Testing of a falling-film evaporator for adsorption chillers

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Abstract

The objective of this work is to test and characterize a falling-film evaporator in a lab-scale adsorption test bench realised at Politecnico di Milano labs. Several ad/desorption cooling cycles were performed setting 15 – 20, 25, and 90 °C the heat transfer fluid temperatures for the evaporation, condensation/adsorption and desorption processes respectively. Preliminary evaluation of performance confirmed an evaporation cooling power of 2.5 – 3.5 kW depending on the refrigerant charge level and operating conditions. The overall heat transfer coefficient UA measured was in the range of 620 – 640 W/K.

Keywords: Adsorption chillers, silica gel, water evaporation

Introduction

Adsorption cooling technology is especially interesting in applications where waste heat for driving the adsorption chiller is a widely available energy source (<90°C). Commercial adsorption chillers are based on fixed beds of silica gel, which leads to a larger adsorber. This disadvantage can be compensated employing novel evaporation concepts that can enhance the adsorption chiller overall efficiency [1] and allow for a compact design.

Among the different types of evaporator (flooded, capillary tubes), the falling film concept appears to be the most suitable under typical operating conditions of adsorption chillers, thanks to the superior global heat transfer coefficient [2, 3].

Generally, water is considered as the best working fluid for adsorption chillers and heat pumps, thanks to the high evaporation enthalpy and low environmental impact. On the other hand, the use of water at low evaporation temperature implies low saturation vapor pressure that require special evaporator design to maximize the evaporation rate during the adsorption phase.

Many efforts have been devoted to the study of sub-atmospheric evaporation process in simplified heat exchanger configurations such as smooth tube [4] and flat-plate [5]. These studies focused on falling film [6] and capillary assisted [7] evaporation processes and in general demonstrated the sensitivity of the evaporation rate to different influencing parameters such as filling level, operating conditions, heat exchange surface type [8 -10].

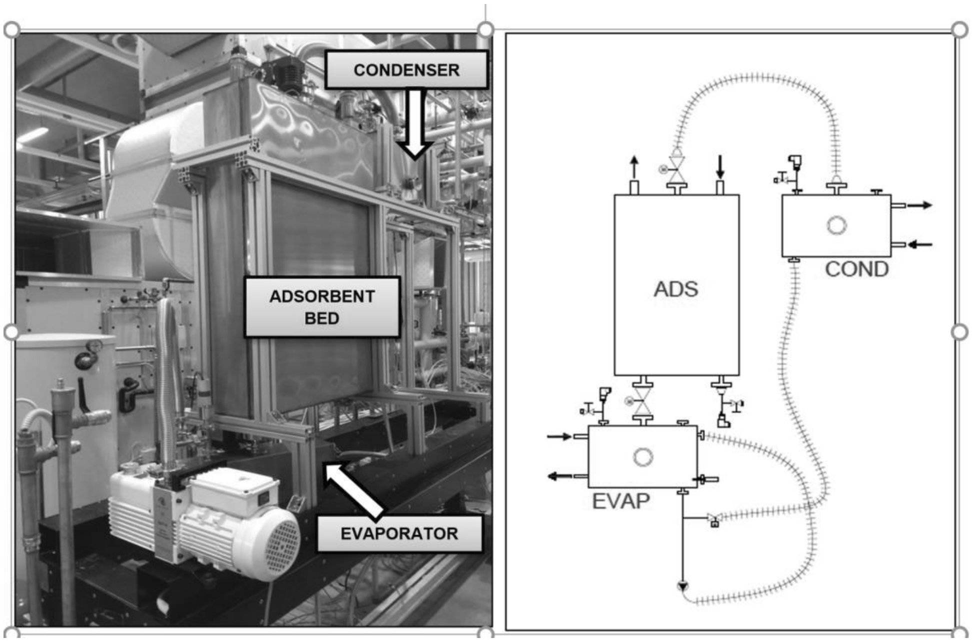
Only few studies have been addressed to the investigation of a full evaporator by means of a real scale test bench able to simulate the adsorption chiller operational mode. Palomba and Frazzica [11] tested an aluminium fin-and-tube heat exchanger by means of a test bench able to achieve evaporation under partially flooded configuration against a condenser. They found that heat transfer fluid temperature and orientation of the heat exchanger significantly affect the evaporation rate. Volmer at al. [12] tested real size copper tube-fin heat exchangers both in thin film and partially flooded evaporation mode. The results showed that some geometric and process parameters (fin density, fluid flow rate, filling level) strongly influence evaporation performance.

