaporation of water among the recent ones there is no comprehensive literature in that field and consequently no approved design guidelines for correspondent heat exchangers. In order to design effective evaporators for heat transformation devices it is essential to better understand the occurring physical principles of sub-atmospheric pressure evaporation and heat transfer mechanisms in the heat exchanger and to identify how geometry- and process-related factors influence evaporation performance.

In this context, the research activity carried out at Fraunhofer-Institute for Solar Energy systems (ISE) based in Freiburg (Germany), had the aim of studying the evaporation performance of a HEx layout developed at CNR-ITAE. The activity was carried out using an “evaporation test bench” available at Fraunhofer – ISE allowing to reproduce the evaporation/condensation step at typical pressure/temperature levels of an adsorption chiller/heat pump.

2 MATERIALS AND METHODS

2.1 Materials

The experimental activity has been carried out on an aluminum radiator, shown in Figure 1, based on finned flat tubes commonly employed for automotive/motorbike applications. The tested HEx, namely HEx1, has two rows of tubes, with rectangular cross section.

Figure 1 Tested heat exchanger and detailed view of the finned pack

The finned pack, based on triangular louvered fins (spaced 360 fins/meter), has a heat transfer surface area density of 15.40 [cm^2/cm^3]. Main fins' features are reported in table 1 as well as other relevant properties of the tested HEx.

	HEx1
Overall lenght [mm]	660
Finned pack dimensions LxWxT [mm]	320x27x35
Finned pack volume, V [dm^3]	0.302
Heat transfer surface area density [cm^2/cm^3]	15.40
Overall heat transfer surface area, A [cm^2]	4650.8
Outer diameter, d_o [mm]	15.96
Inner diameter, d_i [mm]	12.6
Number of flat tubes	2

Table 1 Main features of the tested heat exchanger

2.2 Method: the Fraunhofer ISE evaporation test bench

Main components of the setup, shown in Figure 2, are two vacuum chambers: the heat exchanger to be tested is mounted inside the "measurement chamber" while the "secondary chamber" contains a permanently installed large tube-fin heat exchanger which is partially flooded by refrigerant (water). Each heat exchanger is connected to a circulation thermostat which allows the heat exchangers to be brought to a defined temperature level. Both chambers can be connected or separated by switching the valves of the two connecting lines. The secondary chamber always acts as a counterpart to the measurements chamber: If refrigerant vapour should be condensed on the test object the secondary chamber can act as an evaporator to generate the required vapor. Vice versa the secondary chamber is set to condensing mode in case evaporation takes place on the test object in the measurement chamber. The test setup is equipped with several sensors. Pt-100 temperature sensors measure fluid inlet and outlet temperatures of the two heat exchanger circuits and ambient temperature. Volume flow meters record the fluid volume flow of the two fluid circuits. The vapour pressures inside the chambers are monitored by pressure transmitters. By means of a scroll vacuum pump the whole test rig or an individual chamber can be evacuated.

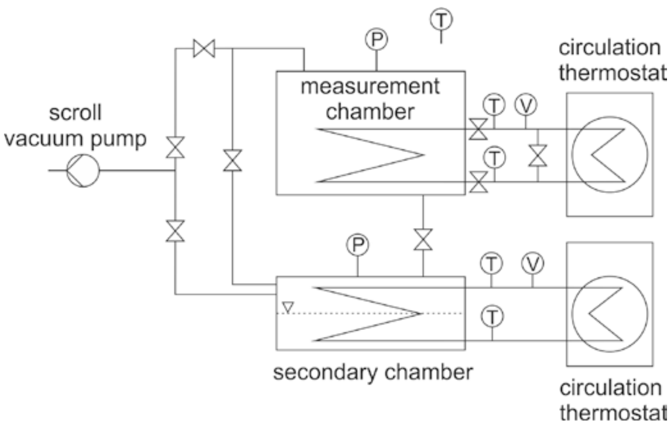

Figure 2 Fraunhofer ISE evaporation test bench

Figure 3 shows the tested HEx installed into the Fraunhofer ISE evaporation test bench.

