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3D Unsteady CFD with Heat and Mass Transfer Simulations of Solar Adsorption Cooling System for Buildings

W. Yaïci, E. Entchev, J. Ranisau

CanmetENERGY Research Centre, Natural Resources Canada, Ottawa, ON, Canada

Introduction

Conventional cooling systems for air conditioning of buildings are responsible for a significant percentage of the greenhouse and ozone depletion effect because of refrigerant harmful gases released into the atmosphere. In recent years, extensive attention has been paid on the application of solar cooling for buildings. Solar cooling technology appears to be a promising alternative to the conventional vapour compression electrical driven machines. Solar cooling systems have the advantage of using harmless working fluids such as water. They can decrease the peak loads for electricity utilities and can contribute to a substantial decrease of the CO_2 emissions, which cause greenhouse effect.

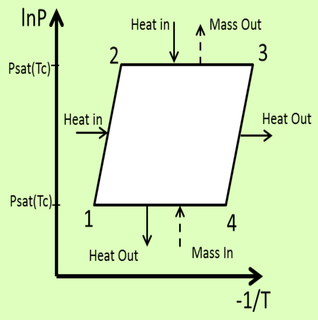
Amongst cooling technologies, low-temperature solar-driven environment-friendly adsorption cooling systems are emerging viable alternatives to electricity-driven vapour compression systems. They seem to have a promising market potential. Adsorption cooling systems are already a commercialised product for more than two decades with several competitors in the market. The greatest challenge for their widespread use is the reduced thermal and mass transfer in the adsorption bed resulting in slow reaction rates, long cycle times, low specific cooling power and small coefficient of performance. Therefore, the technology still needs research for performance design optimisation under different climate conditions when powered by solar heat.

In this investigation, a three-dimensional unsteady Computational Fluid Dynamics (CFD) coupled with heat and mass transfer model of solar-driven adsorption cooling unit using silica gel-water, operating in both adsorption and desorption modes is developed to simulate and analyse the system performance.

Operating Principles

Fig. 1 illustrates the operating principles of a thermodynamic cycle of an adsorption cooling system and a double-bed adsorption chiller.

Operating Cycle



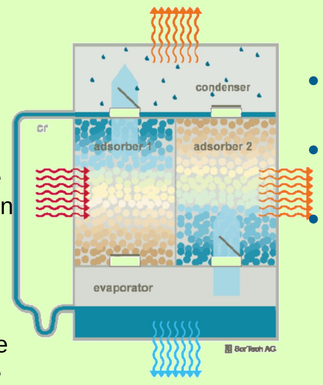
- **Heating desorption condensation**:

A hot water circuit heats the adsorbent bed, desorbing the adsorbate and a heat rejection fluid condenses the vapour.

- **Cooling adsorption evaporation**:

A heat rejection fluid cools the adsorbent bed, adsorbing the adsorbate and a cold water circuit is chilled of evaporation.

Adsorption Chiller



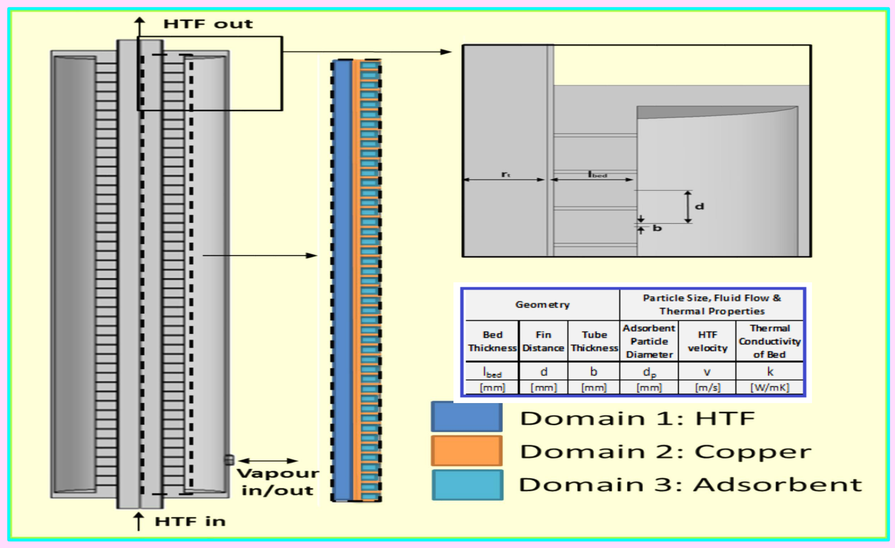
- Working pair: Silica gel – Water
- Driving temperature requirement: 65-75°C
- Environmentally friendly solid sorbent and refrigerant

Fig. 1. Schematics of a diagram of a thermodynamic cycle of an adsorption cooling system and double-bed adsorption chiller [1-3].

Model Geometry

3D unsteady models of plate-fin and finned adsorption cooling units were built in the COMSOL Multiphysics commercial software with CFD, Heat Transfer and Chemical Reaction Engineering modules.

Fig. 2 shows the geometric model of the finned adsorption chiller based on silica gel-water working pair operating on adsorption and desorption modes.



Geometry			Particle Size, Fluid Flow & Thermal Properties		
Bed Thickness	Fin Distance	Tube Thickness	Adsorbent Particle Diameter	HTF velocity	Thermal Conductivity of Bed
l_{bed}	d	b	d_p	v	k
[mm]	[mm]	[mm]	[mm]	[m/s]	[W/mK]

Fig. 2. Schematic of the simulated geometry for a finned adsorption chiller.