Thimmaiah et al [13] tested a flooded evaporator in a real adsorption heat pump employing AQSOA FAM-Z02 as adsorbent. They found that the utilization of turbulent flow generators inside evaporator tubes and a porous coating on the external surface of evaporator tubes can improve the flooded evaporator performance. Giraud et al. [14] tested a smooth stainless steel plate evaporator in a real adsorption heat pump employing silica gel as adsorbent. Results of experiments indicated high influence of the height of the liquid level on the cooling capacity obtained during the adsorption cycle. Li et al. [15] tested a falling film evaporation on tube bundles in vacuum. Evaporation was obtained against a condenser. According to previous literature research, no falling film evaporators have been exhaustively tested in a real scale adsorption heat pump or chiller. Accordingly, in this work an innovative falling-film evaporator, equipped with a recirculation system to maximize the wetted surface, was tested in a lab-scale adsorption test bench recently realised at Politecnico di Milano labs for evaluating heat transfer performances. Tests have been carried out under realistic operating conditions typical of an adsorption chiller. Evaporation performance have been determined in terms of delivered cooling capacity at different refrigerant charges, external fluid flow rate, evaporation and adsorption temperatures. Additionally, from the experimental data the calculation of the external heat transfer has been performed.

Description of the experimental set-up

An experimental set-up has been built at Politecnico di Milano labs for testing adsorption units and their components. A schematic design of the main system and a photo of the testing setup are shown in Fig. 1a, b. The core of the system consists of a single adsorbent bed, a falling-film evaporator (which geometry is reported in Table 1) equipped with a recirculation pump to improve the heat transfer efficiency and a condenser. The adsorbent bed was made of granular RD silica gel embedded in a finned heat exchanger and was oversized with the purpose of assuring stable working conditions at the evaporator for long periods. The three components are connected by two electric-actuated valves to allow the passage of water vapor enabling the ad/desorption phases. The external sinks/sources consist of three hydraulic circuits (cold-water, hot-water and intermediate circuit) with nominal capacities of 2 kW for evaporator and condenser and 5 kW for the adsorber, with flow rates between 200 and 1000 L/h. The mass flow rates and supply temperature of the three circuits can be set indepedenly based on the required conditions. A schematic layout of the hydraulic circuits and the design of the evaporator are shown in Fig. 2 and 3, respectively. The test bench is also equipped with Pt100 temperature sensors, pressure transducers and flowmeters which uncertainties and operating range are reported in Tab. 2**.** The resulting efficiency on the measured heat transfer rate are lower than 1.5% for the three circuits. A real time control and data acquisition software for the test bench was realised by means of the LabView™ language.

Taking into consideration that this is a single-bed adsorption cycle, the test bench can work in two modalities: adsorption-evaporation and desorption-condensation. When carrying out the test in the adsorption-evaporation mode, the cold-water circuit provides the needed heat for the evaporation. At the same time, the medium temperature water loop operates as heat sink allowing the heat rejection during the adsorption phase. On the other hand, when working in the desorption-condensation mode, the medium temperature circuit allows the rejection of condensation heat, while the hot water circuit provides the desorption heat to the adsorbent bed. The switching between the phases of the cycle is achieved by means of two-electric actuated valves.