Figure 3 View of the tested HEx installed into the Fraunhofer ISE evaporation test bench.

2.3 Performance evaluation methodology

To determine the evaporation power $\dot{Q}_{evap}$ the energy balance over the fluid inlet and outlet of the tested heat exchanger was used and corrected by the heat gain $\dot{Q}_{amb}$ from the ambient into the measurement chamber:

$$\dot{Q}_{evap} = |\, \rho_{fl} \cdot \dot{V}_{mc,in} \cdot c_p \cdot (T_{mc,out} - T_{mc,in}) \,| + |\dot{Q}_{amb}| \tag{1}$$

By means of the logarithmic mean temperature difference

$$\Delta T_{lm} = \frac{T_{mc,in} - T_{mc,out}}{\ln\left(\frac{T_{mc,in} - T_{sat}}{T_{mc,out} - T_{sat}}\right)} \tag{2}$$

the UA value as a measure for heat transfer capability of the heat exchanger can be derived:

$$UA = \frac{\dot{Q}_{evap}}{\Delta T_{lm}} \tag{3}$$

The cumulated mass of refrigerant which was evaporated until a time t is calculated by using the enthalpy of vaporization Δh_{evap}:

$$m_{evap}(t) = \int_{t_0}^{t} \frac{\dot{Q}_{evap}(\tau)}{\Delta h_{evap}(\tau)} d\tau \tag{4}$$

For the measurements in partially flooded operation this cumulative mass can be utilized to calculate the time dependent refrigerant filling level, considering the heat exchanger and tray geometry.

2.4 Testing conditions

The measurements were carried out with the aim to evaluate the influence of main operating conditions on the heat transfer performance of HEx during the evaporation process.
Performance, as above detailed, where calculated in terms of UA where U is the global heat transfer coefficient (J/m^{2}K) and A is the overall heat transfer surface. In particular, we studied the effect of the refrigerant filling level, the flow rate of the heat transfer fluid (V), the evaporation temperature and driving delta T (in terms of difference between the average T_{sat} of the testing and secondary chamber of the set-up). The following table reports a summary of all measurements carried.

HEx	Positioning	T_{ev}	Filling level	F [l/h]/Re	$\Delta T/T_{SC}$	Goal
1	plane	15	max to min	turbulent (800 LPH)	5/10	influence of F and level
1	plane	15	max to min	transition (350 LPH)	5/10	
1	plane	15	max to min	laminar (150 LPH)	5/10	
1	plane	10	max to min	turbulent (800 LPH	5/5	influence of T_{ev}
1	plane	20	max to min	turbulent (800 LPH	5/15	
1	plane	15	max to min	turbulent (800 LPH	2/13	influence of driving T
1	plane	15	max to min	turbulent (800 LPH	11/4	

Table 2 Summary of measurements carried out

3 RESULTS AND DISCUSSION

3.1 Influence of filling level and flow rate of the heat transfer fluid

The influence of the flow rate of the heat transfer fluid was evaluated in terms of Reynolds number. Our goal was to reproduce 3 different flow regimes: laminar, transition zone, turbulent. All measurements were carried out at the same evaporation temperature (15°C) and at the same driving force between evaporator and condenser (delta T=5°C).
The following table resume the conditions

Total flow rate [LPH]	Re	Flow
800	7936	turbulent
350	3472	transition
150	1488	laminar

Table 3 Flow rate of the heat transfer fluid

Results showed a strongly increasing of heat transfer properties with the flow rate of the heat transfer fluid. In particular going from the transition regime to the fully developed turbulent regime the performance quickly increase as well as reducing the filling level. This results confirms recent study [8] that demonstrated as the wettability of the surface of HEx as well as the capillarity effect play an important role to the optimization of the evaporator layout.

