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Preliminary model for an adsorption chiller designed for data centre rack-based cooling

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Abstract

A novel concept for a rack-integrated adsorption chiller integrates a compact adsorption chiller within each server rack for hybrid liquid/air cooling. This system utilizes the server's waste heat as the driving input for the ad/desorption processes. The compact design incorporates direct evaporation/condensation heat exchangers, enabling refrigerant distribution entirely in the liquid phase. This work presents a preliminary lumped-parameter model of the rack-integrated adsorption chiller, focusing on its conceptual framework and preliminary results. The model consists of a system of 10 ordinary differential equations, addressing the energy and mass balances of various components.

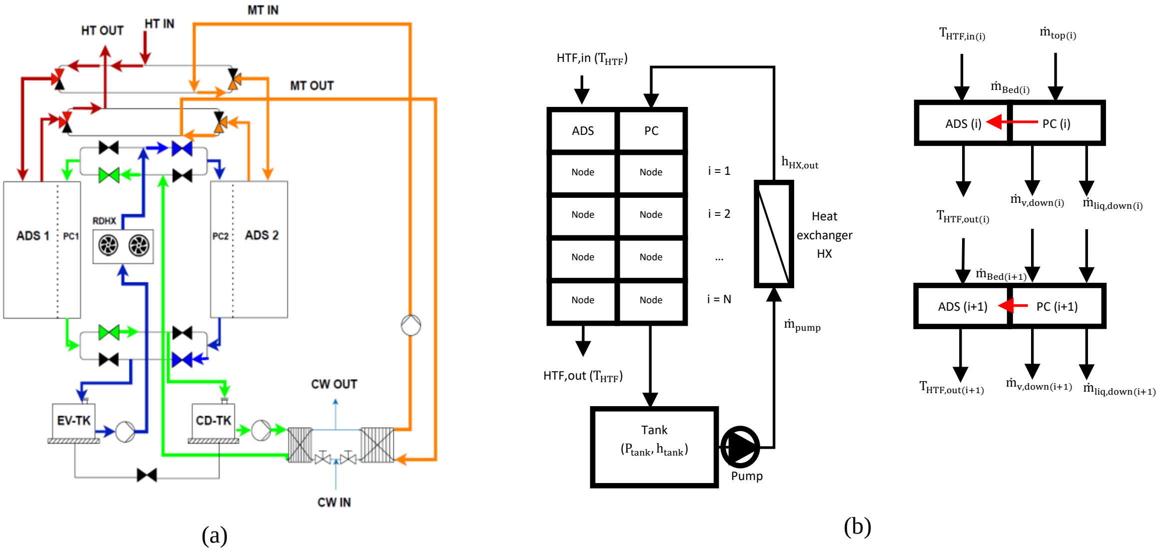
Keywords: adsorption, data centre, rack-cooling, lumped-parameter model

Introduction/Background

Data centre cooling systems can be classified on air-based or liquid-based, and some of them can be focused on room-based, row-based, or rack-based strategies. Recently, a novel rack-integrated adsorption chiller was proposed in a concept that contemplates a compact adsorption chiller integrated within each server rack for hybrid rack-based liquid/air cooling [1,2]. This way, each server is cooled down by its own adsorption chiller, with the server’s waste heat used as driving heat input for the ad/desorption processes. This rack-integrated adsorption chiller is compact enough to fit inside the server racks thanks to new direct evaporation/condensation heat exchangers that allow the refrigerant distribution to be done completely in liquid phase, avoiding large vacuum valves for vapor transport. These new heat exchangers are phase-change chambers in direct communication with the adsorbers where the liquid refrigerant cascade is distributed. The developing and testing of this prototype is also one of the objectives of the EU-funded project HYCOOL-IT [3]. In this work, the preliminary model of this rack-integrated adsorption chiller is presented along with initial results. The model is based on a lumped parameter approach composed of a system of ordinary differential equations that solves the energy and mass balances of different sections/components of the machine. Currently, new simulations and prototype laboratory tests are ongoing for the model’s validation.