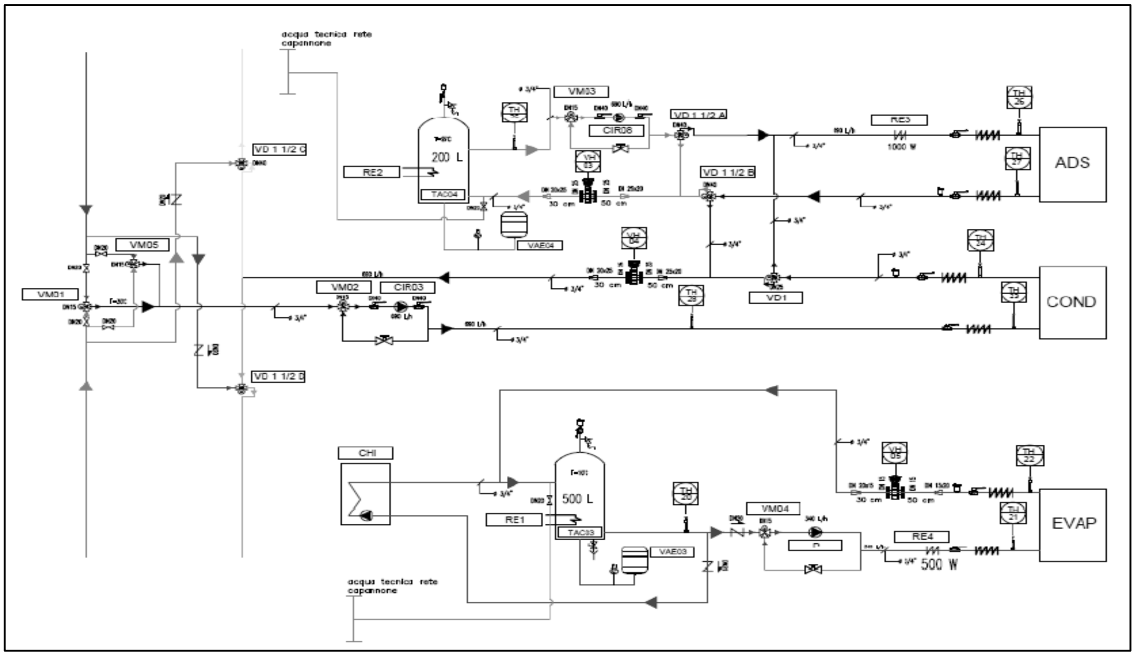


Figure 1a, b – Adsorption test rig schematic and photo

Figure 2 – Hydraulic circuits scheme

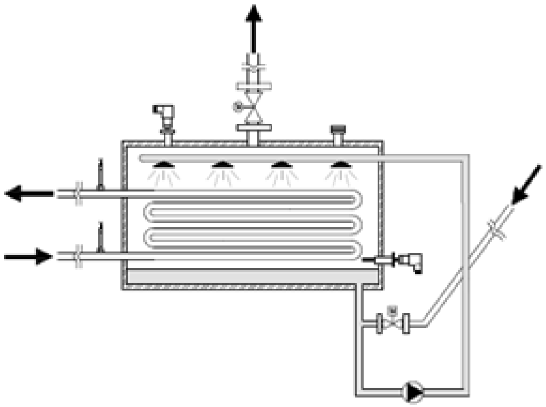


Figure 3 – Evaporator scheme

Table 1. Evaporator parameters

Parameter	Value	Description
a (m)	0.503	evaporator casing width
b (m)	0.113	evaporator casing depth
c (m)	0.283	evaporator casing height
L_{pipe} (m)	5.4191	total length of the evaporator internal pipe
N°C (-)	2	number of coils
N°L (-)	6	number of levels for each coil
$d_{ext,pipe}$ (m)	0.016	external base pipe diameter
$d_{int,pipe}$ (m)	0.015	internal base pipe diameter
h (m)	0.003	fin height
p (m)	0.004	space between consecutive fins
A_{ext} (m^2)	0.7619	external exchange surface of the evaporator internal pipe
A_{int} (m^2)	0.6124	internal exchange surface of the evaporator internal pipe
V_{ref} (m^3)	0.0136	internal volume of the exchanger occupied by the liquid refrigerant

Table 2. Sensors range and accuracy.