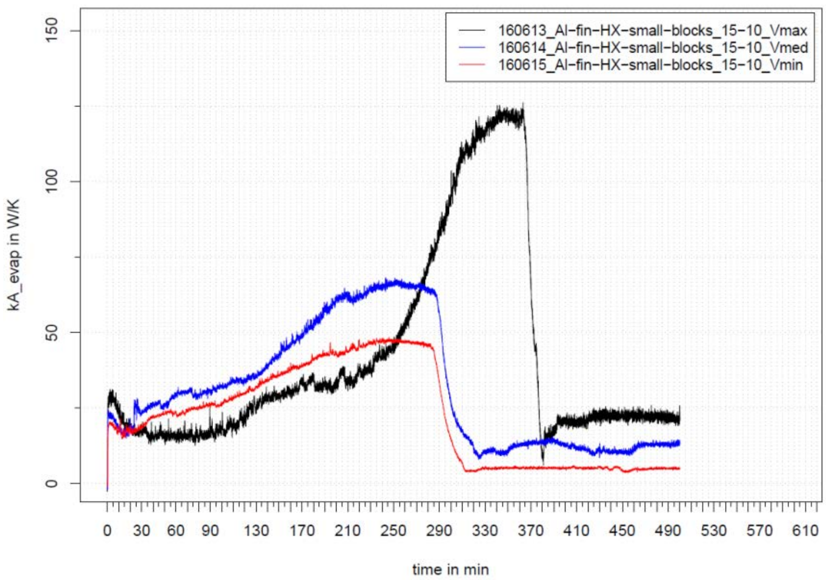

Figure 4 UA versus time at different flow rates of HT fluid (T_{ev}=15°C, ΔT=5°C)

3.2 Influence of the evaporation temperature

All measurements were carried out at the same flow rate of the heat transfer fluid ($V=V_{max}$=800 lph) and the same driving temperature between the evaporator and the condenser (ΔT=5°C).
The following table resume the conditions

Evaporation T [°C]	Condensation T [°C]	Flow rate [lph]
10	5	800
15	10	800
20	15	800

Table 4 testing conditions

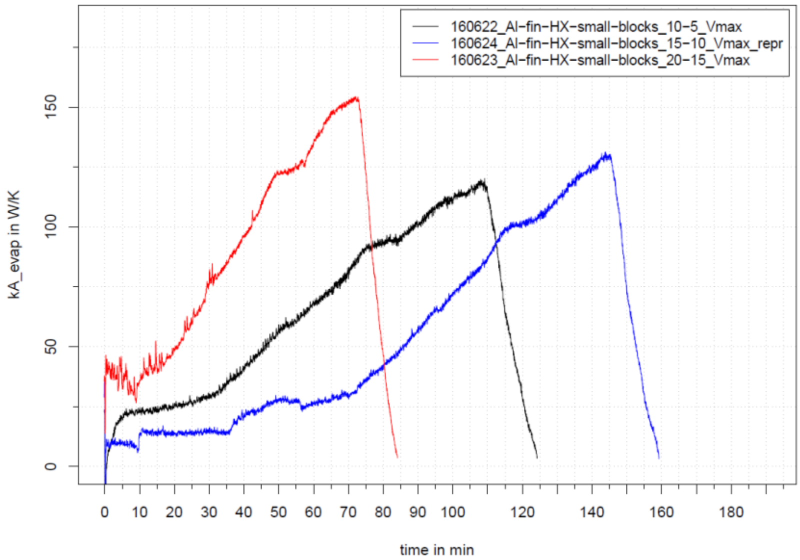

Figure 5 UA versus time at different evaporation temperature (V= 800 lph, ΔT=5°C)

Results showed an increasing of maximum value of UA going from 10 to 20 °C of evaporation temperature.

3.3 Influence of the driving force (T or p)

All measurements were carried out at the same flow rate of the heat transfer fluid ($V=V_{max}$=800 lph) and the same evaporation temperature while the driving temperature between the evaporator and the condenser was changed as detailed in following table. Results showed that the driving temperature is strongly related with the evaporation power. Higher delta T leads to an improvement of the cooling power.