Discussion and Results

Figure 1a shows a schematic of the rack-integrated adsorption chiller [2]. As seen in Figure 1a, the machine is composed by two adsorption modules for ad/desorption processes (“ADS 1/2”), their respective phase-change chambers for direct evaporation/condensation (“PC 1/2”), two refrigerant tanks for condensation/evaporation (“CD-TK”, “EV-TK”), and an air-cooler heat exchanger on the evaporation loop (“RDHX”). The working principle of this new adsorption chiller contemplates cyclic adsorption/desorption processes for each module, as well as heat recovery stages, all organized into four phases. With reference to Figure 1a, during phase 1, hot water is redirected to module 1 for desorption/condensation, where the desorbed refrigerant condenses on the bottom of the phase-change chamber and into the condenser tank. It is then pumped for heat rejection before going back to the top of the phase-change chamber to carry more condensed refrigerant. Simultaneously, adsorption/evaporation happens inside module 2, where a fraction of the liquid refrigerant entering the respective phase-change chamber evaporates and is adsorbed, with the remaining refrigerant falling back to the evaporator tank. The refrigerant is then pumped and circulates through the RDHX for low-temperature heat input before entering again into the phase-change chamber for further evaporation. Phase 3 is like phase 1, with the only difference being that the modules switch operation (i.e., from adsorption to desorption and vice versa). Phases 2 and 4 are heat recovery phases where the pressure inside the modules is adjusted (with either hot or cold water) before switching working operation. The need for developing a dynamic model arises because the new direct evaporation/condensation processes within the adsorbers can represent a bottleneck situation for the proper functioning and development of the compact prototype. Desorption/condensation processes can be halted by either incorrect refrigerant flowrate through the phase-change chamber or too-high desorption temperatures (i.e., 80°C), leading to a significant pressure increase within the adsorber because of vapor accumulation due to insufficient condensation (i.e., overheating inside the condenser). The dynamic model can be an important tool for both fault-detection and development of control strategies that can optimize the heat/mass exchange processes and speed up the prototype's development. The preliminary model for this prototype contemplates an ordinary differential equation (ODE) system focused on solving the energy and mass balances of the modules and phase-change chambers, external and internal heat exchangers, and refrigerant tanks. As presented in Figure 1b, the adsorption beds, their internal heat exchangers, and the phase-change chambers are discretized into "N" layers/nodes, each with an associated energy and mass balance to calculate the sorbent material temperature ($T_{sw,i}$), internal heat transfer fluid temperature ($T_{HTF,i}$), temperature of the inert material inside the phase-change chamber ($T_{inert,i}$), refrigerant enthalpy ($h_{ref,i}$), and water uptake variation (ω_i) in time. In total, for the entire system, 10 differential equations are solved in each timestep (with 5 solved for each node), with the refrigerant's pressure (P_{ref}) and enthalpy ($h_{ref,i}$) considered as state variables.



(a) (b)

Figure 1. (a) Rack-Integrated Adsorption Chiller schematic (b) Model concept

The main differential equations that compose the ODE system are presented as follows from equation (1) to (10), with the first five considered for each node/layer “i”.

$$\frac{\mathrm{dT_{inert,i}}}{\mathrm{dt}} = \mathrm{UA_{ref\rightarrow inert}} \cdot \frac{\left(\mathrm{T_{ref,i}} - \mathrm{T_{inert,i}}\right)}{\mathrm{(M\cdot c)_{inert,i}}} \tag{1}$$

$$\mathrm{V_{ref,i}} \cdot \left(\frac{\mathrm{d\rho_{ref,i}}}{\mathrm{dP_{ref}}} \cdot \frac{\mathrm{dP_{ref}}}{\mathrm{dt}} + \frac{\mathrm{d\rho_{ref,i}}}{\mathrm{dh_{ref,i}}} \cdot \frac{\mathrm{dh_{ref,i}}}{\mathrm{dt}}\right) = \mathrm{\dot{m}_{top,i}} - \mathrm{\dot{m}_{Bed,i}} - \mathrm{\dot{m}_{v,down,i}} - \mathrm{\dot{m}_{liq,down,i}} \tag{2}$$