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Model Set-up

The Navier-Stokes and energy equations in three-dimensional form were used to solve for the transient hydrodynamic, mass and thermal fields. Therefore, the resulting governing equations can be written as follows:

***Momentum balance*:**

$$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=\nabla\cdot[-pI+\mu(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^2)]$$
$$\rho\nabla\cdot(\boldsymbol{u})=0$$

Energy balance:

Heat Transfer in the HTF:

$$\rho_f c_f\frac{\partial T_f}{\partial t}-k_f\Delta^2 T_f+\rho_f c_f v_f\Delta T_f=0$$

Heat Transfer in the metal:

$$\rho_t c_t\frac{\partial T_t}{\partial t}-k_t\Delta^2 T_t=0$$

Heat Transfer in the adsorbent:

$$(1-\varepsilon)\rho_s c_s\frac{\partial T_s}{\partial t}-\varepsilon\rho_v c_{p,v}\frac{\partial T_s}{\partial t}+(1-\varepsilon)\rho_s X c_{p,l}\frac{\partial T_s}{\partial t}$$
$$-(1-\varepsilon)\rho_s|\Delta H|\frac{\partial X}{\partial t}-k_s\Delta^2 T_s+\rho_v c_{p,v}\boldsymbol{u}\Delta T_s=0$$

***Mass balance*:**

$$\varepsilon\frac{\partial\rho_v}{\partial t}+(1-\varepsilon)\rho_s\frac{\partial X}{\partial t}-D_m\Delta^2\rho_v+\Delta(\boldsymbol{u}\rho_v)=0$$

Linear driving force model for the internal mass transfer resistance

$$\frac{\partial X}{\partial t}=k_m(X_e-X)$$

For the water adsorption process:

Temperature dependent mass transfer coefficient and diffusion coefficient [4]:

$$k_m=\frac{15}{r_p^2}D_m \qquad D_m=D_o\exp\left(-\frac{E_a}{RT_S}\right)$$

Kinetic expression for silica gel RD [5]:

$$X_e=a\left(\frac{P}{P_{sat}}\right)^b$$

$$a=a_0+a_1T_s+a_2T_s^2+a_3T_s^3$$
$$b=b_0+b_1T_s+b_2T_s^2+b_3T_s^3$$

$$P_{sat}\,[kPa]=0.1333\cdot 10^{8.07131-\frac{1730.63}{T_s-39.724}}$$

Simulation Results

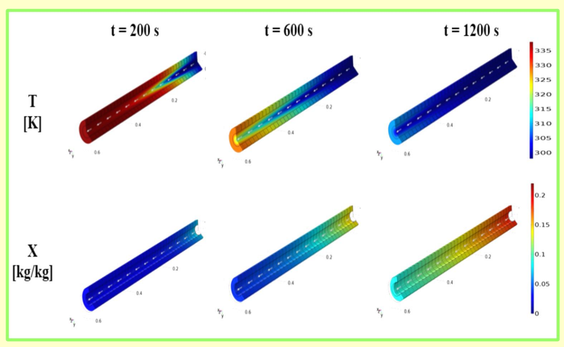

Fig. 3. 3D temperature and adsorbed water profiles at t = 200, 600 and 1200 s for the adsorption cooling system in adsorption mode.

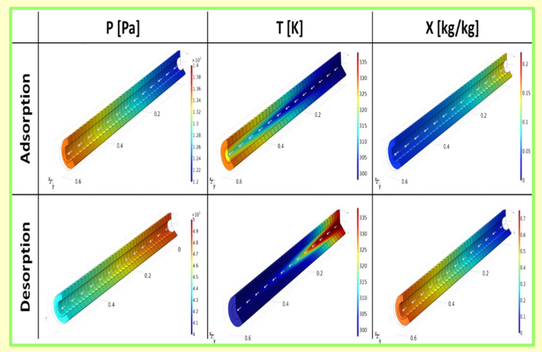

Fig. 4. 3D view of the adsorption and desorption cyclic performances at t = 600 s.

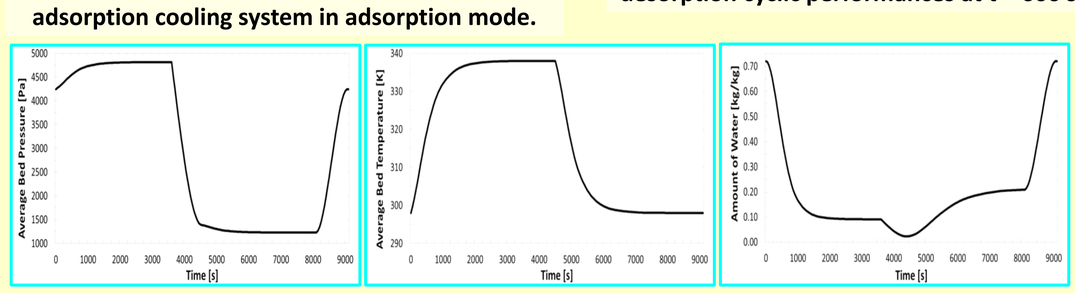

Fig. 5. 1D profiles for an adsorption-desorption cycle of average bed pressure, average bed temperature and amount of water. The cycle starts with desorption for 3600 s, then an evaporator pressure change for 1000 s, adsorption for 3600 s and ends with a condenser pressure change for 1000 s.

Conclusion

This study presented the results of 3D unsteady CFD with heat and mass transfer simulations using COMSOL to investigate the influence of design and operating parameters on the performance of a solar powered adsorption cooling system. Validation of the unsteady flow computation of plate-fin and finned adsorption results with experimental data found in literature showed a good agreement. A base case adsorption cooling system using silica gel-water as the working pair is simulated. The computational results confirmed the importance of the combined geometrical and operating effects on the system performance. The model may serve as an effective tool to improve and optimise adsorption cooling system parameters on existing prototypes or at early design stages.

References

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