Lab-scale sorption chiller comparison of FAM-Z02 coating and pellets

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Simon Fraser University

Heat Powered Cycles Conference

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Center of Energy Technology, University of Bayreuth, Germany

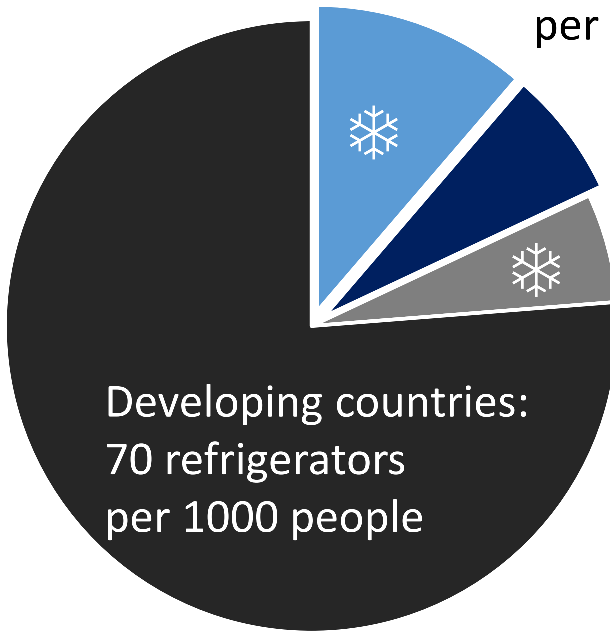
The food cold-chain

World population: 7.3 billion

Food losses due to
lack of refrigeration: 25%

Projected population:
8.5 billion by 2030

Developed countries:
627 refrigerators
per 1000 people



How much power would be required to provide cold storage to this portion of the world population?

S.J. James, C. James, “The food cold-chain and climate change”, *Food Res. Int.*, **43** (2010) p. 1944

Transportation of refrigerated and frozen food

The current worldwide cold-chain for transport of food uses approximately:

- 1300 refrigerated cargo ships
- 80,000 refrigerated railcars
- 650,000 refrigerated containers
- 1.2 million refrigerated trucks

Heap, 2006; McKinnon & Campbell, 1998; Brodt, Chernoh, & Feenstra, 2007

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Sorption Chiller

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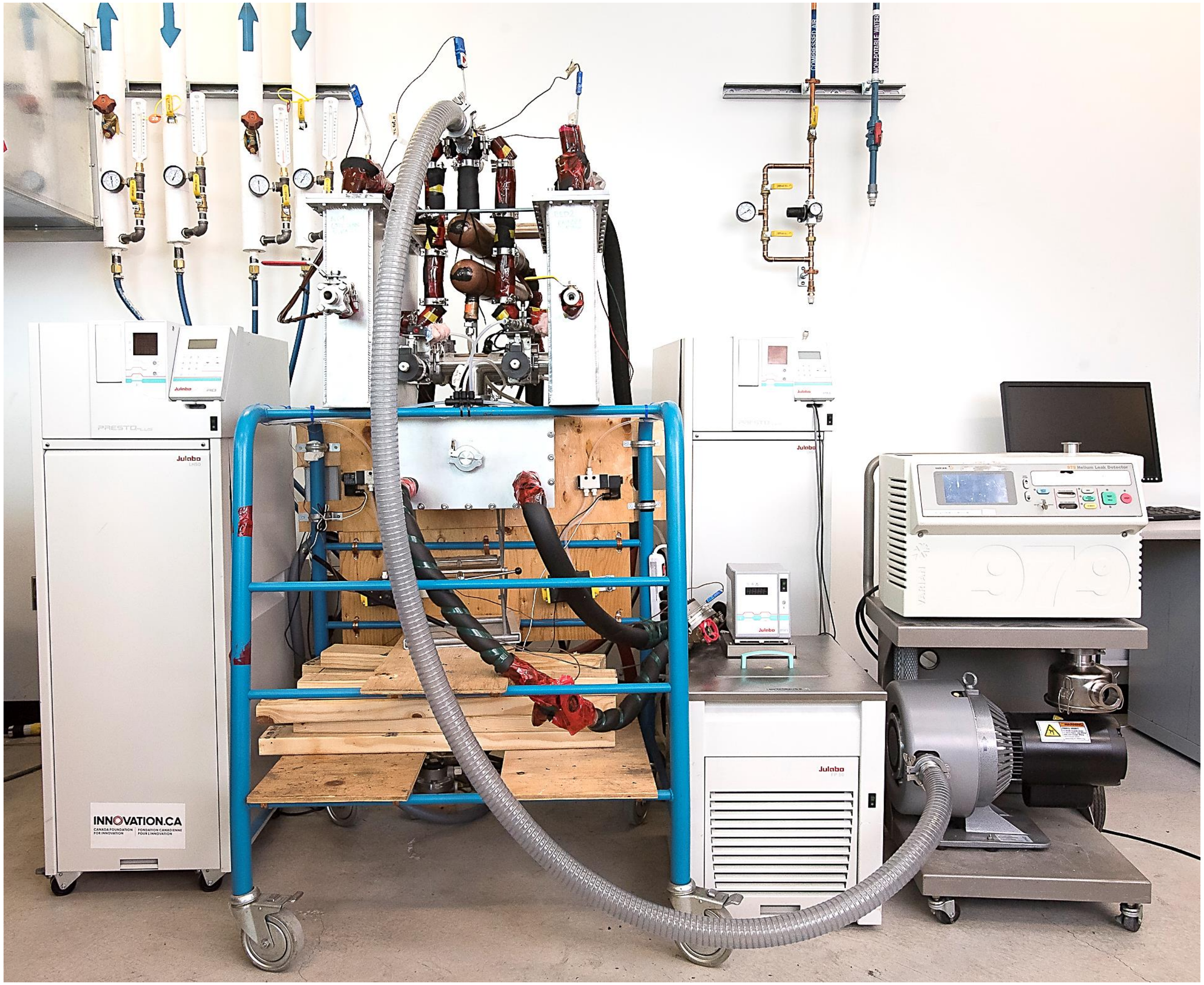

Review of tests of Z02-water samples and sorption chillers

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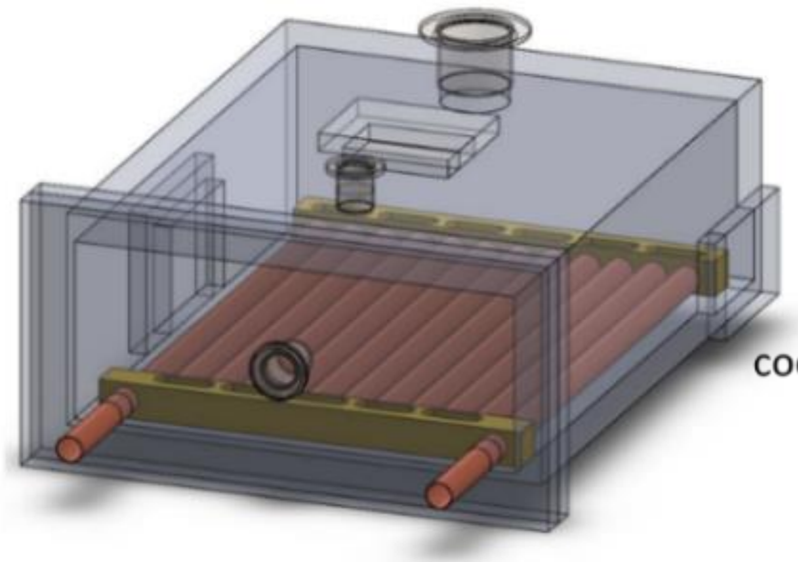
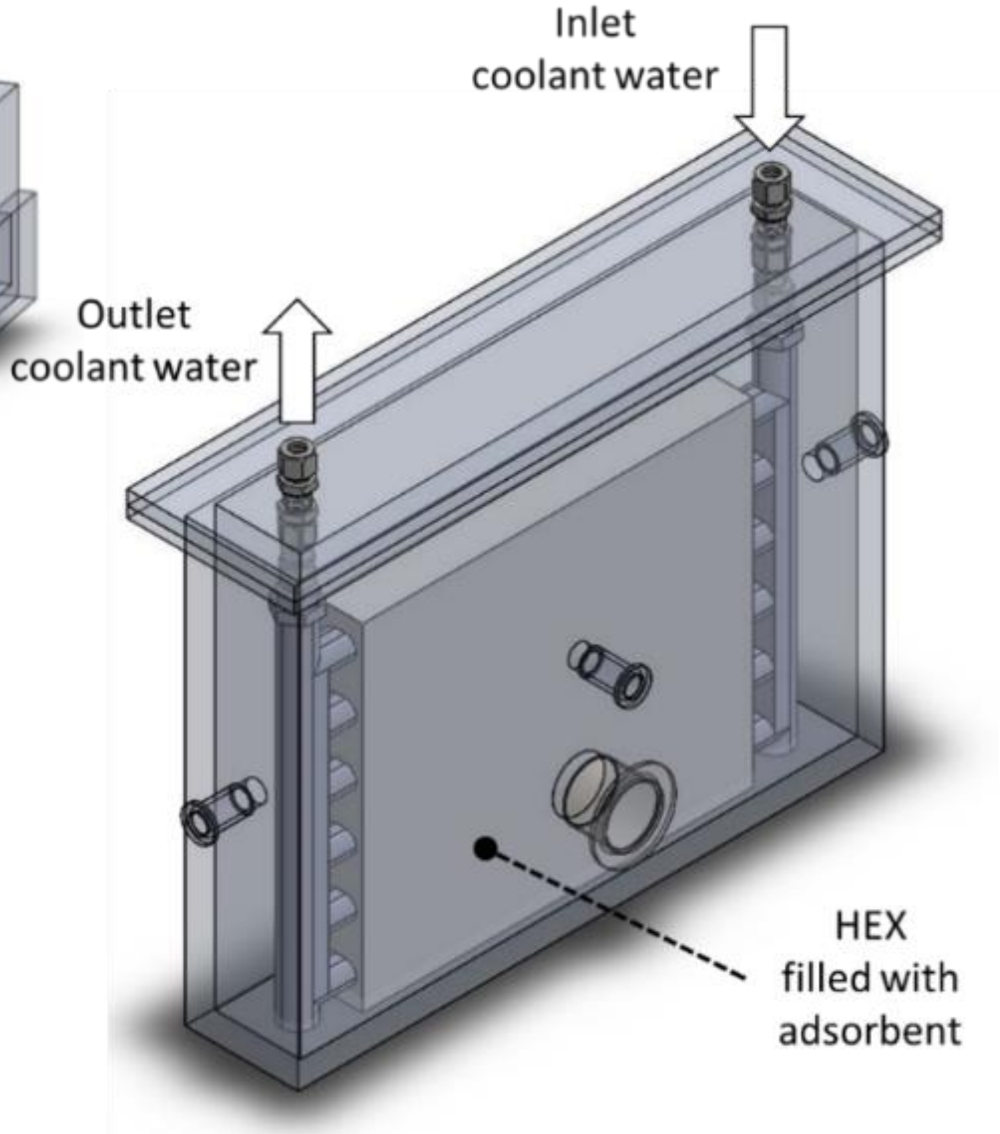
- Freni et al. (2015): 0.1 mm SAPO-34 (84 g) on aluminium finned flat tube HEx (510 g) with SCP 675 W/kg, VSCP of 93 W/dm^3 (5 min cycles under 15 °C/28 °C/90 °C)
- Santamaria et al. (2014): Temperature jump tests on small HEX (70-90 g of Z02 grains) with cooling powers up to 2.3 kW/kg, 6-8 times greater than tests larger prototypes (ie. 280-380 W/kg)
- Dawoud et al. (2013): Adsorption kinetics of Z02 coatings (0.2-0.5 mm) on small substrates and extruded finned-tube and finned-plate Hex.

The specific cooling power of our first runs of Z02 coated heat exchangers in our sorption chiller peaked at a specific cooling power ~200 W/kg, indicating that the overall system needed improvement.