Test bench sensors	Measured parameter	Range	Accuracy
Resistance temperature detector Pt 100 1/10 DIN class	Temperature of the water at the inlet/outlet of the component	from -10°C to 100°C	± 0.03°C at 0°C
Pressure transmitter	Pressure inside the component	0 - 20 kPa	0.25% of reading
Magnetic flow meter	Flow rate of the water inside the component	200 - 1000 L/h	always < 0.5% of reading

Test procedure

Considering that the goal of this experimental work is to study the behaviour of an innovative falling-film evaporator for adsorption chillers, the focus has been set mostly on the adsorption-evaporation phase of the cycle. Several tests of this process were carried out with the same heat transfer fluid flow rates (0.4 m^3/h for the evaporator and 0.65 m^3/h for the adsorbent bed) and the same adsorption bed temperature (25°C), varying both the evaporator inlet water temperature from 15 to 20°C and the initial mass of liquid refrigerant inside the evaporator (from 0.85 to 1.57 kg). Before each test, the incondensable gases were removed by means of a regeneration process at about 90°C under vacuum. The switching from the adsorption to the desorption phases and vice versa was done A temperature difference between adsorber water inlet and outlet below 0.2°C was used as criterion for switching from one cycle phase and following phase, with the purpose of beginning the absorption and desorption processes with uniform temperatu e inside the bed. Moreover, the recirculation pump which circulates the refrigerant on the evaporator was activated as the valve between the evaporator and the adsorption bed opened. This procedure guarantees both uniform initial conditions at the beginning of the tests and repeatable operation.

Experimental results

In the experimental tests the chilled water flow rate inside the evaporator as well as the temperature difference between inlet and outlet of this element were measured. Consequently, the instantaneous heat transfer rate was calculated by applying an energy balance on the evaporator referred to the chilled water side. Moreover, the pressure inside the evaporator is also measured and, based on this measure, the refrigerant saturation temperature was calculated. The overall UA is obtained by dividing the exchanged thermal power by the mean logarithmic temperature difference across the heat exchanger. The hA (referred to the external side of the pipe inside the evaporator) is calculated from the heat transfer rate and the conductive resistance of the pipes and the internal convective resistance.

From Fig. 4, it can be noticed that, as soon as the process starts, the evaporator outlet water temperature decreases rapidly due to the initial intense adsorption process. After this sudden temperature decrease, the profile remains roughly constant with the continuous evaporation of refrigerant. From Fig. 4 it can also be said that, after the initial temperature decrease, there is a sort of plateau section of the profile with an almost constant profile. The maximum temperature difference reached with tests with an inlet water temperature of 20°C is around 7.2°C, while tests with inlet water temperature of 15°C had a maximum temperature difference of 5.5 °C. The average pressure value during the plateau section was in the range of 1100 Pa – 1300 Pa. Given the constant inlet temperature, the same path is followed by the heat tranfer rate.in Fig. 5. Both the calculated external hA and overall UA parameters are reported in Fig. 5 and 6, respectively for the test with 20°C evaporator inlet temperature and evaporator flowrate of 0.4 m^3/h. The average value of the overall UA during the plateau interval is in a range of 620 – 640 W/K while the range for the average external hA is 1040 – 1150 W/K.. In Fig. 6 it can also be seen the profile of the mass of refrigerant, which smoothly decreases as the test progresses. A possible explanation of the reduction of the hA value can be explained with the reduction of the reduction of the refrigerant content in the evaporator, with reduces the mass flow rate of recirculated refrigerant due to cavitation and consequently the actual wetted area of the evaporator Furthermore, the amount of refrigerant inside the evaporator influences the duration of the test. All tests were ensured to begin with a water level below the final tube of the coil to avoid pool boiling and only having falling film evaporation. The duration of each adsorption-evaporation phase increased with the increase of refrigerant mass inside the evaporator.