Evaporation T [°C]	Condensation T/ΔT	Flow rate [lph]
15	13/2	800
15	10/5	800
15	4/11	800

Table 5 testing conditions

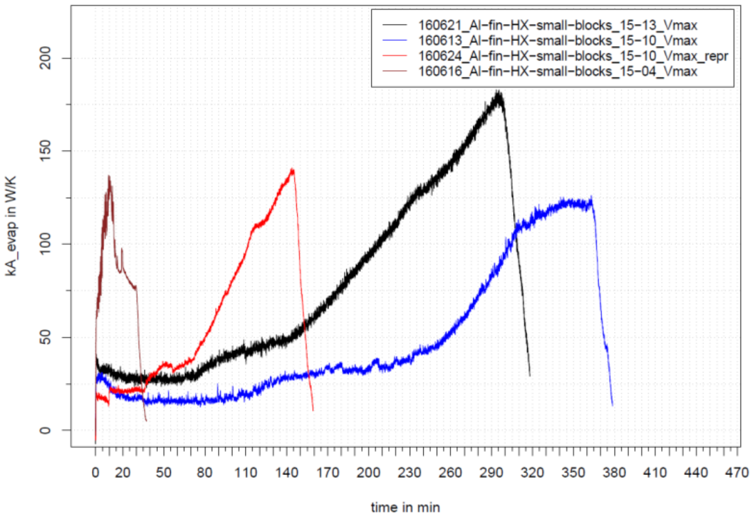

Figure 6 UA versus time at different driving temperature (V= 800 lph, Tev=15°C)

4 CONCLUSIONS

The activity carried out at ISE allowed us to measure the evaporation performance of a compact aluminum heat exchanger developed at CNR-ITAE. The results showed that the capillarity effect strongly influences the performance suggesting to develop evaporators with high wettability and surface structures aimed to support the capillarity effect. Influence of other relevant parameters was also evaluated.The work will be extended by the test of the same HEx by an evaporation test bench available at CNR-ITAE.

5 REFERENCES

[1] N. Yu, R.Z. Wang, L.W. Wang, Sorption thermal storage for solar energy, Progress in Energy and Combustion Science 39 (2013) 489-514

[2] R.Z. Wang, R.G. Oliveira, Adsorption refrigeration—An efficient way to make good use of waste heat and solar energy, Progress in Energy and Combustion Science 32 (2006) 424–458

[3] Biplab Choudhury, Bidyut Baran Saha, Pradip K. Chatterjee, Jyoti Prakas Sarkar - An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling - Applied Energy 104 (2013) 554–567

[4] Aristov YuI, Girnik IS, Glaznev IS. Optimization of adsorption dynamics in adsorptive chillers: Loose grains configuration. Energy 2012; 46: 492-484.

[5] Aristov YuI. Optimal adsorbent for adsorptive heat transformers: Dynamic considerations. Int. J. Refrig. 2009; 32: 686-675.

[6] Sapienza A, Santamaria S, Freni A, Aristov YuI. Dynamic study of adsorbers by a new gravimetric version of the large temperature jump method. Applied Energy 2014;113: 1251-1244.

[7] Salvatore Santamaria, Alessio Sapienza, Andrea Frazzica, Angelo Freni, Ilya S. Girnik, Yuri I. Aristov, Water adsorption dynamics on representative pieces of real adsorbers for adsorptive chillers, Applied Energy 134 (2014) 11-19

[8] Franz Lanzerath, Jan Seiler, Meltem Erdogan, Heike Schreiber, Matthias Steinhilber, André Bardow, The impact of filling level resolved: Capillary-assisted evaporation of water for adsorption heat pumps, Applied Thermal Engineering 102 (2016) 513–519

[9] L. Schnabel, K.T. Witte, Water as refrigerant – evaporator development forcooling applications, in: Heat Powered Cycles Conference Proceedings, 2009.