Components

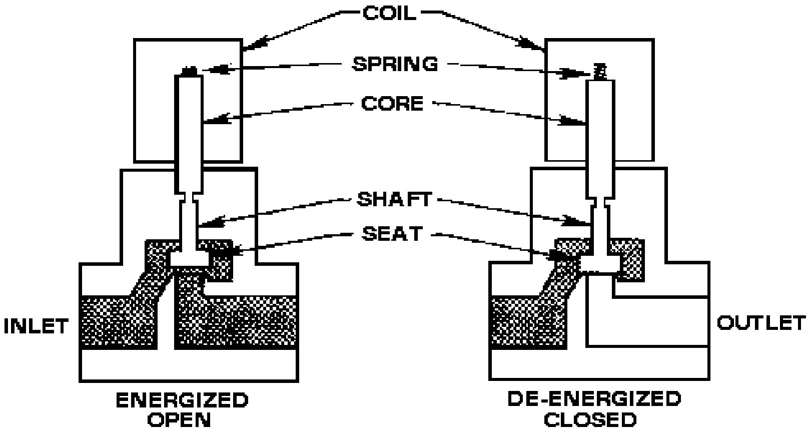



Inlet
coolant water
Outlet
coolant water
HEX
filled with
adsorbent

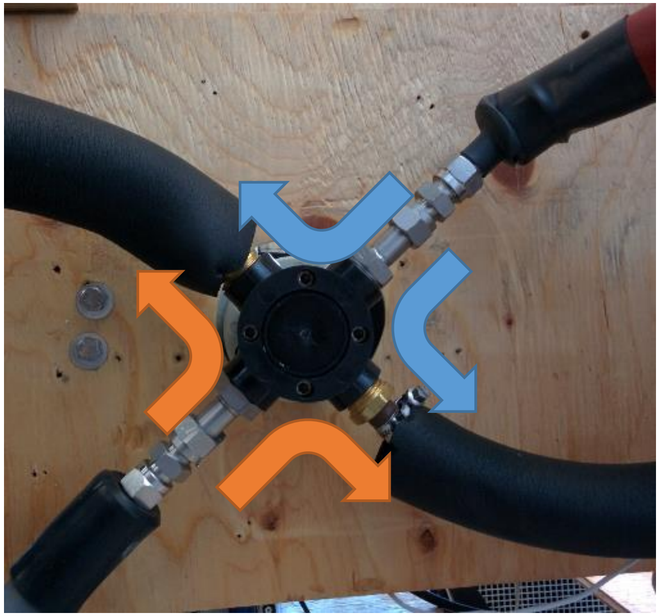
Flow Control

8 solenoid valves for controlling the heating/cooling fluid flow to the beds

Back pressure in a solenoid valve will lead to reverse flow



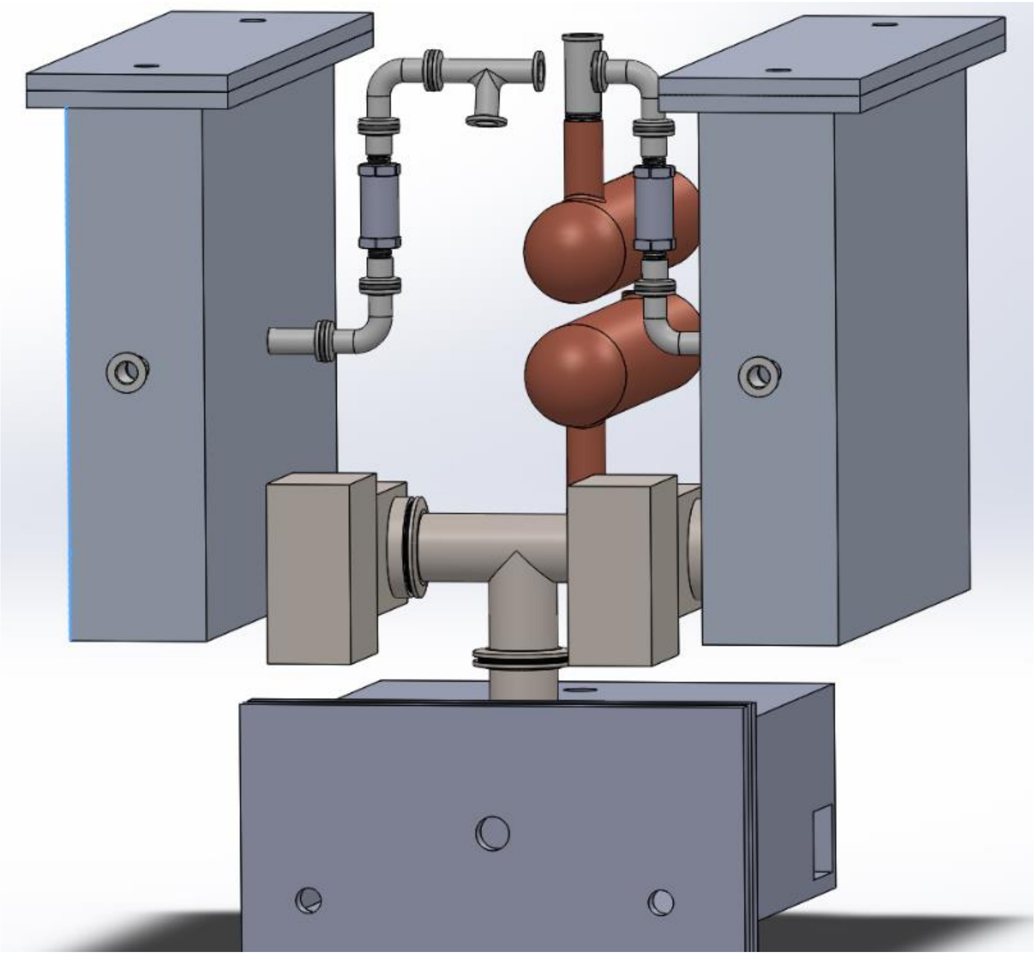
Replaced eight valves with two 4-way valves



4-way valves for faster switching and elimination of crosstalk between the chillers

(actually, reduce crosstalk… we operate with a deliberate switching delay between change of inlet sources, and change of outlet

Upgrade to gate valves for the evaporator

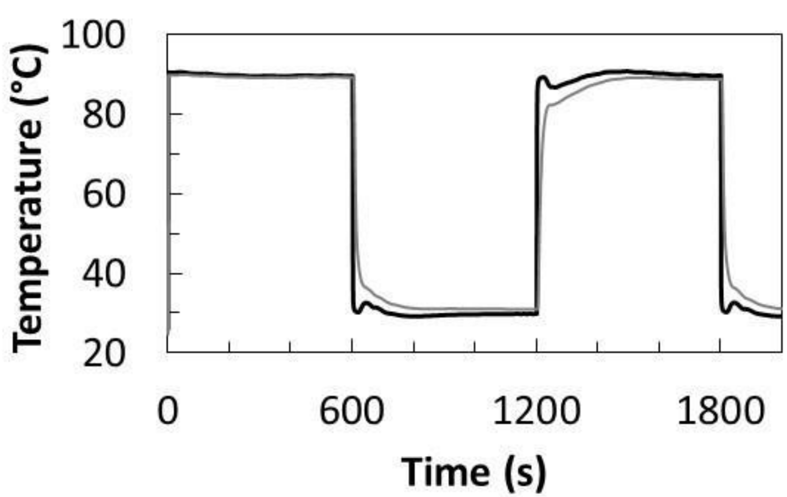


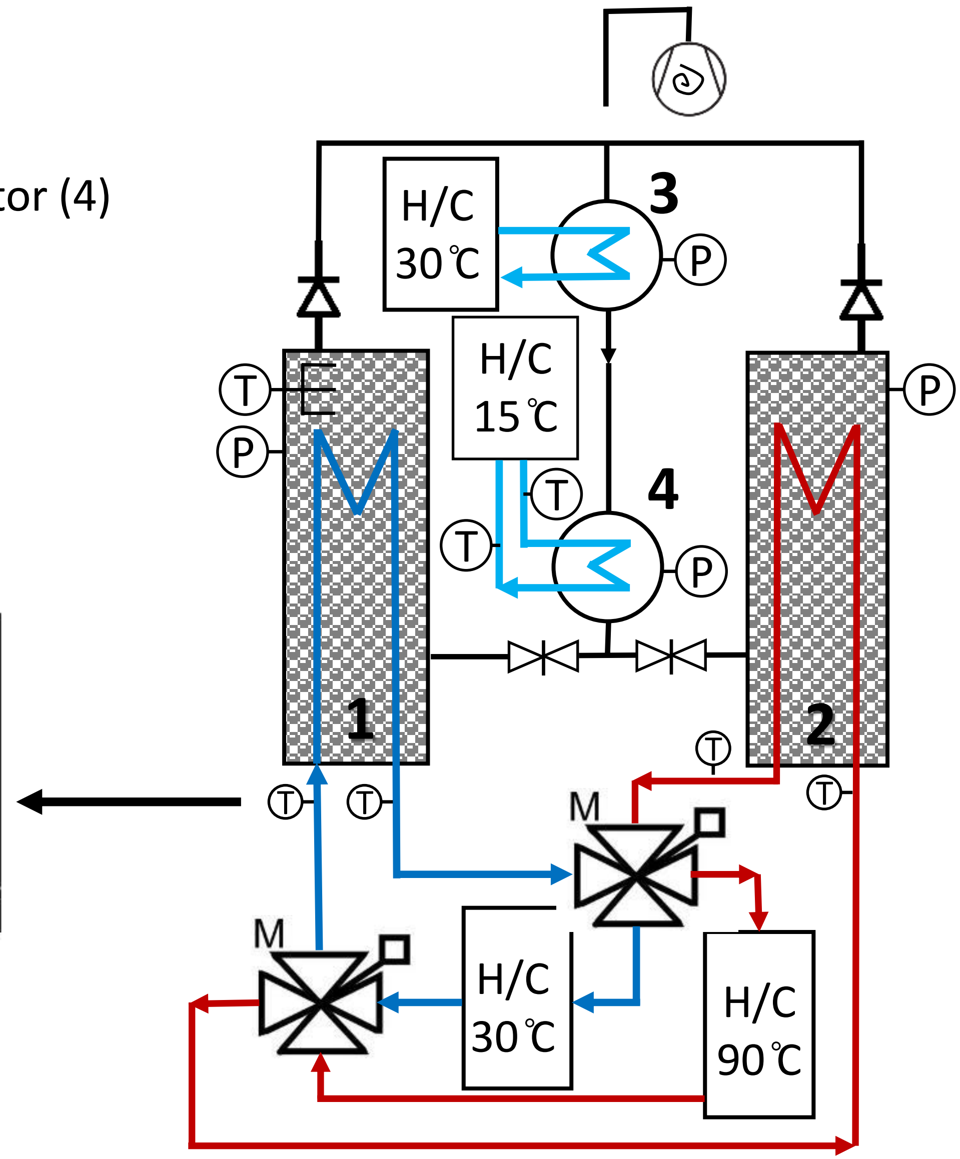
- Observed 1 kPa pressure difference between evaporator and the bed in early tests

- Larger piping and valves reduce pressure drop between the beds and the evaporator

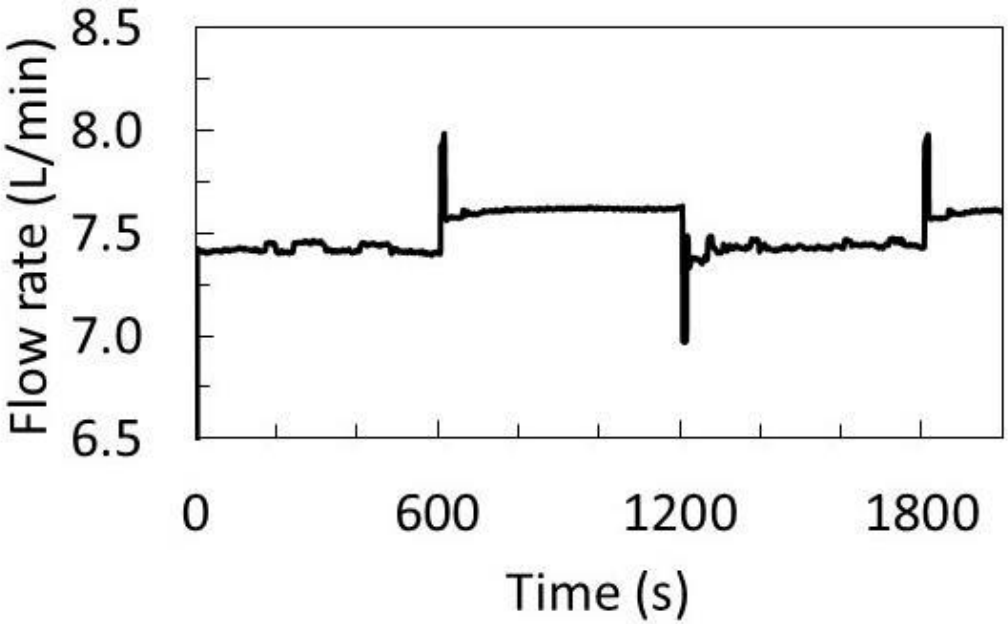
LAEC Modular 2-Bed Sorption Chiller

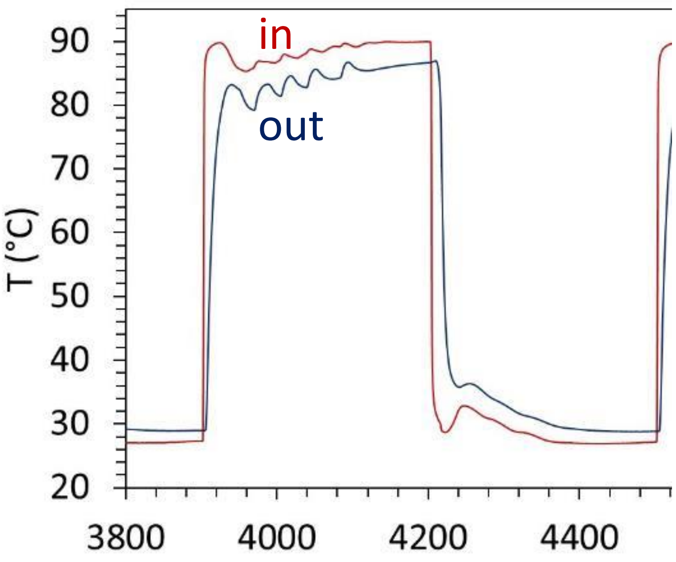
Two sorber beds (1,2)
Condenser (3)
Capillary-assisted low-pressure evaporator (4)
Check valves, gate valves, 4-way values
Four heating/cooling (H/C) circulators
Thermocouples, pressure sensors
Flow meters
Scroll vacuum pump