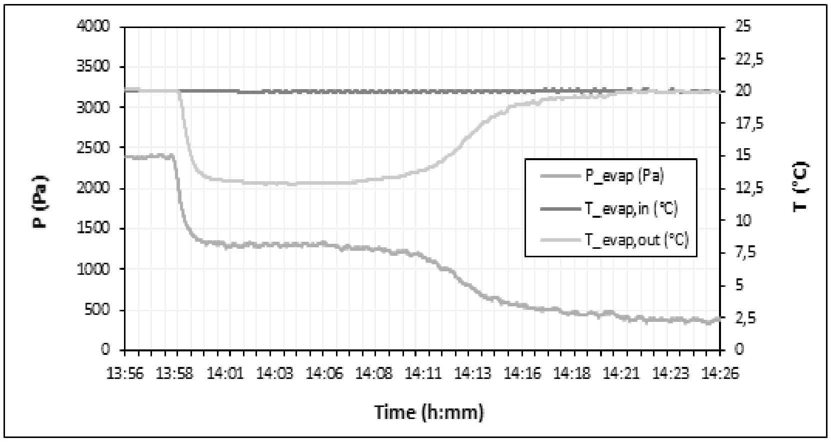


Figure 4 – Pressure-Temperature graph

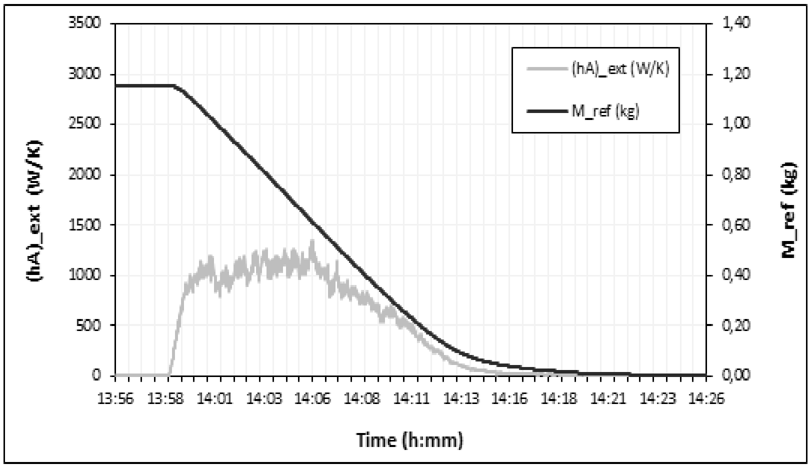


Figure 5 – Overall hA and remaining mass of refrigerant

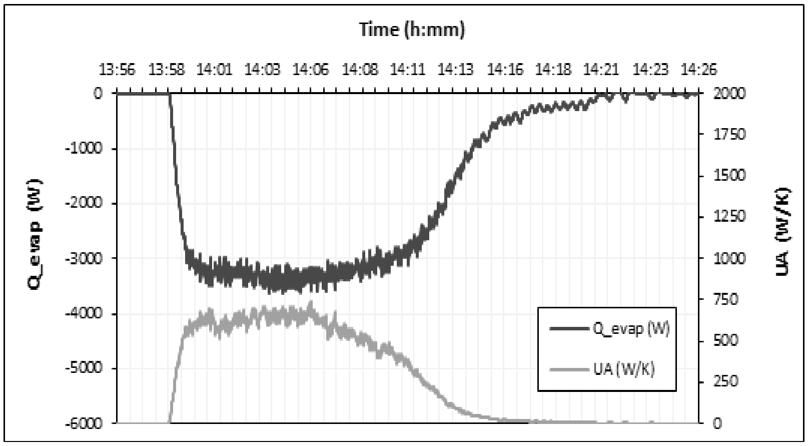


Figure 6 – Overall UA and heat transfer rate

Summary/Conclusions

A falling-film evaporator for adsorption chillers has been tested by a laboratory test-rig with different liquid refrigerant contents (1.57 – 0.85 kg) and different inlet temperatures (15 °C – 20 °C). The cooling capacity obtained in the 15 °C tests is almost 2.5 kW, with an overall UA coefficient of about 640 W/K and an external hA coefficient of about 1150 W/K. Moreover, in the 20 °C tests, the obtained cooling capacity is around 3.5 kW, with an average overall UA coefficient of about 620 W/K and an external hA coefficient of about 1040 W/K. The hA values is stable during the first phase of the evaporation before decreasing considerably as the process is completed. The reduction of the recirculated refrigerant flow rate is presented as a possible explanation. This will be further investigated with more tests and adding a measure of the recirculted refrigerant mass flow rate to the analysis.

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