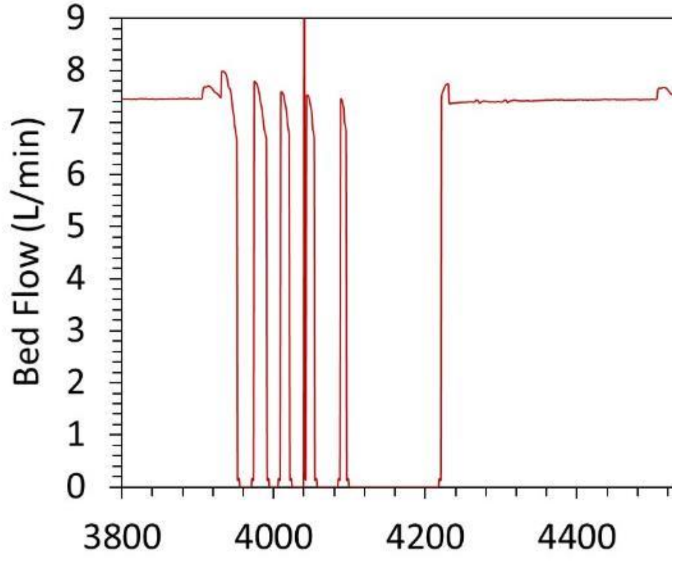




Flow meters don't like temperature swings







FIX: Change the positions of the flow meters so they operate at a singe temperature

Flomec (OM015S001-222) meters, rated to 120°C

Effect of Residual Gas on Water Adsorption Dynamics

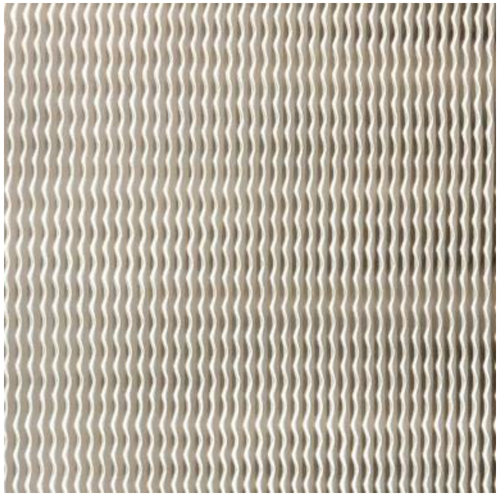
Temperature jump tests by Glaznev et al. on loose grain silica gel and salt/silica gel composites showed reduction of the adsorption rate even for low partial pressure of residual air (e.g. 0.06 mbar) [1], [2]

The custom-built capillary-assisted low pressure evaporators used in our system has finned copper tubes. It is operated in an aluminum vacuum chamber, therefore corrosion is expected.

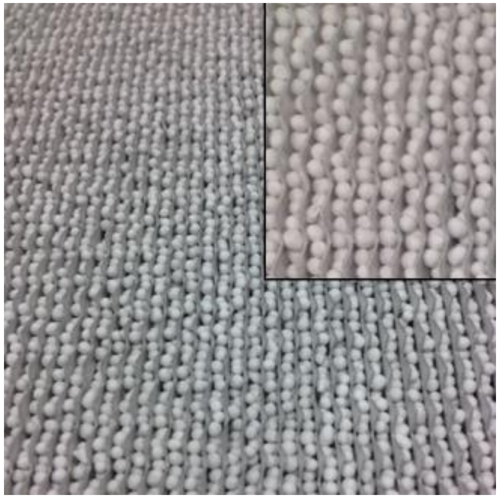
When we swing adsorber bed temperature, the valves connecting the adsorber bed to the condenser and the evaporator are both closed for several seconds, allowing us to evacuate residual gas "on the fly" between cycles during runs.

[1] I. Glaznev, D. Ovoshchnikov, Yu. Aristov, "Effect of Residual Gas on Water Adsorption Dynamics Under Typical Conditions of an Adsorption Chiller" *Heat Transfer Engineering* 31 (2010) 924
and
[2] A. Sapienza, et al. "Dramatic effect of residual gas on dynamics of isobaric adsorption stage of an adsorptive chiller" *Applied Thermal Engineering* 96 (2016) 385-390

Lab-scale Sorption Chiller



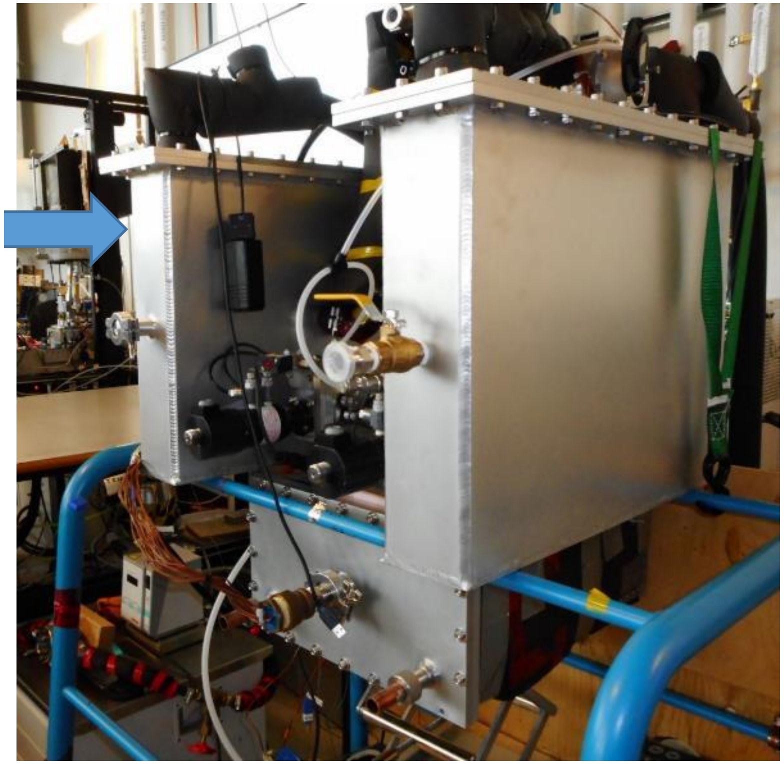
0.8 kg, 0.33 mm sorbent coating



1.9 kg, 1.9 mm diameter sorbent pellets

- The heat and mass transfer resistances increase with increasing sorbent layer thickness and pellet size
- This lowers the water uptake rate and the specific cooling power of the system

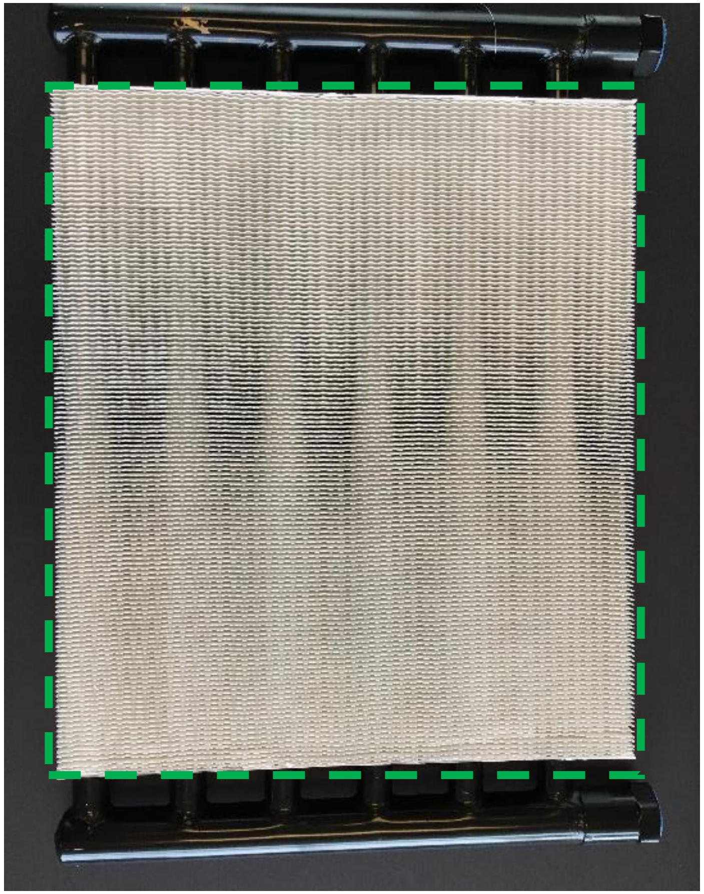
FAM AQSOA-Z02 silicoaluminophosphate developed by Mitsubishi Plastics



Sorption cooling system

A. Sharafian, et al., *Energy* 112 (2016) 481
Dawoud, *Appl Therm Eng* 50 (2013) 1645

Adsorber bed heat exchanger



Copper tube (black painted), aluminum fin

HEx (L,W,H)	35.2×3.8×30.5 cm^3
Fin spacing	2.54 mm (10 fpi)
Surface area	2.8 m^2
HEx weight	2.51 ± 0.03 kg
Z02 coating	0.80 kg per HEx
Z02 pellets	1.97 kg per HEx

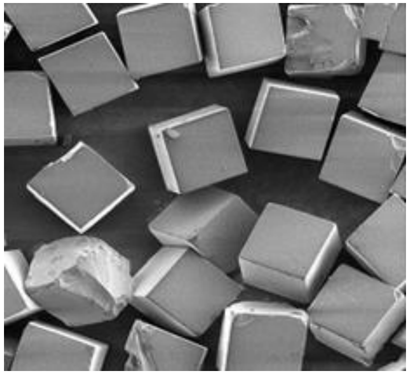
$$Q_{evap} = \int_0^{\tau} \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) dt$$

$$COP = Q_{evap}/Q_{heat}$$

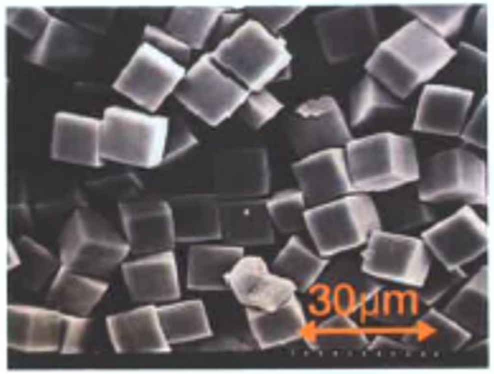
$$SCP = Q_{evap}/(m_{ads} \cdot t_{cycle})$$

$$VSCP = Q_{evap}/(V_{ads} \cdot t_{cycle})$$

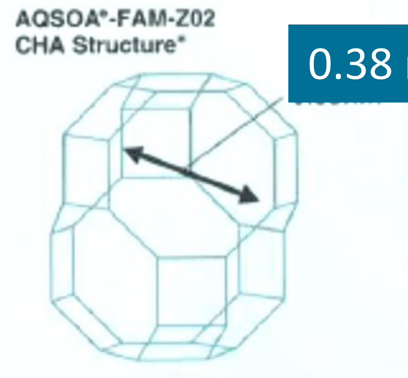
Functionalized Adsorbent Material (FAM)
ASQOA-Z02



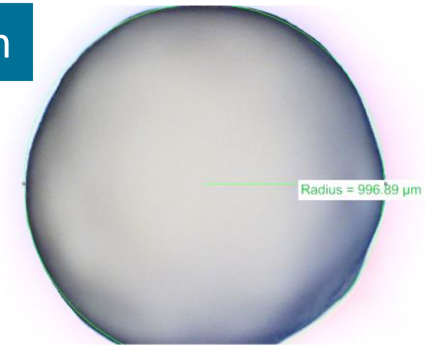
SAPO-34 crystallites. Y. Iwase, *Phys. Chem. Chem. Phys.* (2009), **11**, 9268



Mitsubishi



0.38 nm



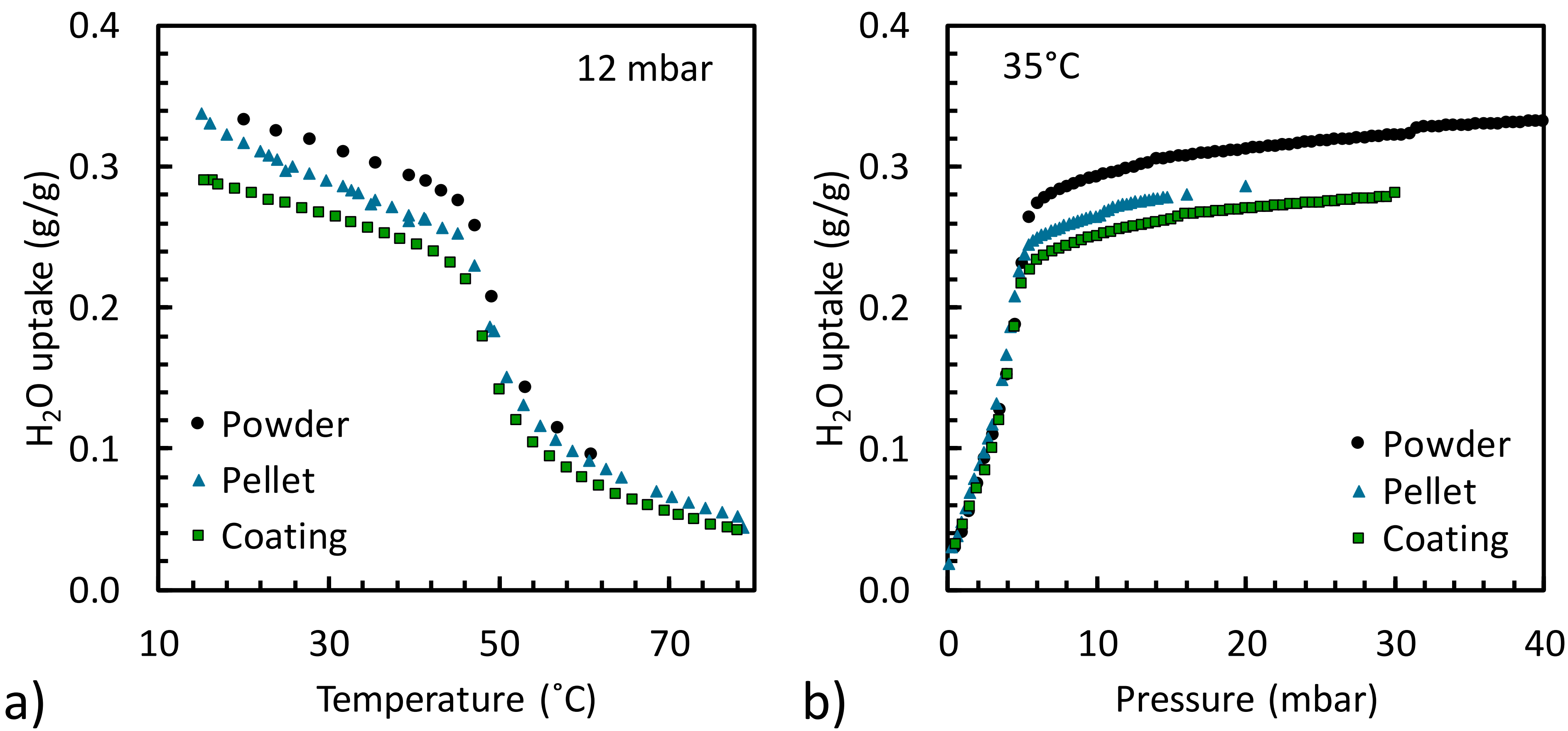
$$Si_xAl_yP_zO_2 \cdot nH_2O$$

x = 0.05–0.25, y = 0.4–0.6, z = 0.25–0.50, n = 0–1.5

FAM ASQOA-Z02 is a silicoaluminophosphate developed by Mitsubishi Plastics (similar to SAPO-34)

Pellets: 1.9 mm
Zeolite: 83-94% wt
SiO_2 binder: 6-17% wt

Isobar and Isotherm for FAM-Z02



- The Z02 pellets adsorbed ~9% less than the Z02 powder
- The Z02 coating adsorbed ~ 13.6% less that the Z02 powder

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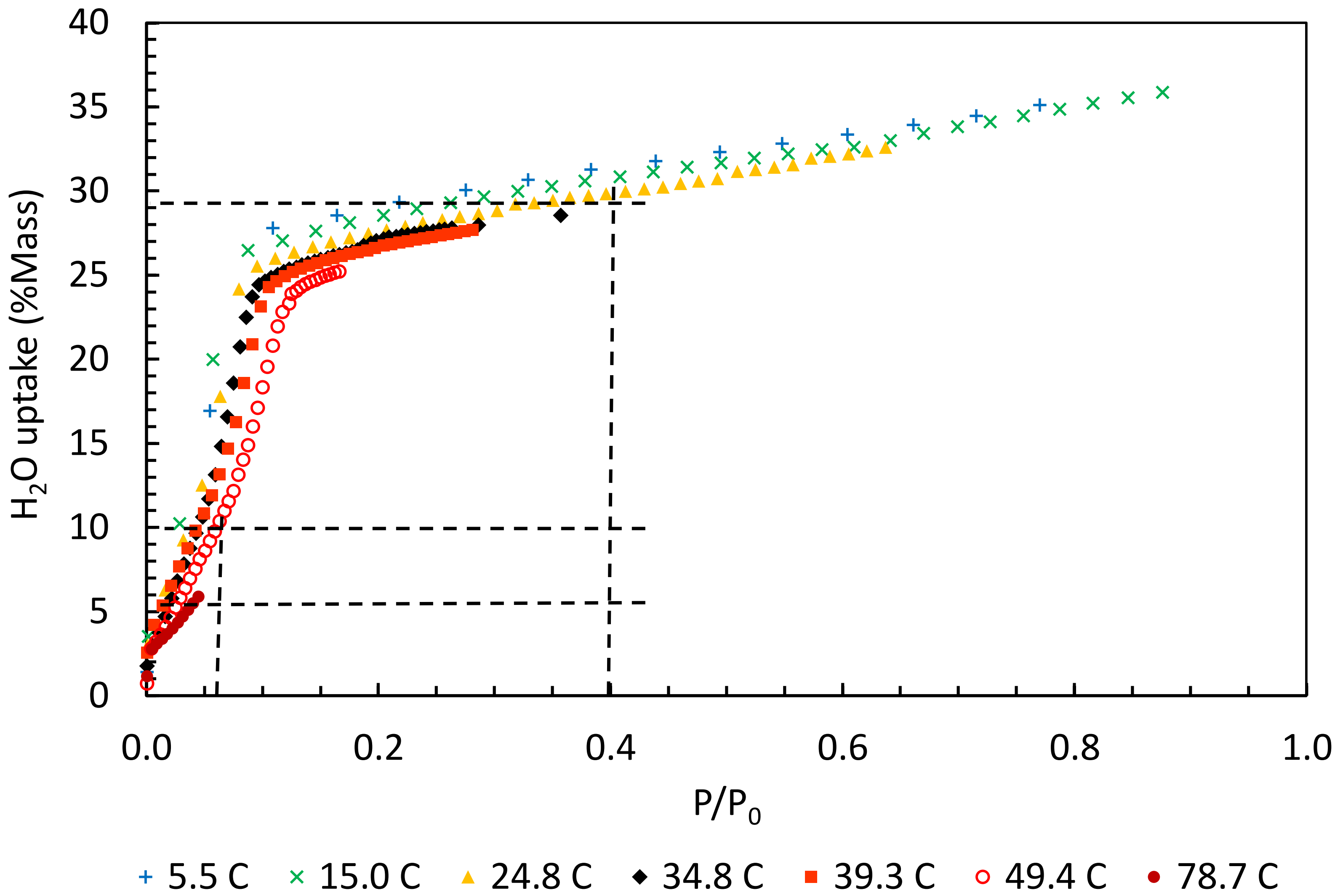
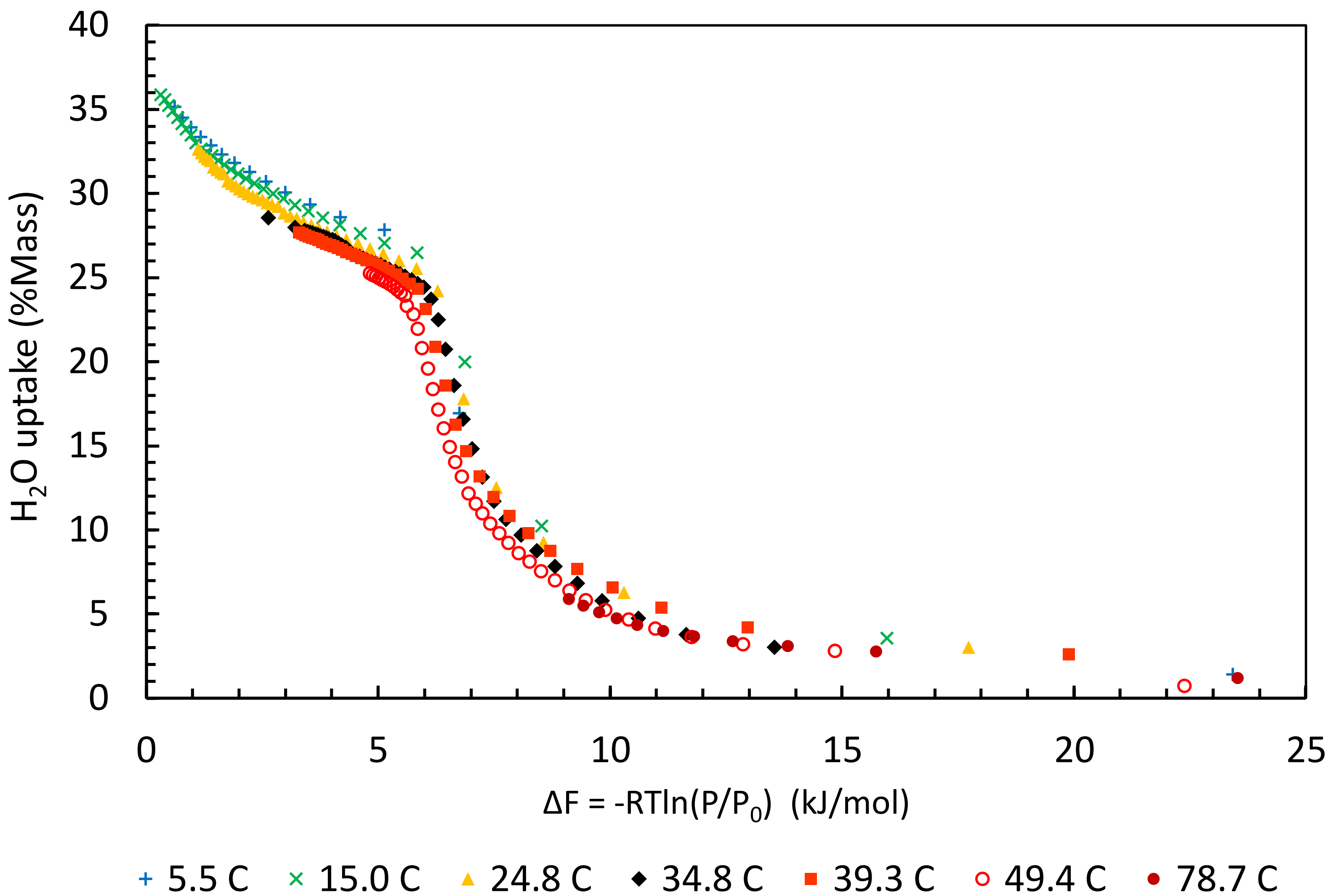
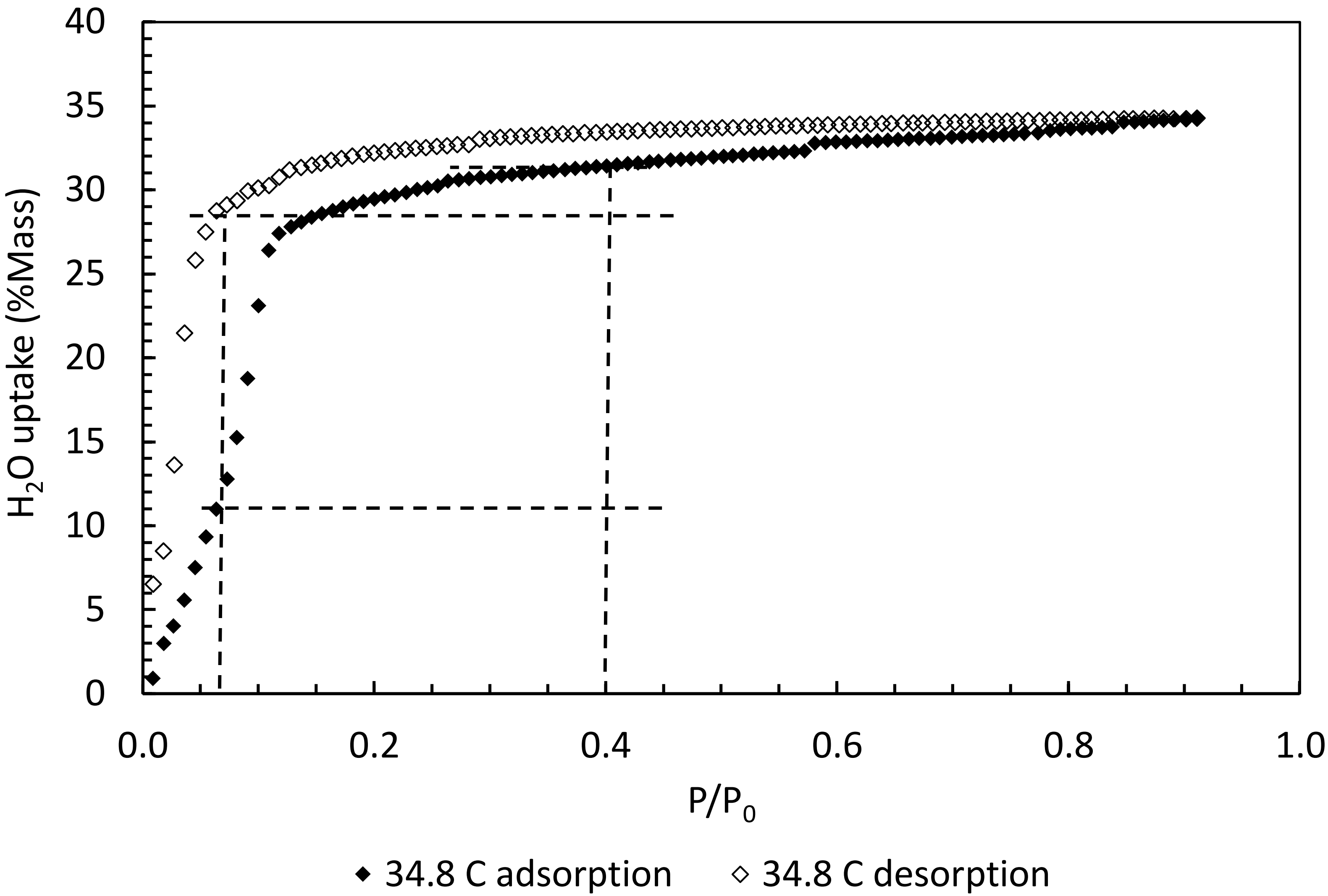
Water isotherms for Z02 pellets: Adsorption curves



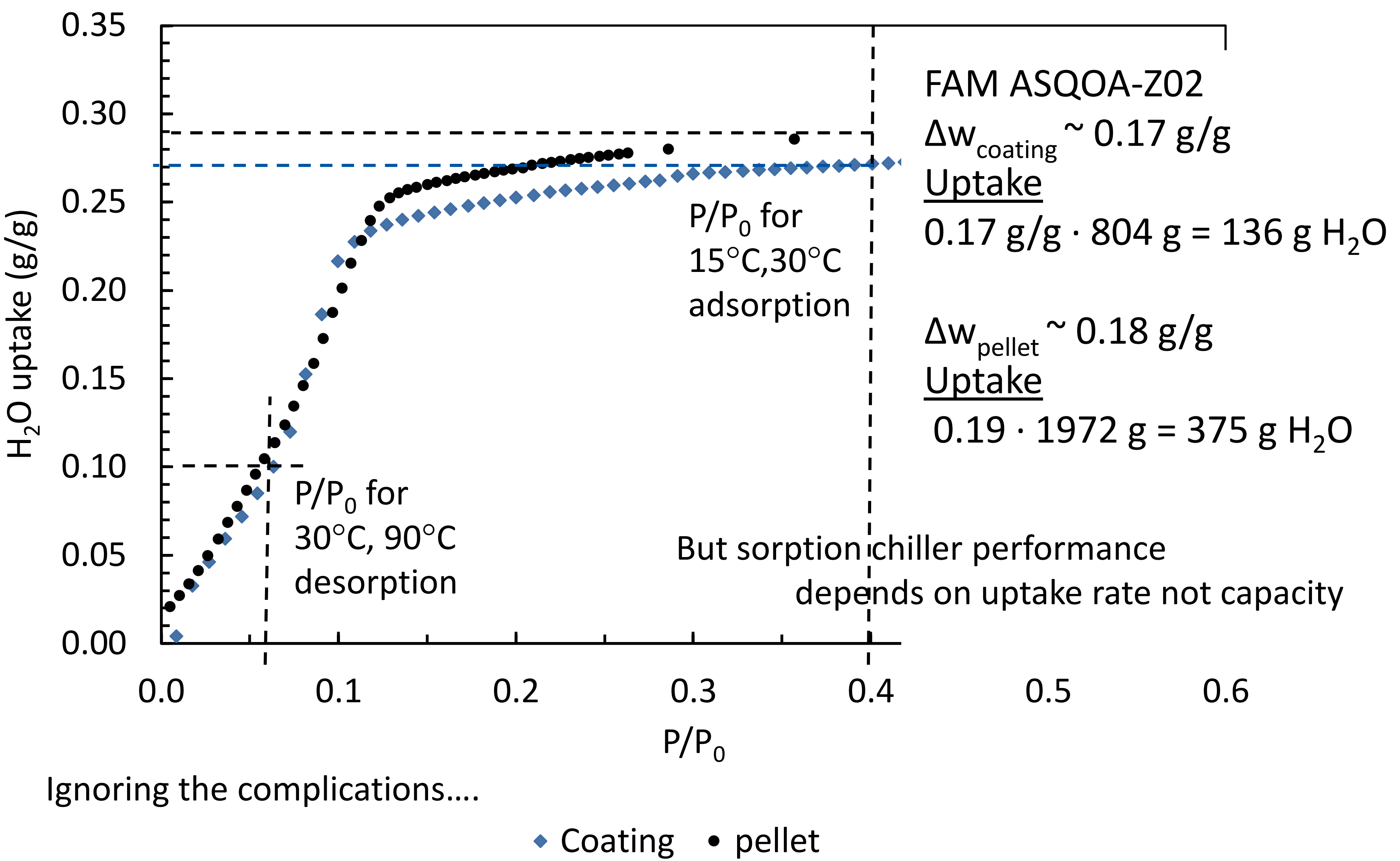
Z02 pellet characteristic curve



Water sorption isotherms for Z02 powder: Adsorption and desorption curve



Coating and pellet isotherms: Adsorption curves at 35°C



Ignoring the complications....

Specific cooling power as a function of cycle time

Performance of two adsorber bed sorption chiller, testing of two Z02 coated beds and two Z02 pellet beds

Heat Transfer at the Evaporator

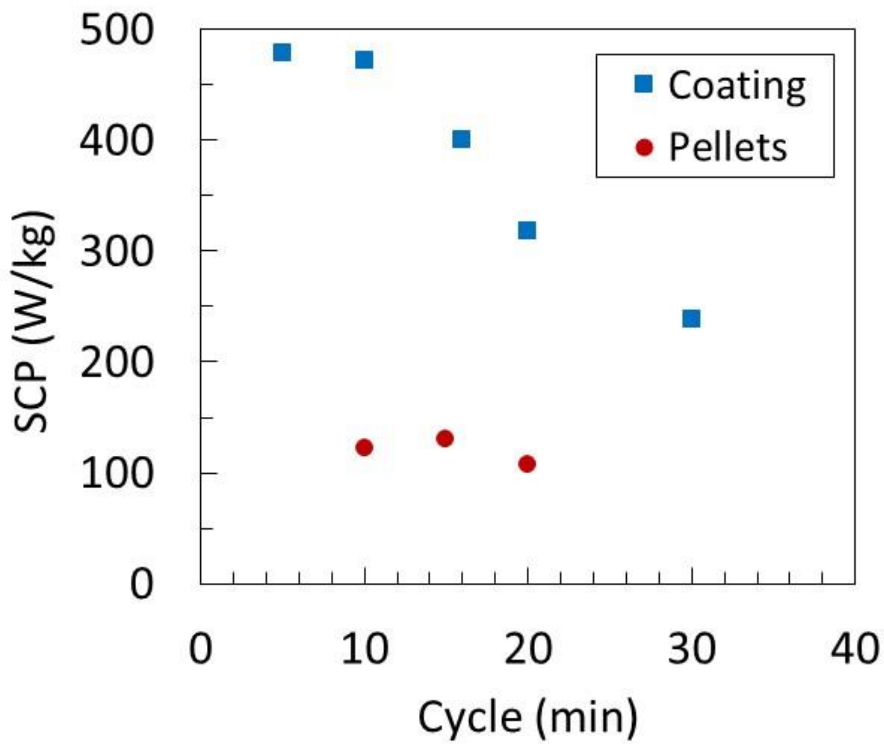
$$Q_{evap} = \int_0^{\tau} \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) dt$$

Specific Cooling Power

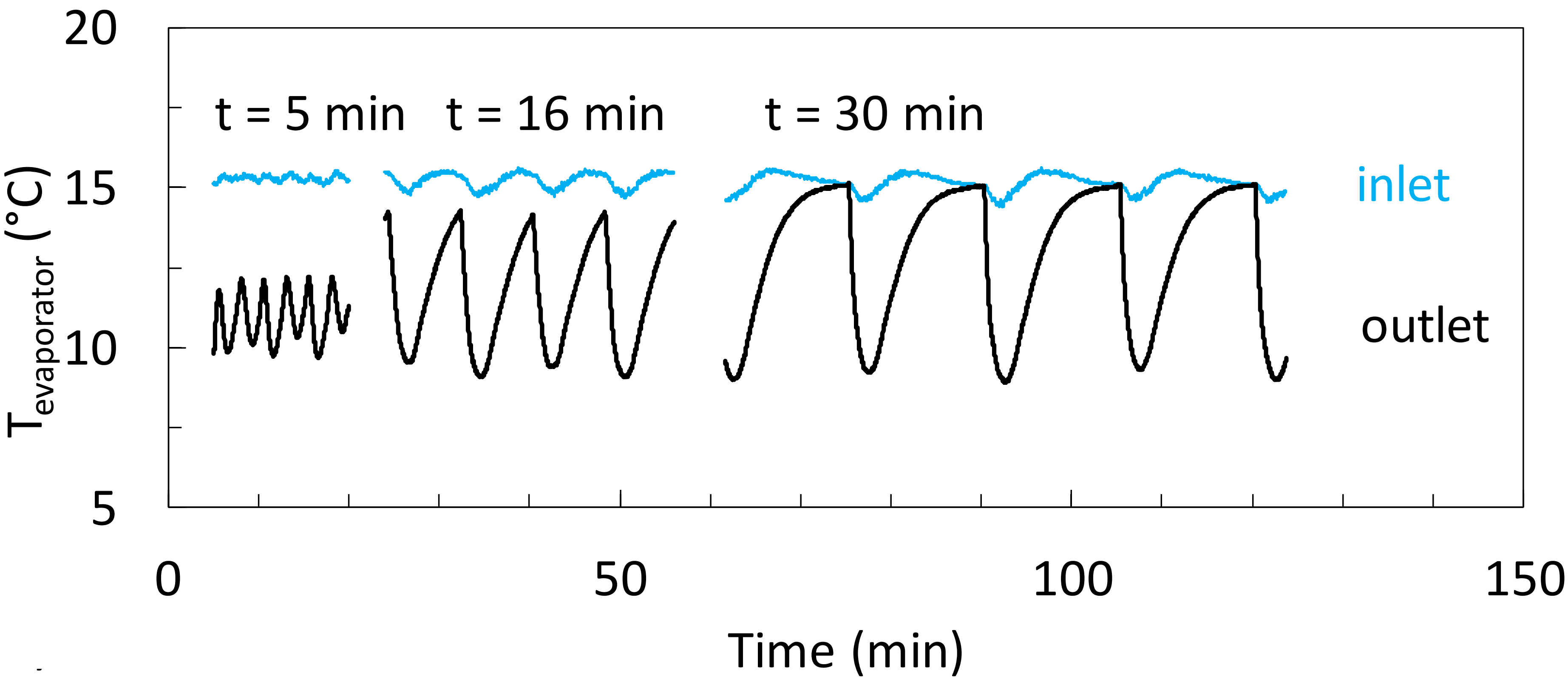
$$SCP = Q_{evap} / (m_{ads} \cdot t_{cycle})$$

Volumetric Specific Cooling Power

$$VSCP = Q_{evap} / (V_{ads} \cdot t_{cycle})$$

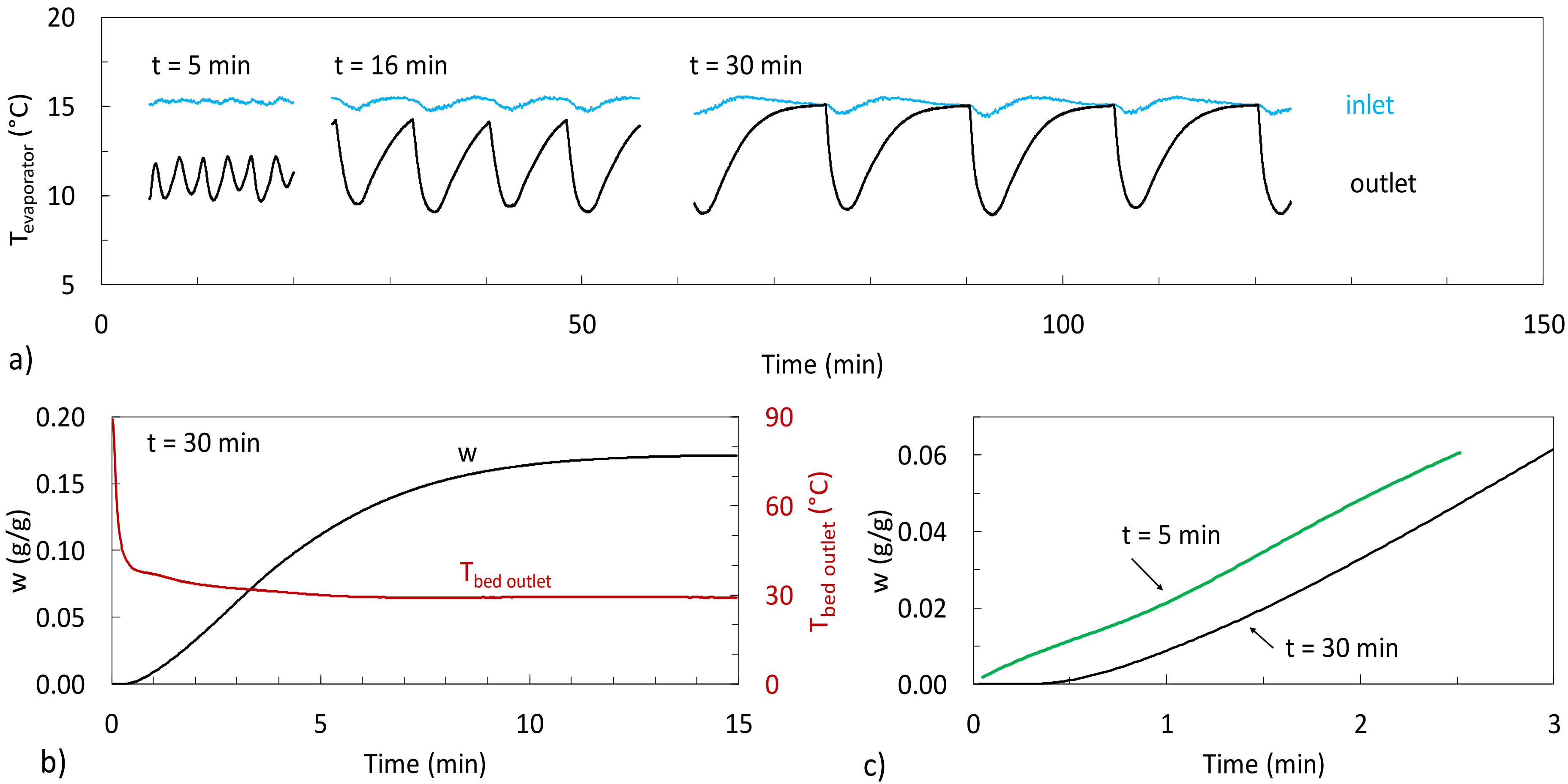


Operating conditions: T_{evap}= 15°C, T_{cond}=T_{ads}= 30°C, and T_{des}= 90°C



Evaporator cooling power can be used to calculate the water uptake rate of the sorbent.

Adsorption dynamics

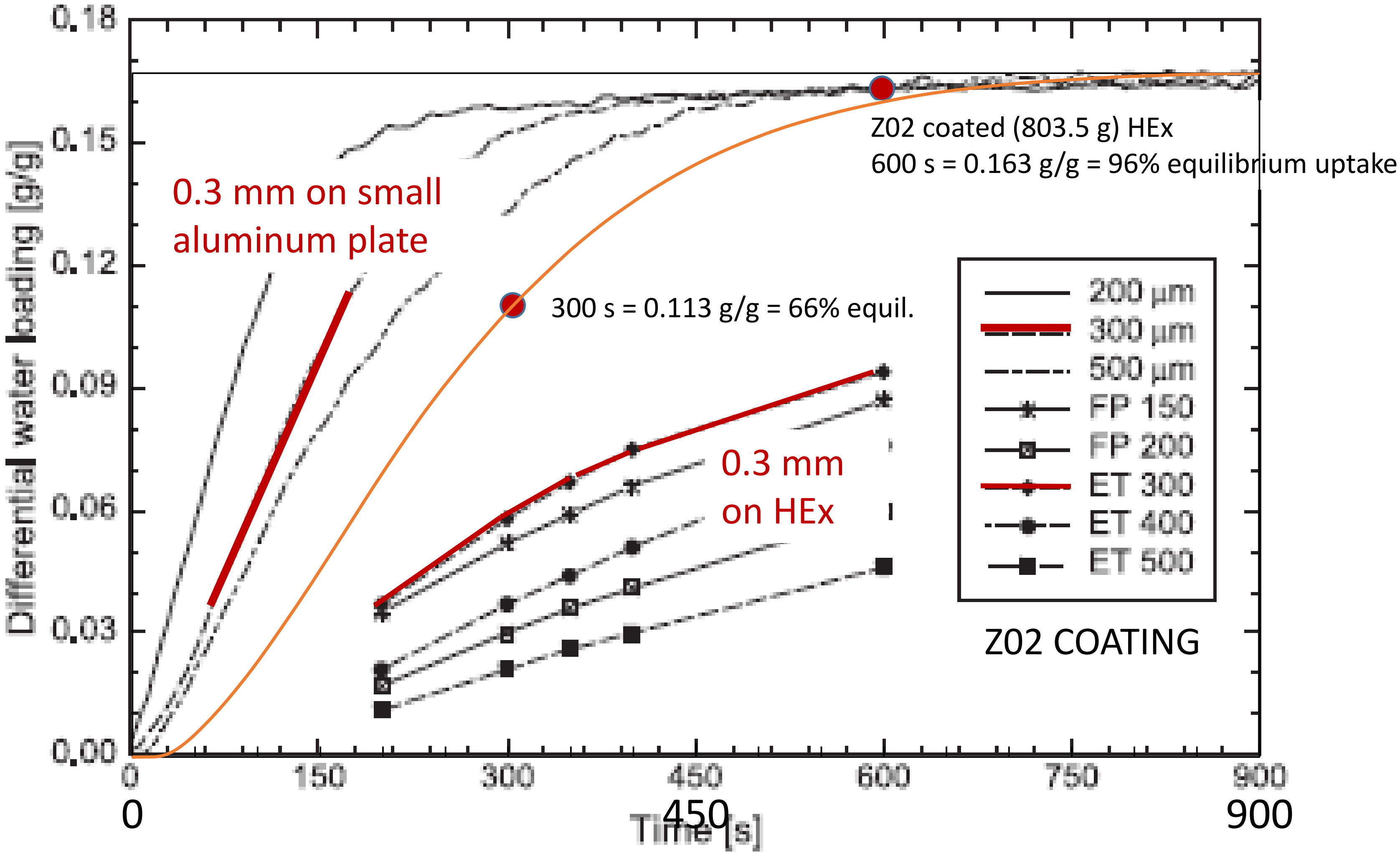


Characteristic time, τ, by fitting of dimensionless uptake vs time

$$X(t) = 1 - \exp(-t/\tau)$$

$\tau = 194 \pm 2$ s

Comparison to other tests of similar thickness Z02 coating (small samples and heat exchangers)



B. Dawoud, *Applied Thermal Engineering*, 50 (2013) 1645-1651

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Summary and Future Work

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- The sorption chiller system performance is now satisfactory
- Two Z02 coated HEx operated with 10 min cycles at 15, 30, 90 °C operating conditions had a SCP of 456 W/kg (90 kW/m^3) and COP of 0.27
- We have since tempted fate, running $CaCl_2$-silica gel adsorber beds in the lab scale chiller (some good data, and then, during downtime, corrosion in the evaporator accelerated beyond reason)
- The aluminum evaporator chamber was bead blasted and cleaned, and an anti-corrosion coating and a thin Teflon liner have been added
- Restart tests have been conducted with a Z02 coated bed and a loose grain microporous silica gel bed (Grace 408)
- Future test work includes new composites, new evaporator designs, new adsorber bed designs and difference chamber configurations

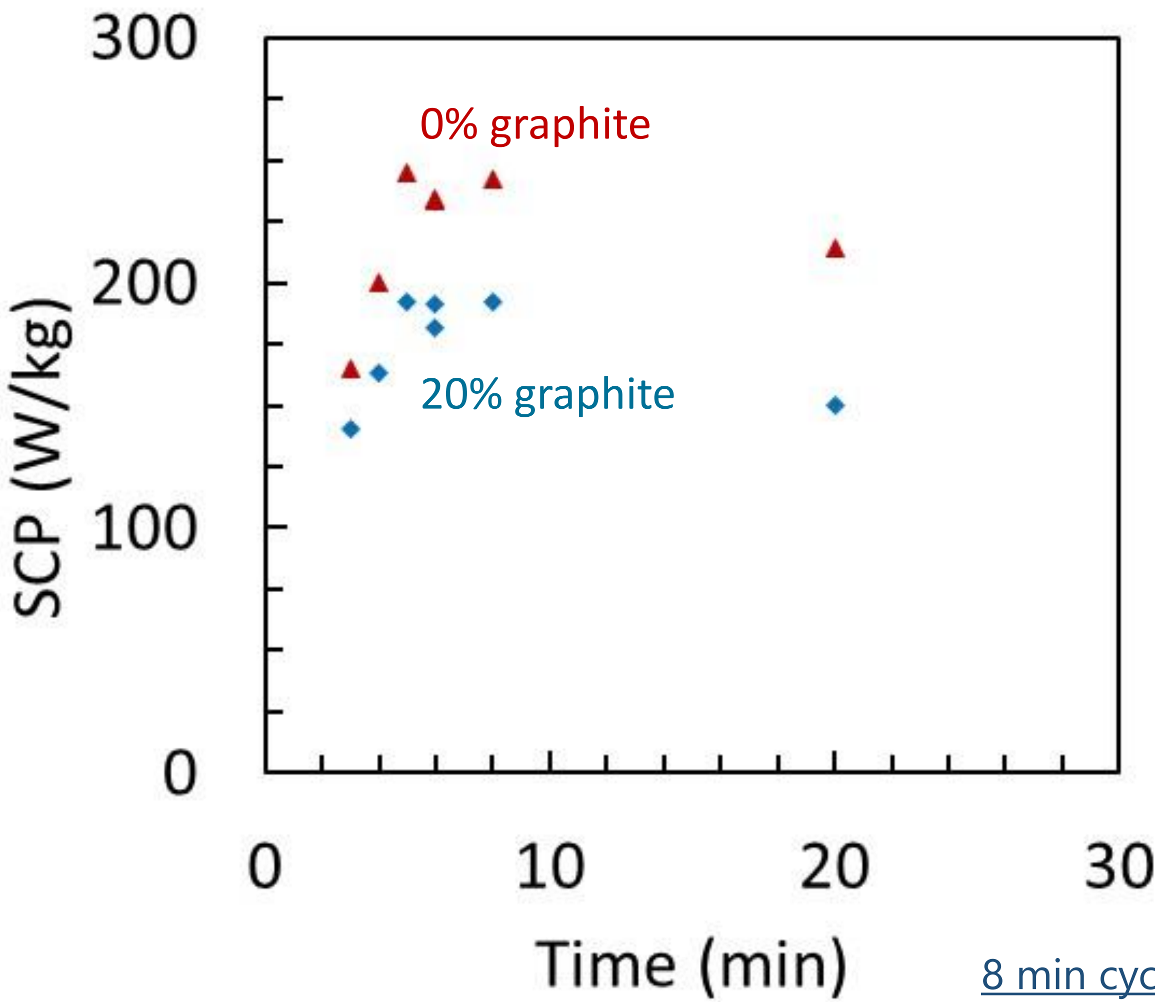
Thanks

Thank you for your attention!

Sorption chiller testing is a team effort.

Mina & Ecem have talks in the 14:15 session this afternoon (H31)

Specific Cooling Power: $CaCl_2$ composite tests



NEXT:
Swap the beds.

Increase uptake capacity.
Increase thermal conductivity.

Review data.
Think.

8 min cycles

	SCP	(System Power)
$CaCl_2$ 0%G	242 W/kg	(630 ± 20 W)
$CaCl_2$ 20%G	192 W/kg	(580 ± 20 W)

Performance of Sorption Chiller Composite Beds
$CaCl_2$, B150 silica gel, PVA with 0% or 20% graphite flakes

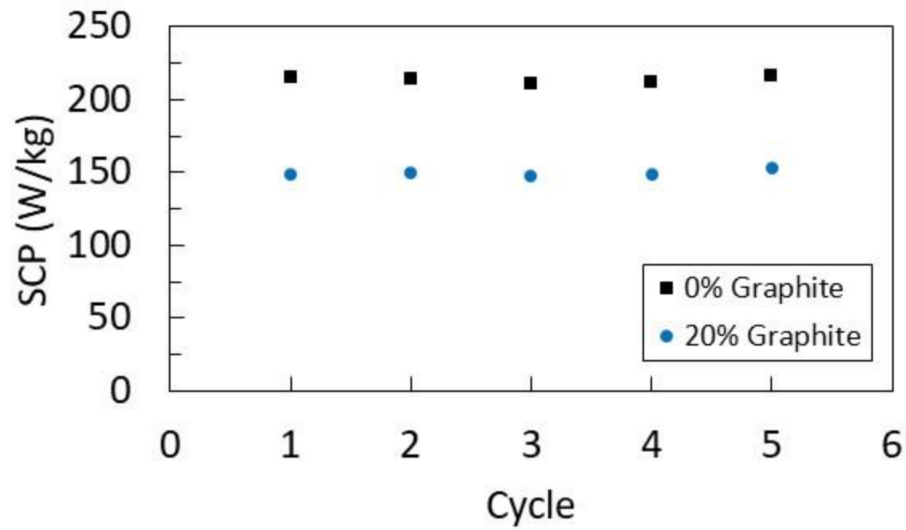
Sorption Chiller Performance

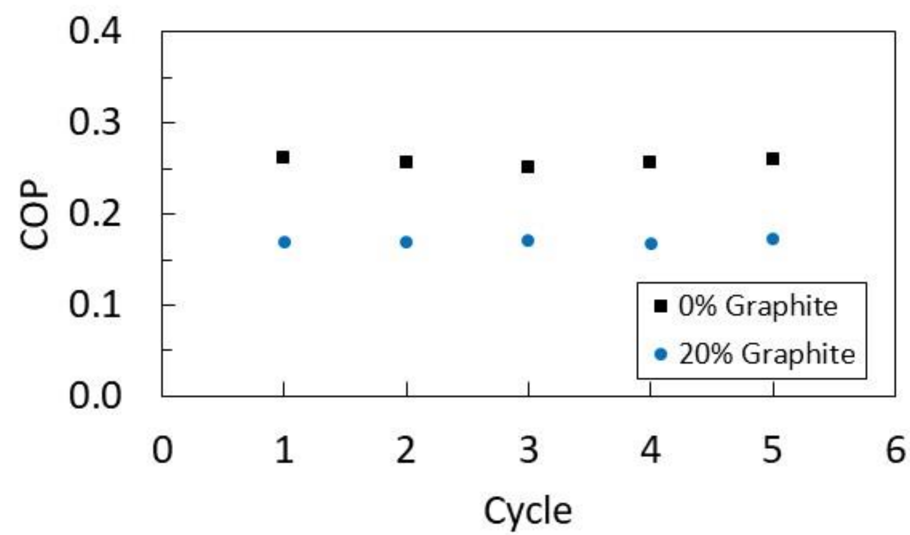
15°C, 30°C, 90°C
20 min (1200 s) cycles

214 ± 2 W/kg $CaCl_2$ composite with 0 wt% graphite flakes

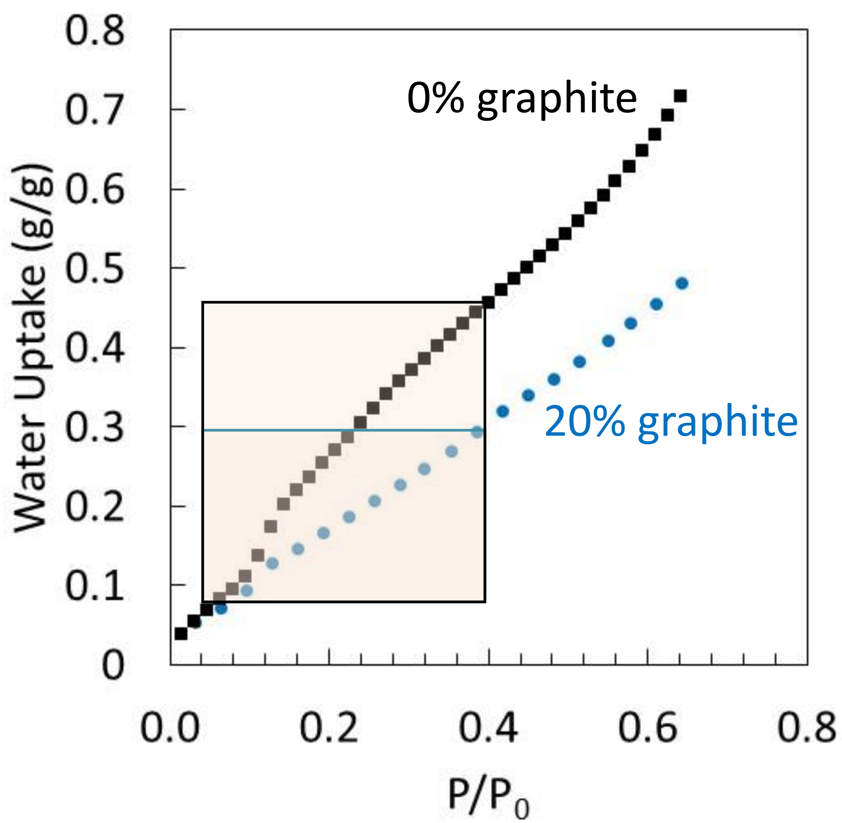
150 ± 2 W/kg $CaCl_2$ composite with 20 wt% graphite flakes

The difference in SCP for long cycles (beds adsorbing and desorbing to near equilibrium) reflects the difference in uptake capacities between the beds.





Expectations from sorption isotherm data



For a long cycle, we get 70% SCP from the graphite containing composite with 60% uptake capacity.

15°C/30°C $P/P_0 = 0.06$

30°C/90°C $P/P_0 = 0.40$

0% graphite composite

$\Delta w = 0.45\text{-}0.08 = 0.37$ g/g

20% graphite composite

$\Delta w = 0.30\text{-}0.08 = 0.22$ g/g

<u>Sorption Chiller Performance</u>
for 15/30/90°C and 600 s cycles

214 ± 2 W/kg $CaCl_2$ composite with 0 wt% graphite flakes

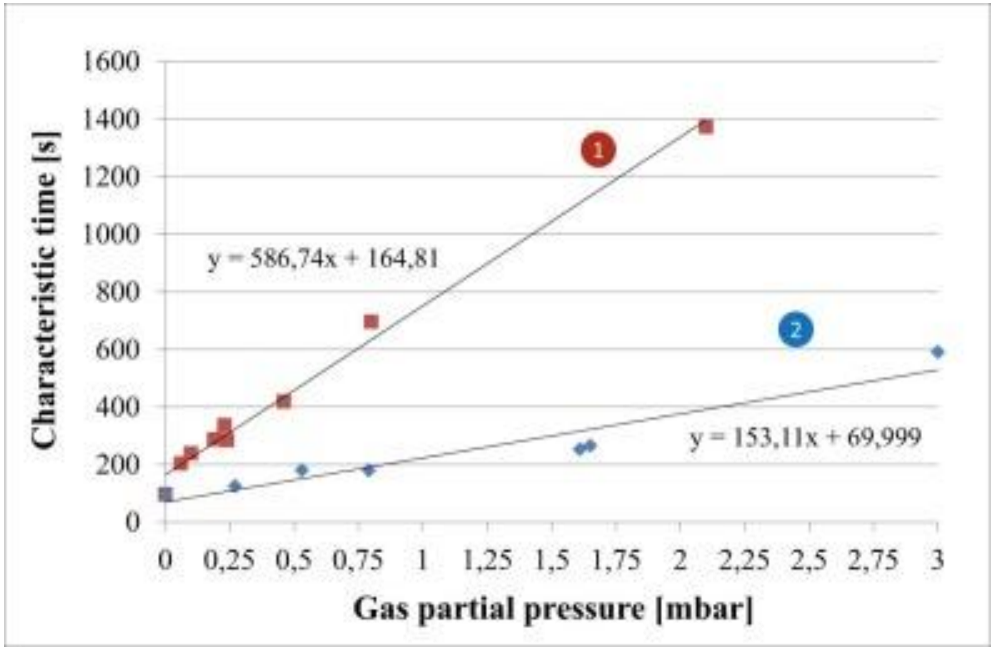
150 ± 2 W/kg $CaCl_2$ composite with 20 wt% graphite flakes

Dramatic effect of residual gas on dynamics of isobaric adsorption stage of an adsorptive chiller

A. Frazzica et al., Applied Thermal Engineering 96 (2016) 385-390

Adsorption dynamics studied by a gravimetric large temperature jump method

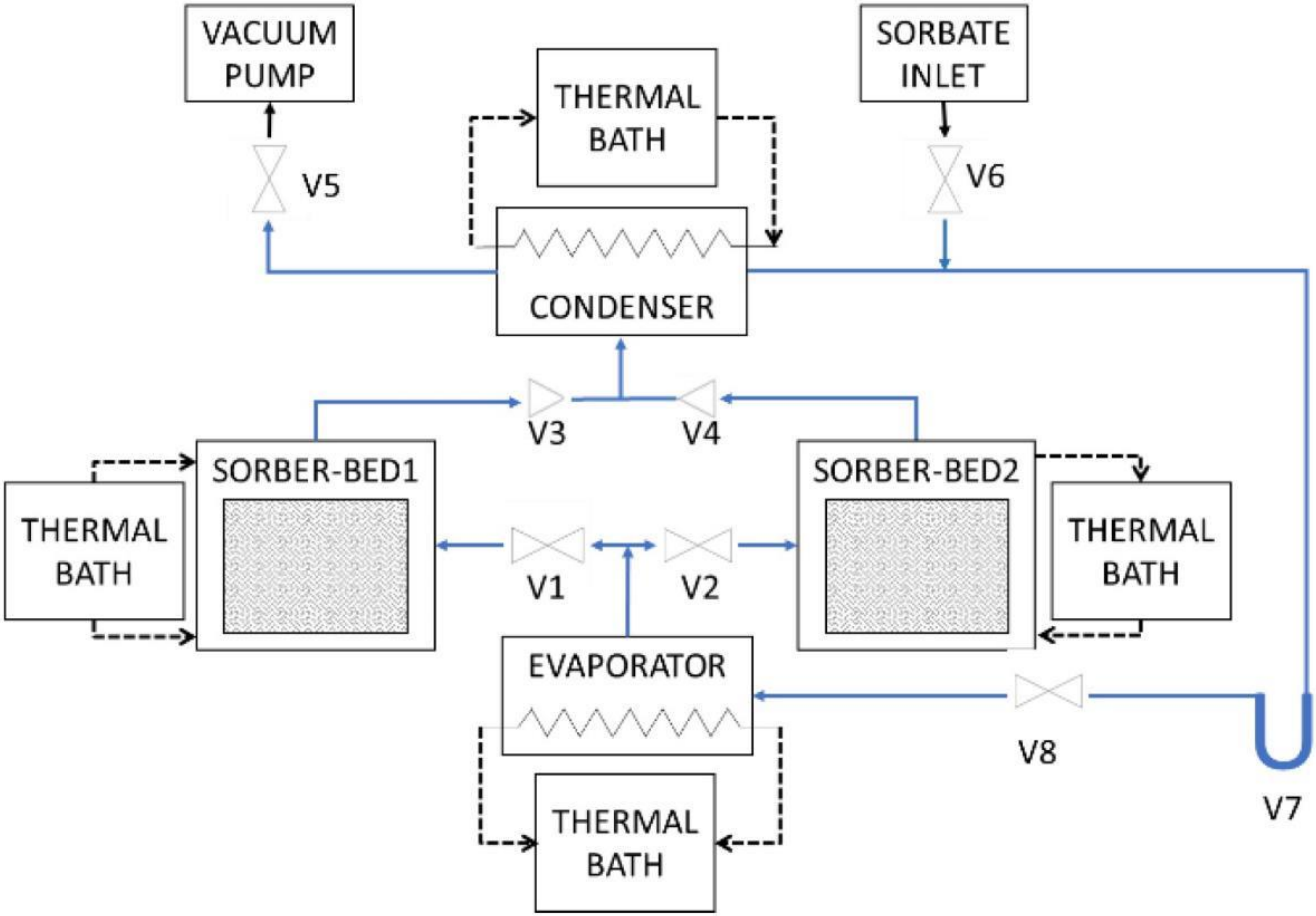
Tested small scale adsorbers, based on commercial heat exchangers (HExs) filled with loose grains of the adsorbent AQSOA™-FAM-Z02.



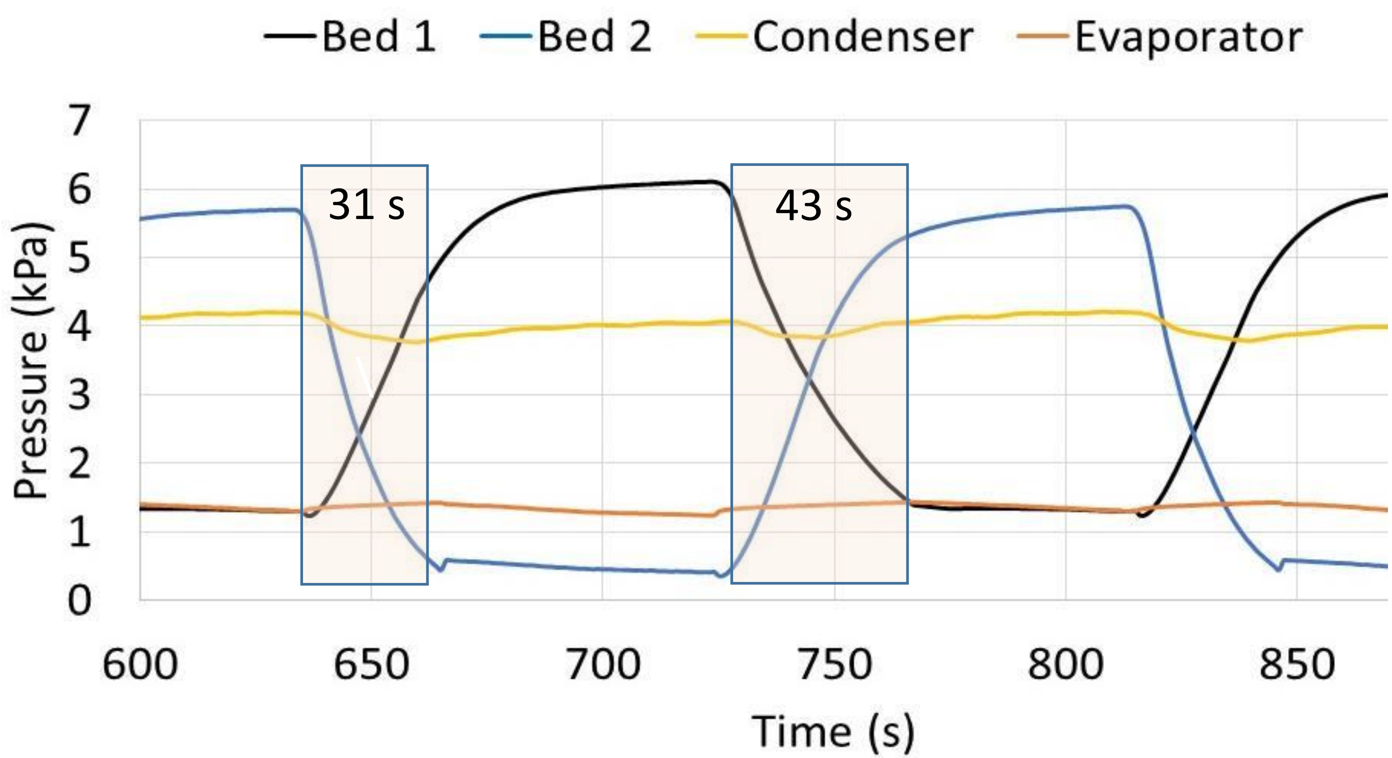
- The experimental uptake curves are exponential
- Adsorption rate is extremely sensitive to traces of residual air
- The effect of hydrogen is less dramatic as compared with air

HEx (L,W,H)	35.2×3.8×30.5 cm^3	Cycle times	5, 10, 20, 30 min
Fin spacing	2.54 mm (10 fpi)	$T_{desorption}$	75, 80, 90 °C
Surface area	2.8 m^2	$T_{adsorption}$	20, 30, 40 °C
HEx weight	2.51 ± 0.03 kg	$T_{condenser}$	20, 30, 40 °C
Z02 coating	0.80 kg per Hex	$T_{evaporator}$	5, 10, 15 °C
Z02 pellets	1.97 kg per Hex		

Sorption System Schematic



Switchover times

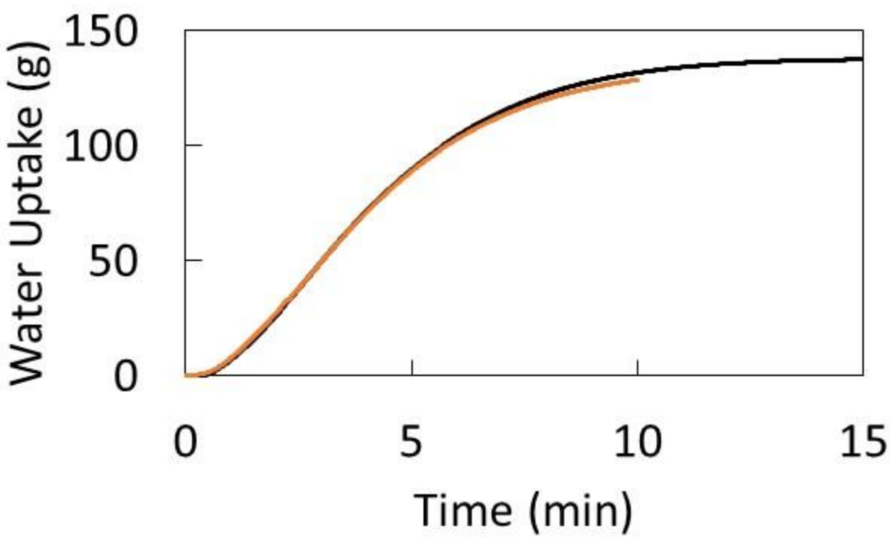


The temperature of the beds switch at the programmed cycle time, but adsorption only begins once the pressure in the adsorber drops to the trigger point for opening the gate valve.

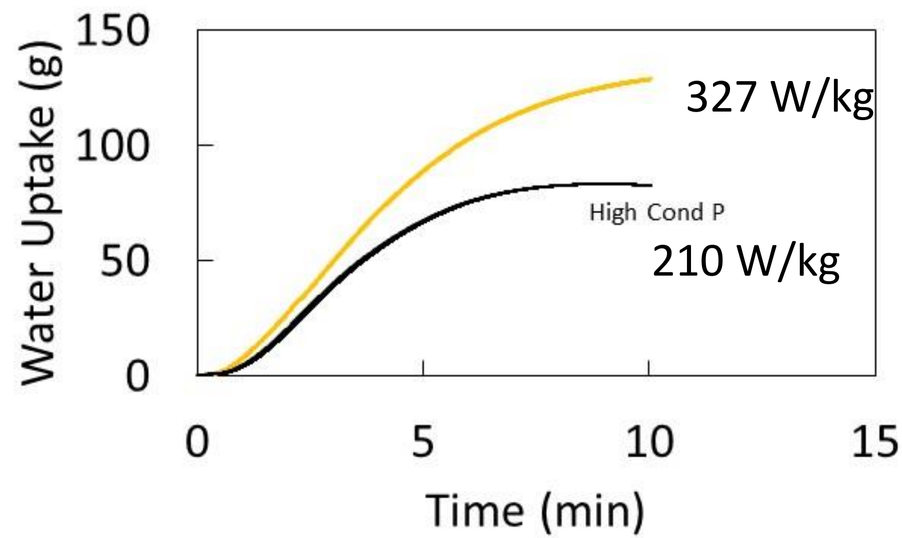
The pressure drop time for Bed 1 and Bed 2 differ significantly.

Example of non-condensable gas effect in our system

30 min and 20 min cycles



20 min cycles



High condenser pressure decreased both uptake rate and total water uptake per 10 min half cycle

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Effect of Residual Gas on Water Adsorption Dynamics Under Typical Conditions of an Adsorption Chiller

I. Glaznev, D. Ovoshchnikov, Yu. Aristov, *Heat Transfer Engineering* 31 (2010) 924

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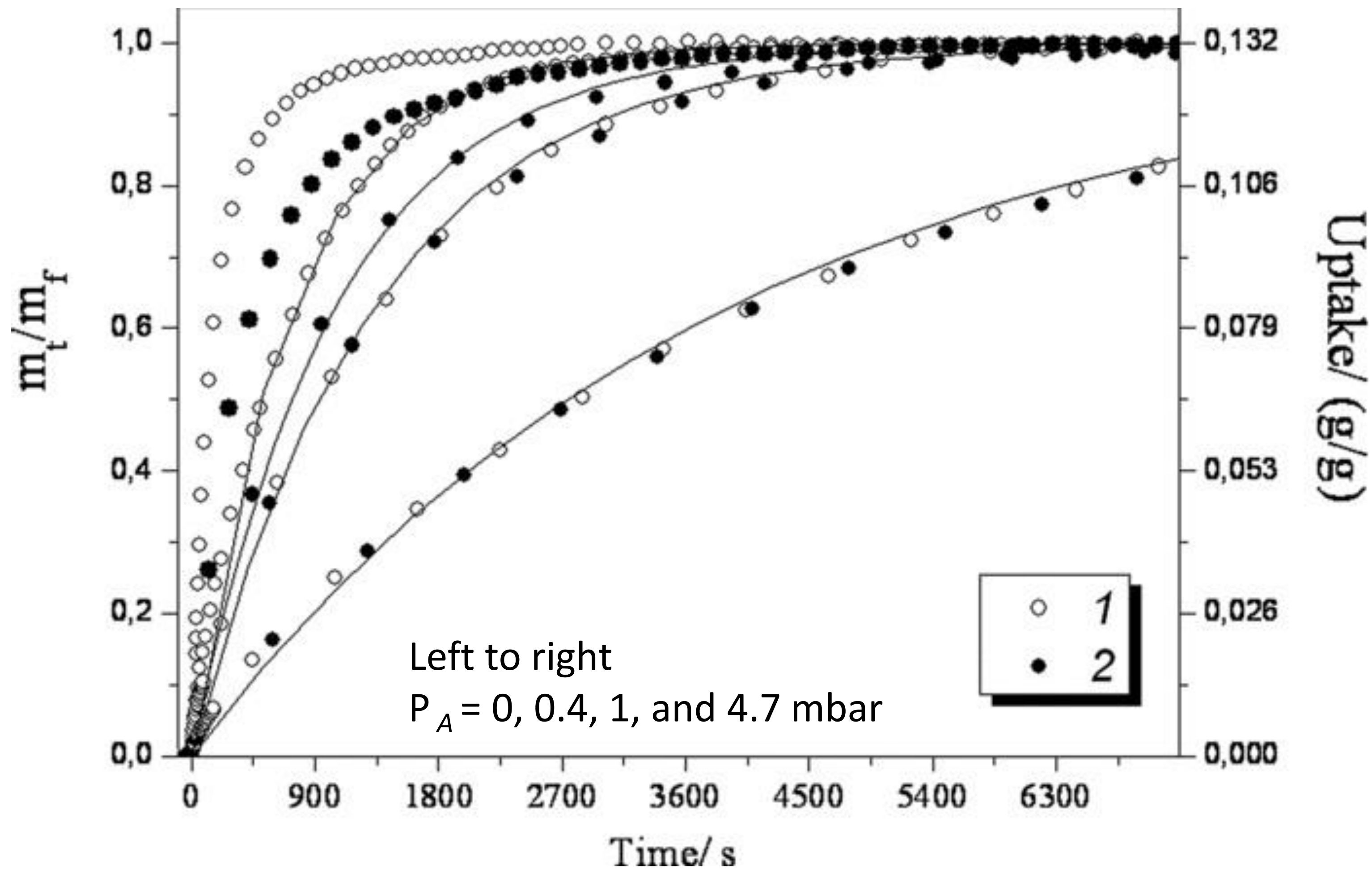
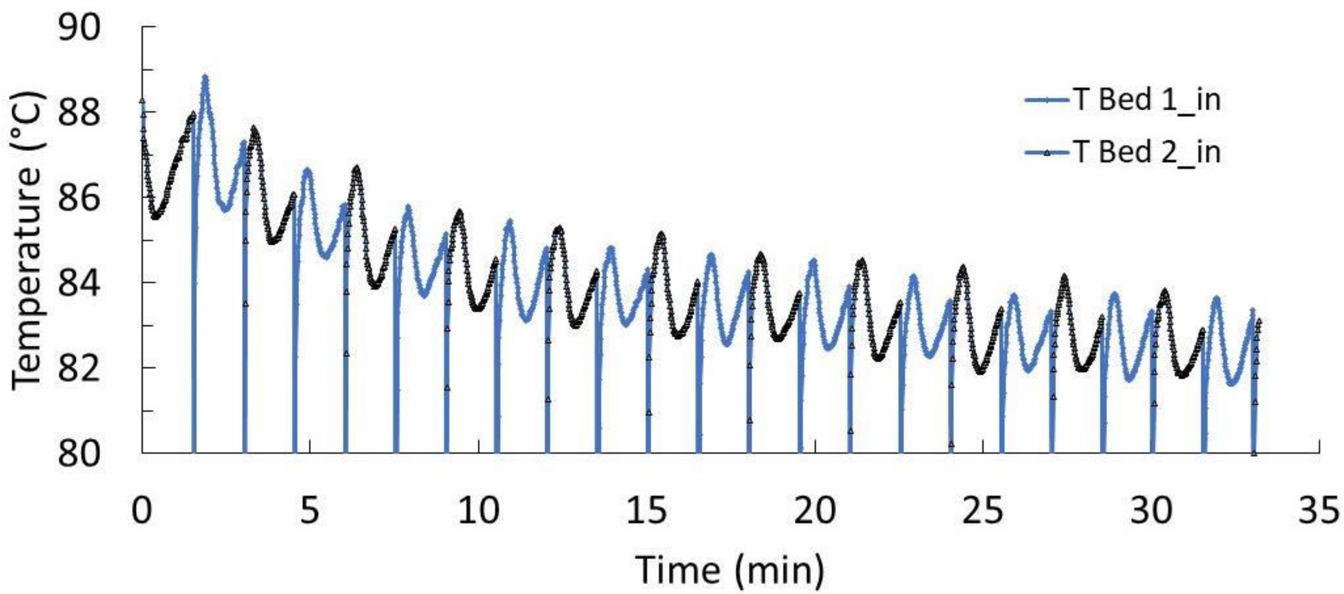


Adsorption rate for SWS-1L loose grains 0.8–0.9 mm (1) and 1.4–1.6 mm (2) in the presence of different partial pressure of air (P_A). Symbols = experimental data; lines $m_t = m_0 + (m_f - m_0)[1 - \exp(-t/\tau_{exp})]$.

Challenges: Heating/cooling circulator power



For tests with short cycles and high SCP, the heater on circulator for desorption can be overwhelmed.

Desorption temperature drops with repeated cycling, resulting in a SCP decrease.

A rise in condenser temperature (and therefore pressure) can also be observed for individual cycles.