$$\begin{gathered}\mathrm{V_{ref,i}} \cdot \left(\frac{\mathrm{d\rho_{ref,i}}}{\mathrm{dt}} \cdot \mathrm{h_{ref,i}} + \frac{\mathrm{dh_{ref,i}}}{\mathrm{dt}} \cdot \mathrm{\rho_{ref,i}} - \frac{\mathrm{dP_{ref}}}{\mathrm{dt}}\right) = \\ \mathrm{\dot{m}_{top,i}} \cdot \mathrm{h_{top,i}} - \mathrm{\dot{m}_{Bed,i}} \cdot \mathrm{h_{Bed,i}} - \mathrm{\dot{m}_{v,down,i}} \cdot \mathrm{h_{v,down,i}} - \mathrm{\dot{m}_{liq,down,i}} \cdot \mathrm{h_{liq,down,i}} - \mathrm{Q_{ref\rightarrow inert}}\end{gathered} \tag{3}$$

$$\frac{\mathrm{dT_{sw,i}}}{\mathrm{dt}} = \frac{\mathrm{\dot{m}_{Bed,i}} \cdot \mathrm{h_{Bed,i}} - \mathrm{Q_{Bed\rightarrow HTF,i}} - \mathrm{M_{s,i}} \cdot \frac{\mathrm{dh_{sw,i}}}{\mathrm{d\omega i}} \cdot \frac{\mathrm{d\omega i}}{\mathrm{dt}}}{\mathrm{M_{s,i}} \cdot \frac{\mathrm{dh_{sw}}}{\mathrm{dT_{sw}}} + \mathrm{(M\cdot c)_{Bed,HX,i}}} \tag{4}$$

$$\frac{\mathrm{dT_{HTF,i}}}{\mathrm{dt}} = \frac{\mathrm{\dot{m}_{HTF}} \cdot \mathrm{c_{HTF}} \cdot \left(\mathrm{T_{HTF,i-1}} - \mathrm{T_{HTF,i}}\right) + \mathrm{Q_{Bed\rightarrow HTF,i}}}{\left(\mathrm{(M\cdot c)_{HTF,i}}\right)} \tag{5}$$

$$\frac{\mathrm{d\omega_i}}{\mathrm{dt}} = \frac{\omega_{\mathrm{eq_i}} - \omega_\mathrm{i}}{\tau} \tag{6}$$

$$\frac{\mathrm{dh_{HX,out}}}{\mathrm{dt}} = \frac{\mathrm{\dot{m}_{pump}} \cdot \left(\mathrm{h_{HX,in}} - \mathrm{h_{HX,out}}\right) + \mathrm{Q_{HX}}}{\mathrm{M_{HX}}} \tag{7}$$

$$\frac{\mathrm{dP_{tank}}}{\mathrm{dt}} \cdot \left(\frac{\mathrm{d\rho_{tank}}}{\mathrm{dP_{tank}}} \cdot \mathrm{h_{tank}} - 1\right) + \frac{\mathrm{dh_{tank}}}{\mathrm{dt}} \cdot \left(\frac{\mathrm{d\rho_{tank}}}{\mathrm{dh_{tank}}} \cdot \mathrm{h_{tank}} + \mathrm{\rho_{tank}}\right) = \frac{\mathrm{\dot{m}_{liq,down,i=N}} \cdot \mathrm{h_{liq,down,i=N}} + \mathrm{\dot{m}_{v,down,i=N}} \cdot \mathrm{h_{v,down,i=N}} - \mathrm{\dot{m}_{pump}} \cdot \mathrm{h_{tank}}}{\mathrm{V_{tank}}} \tag{8}$$

$$\mathrm{V_{tank}} \cdot \frac{\mathrm{d\rho_{tank}}}{\mathrm{dP_{tank}}} \cdot \frac{\mathrm{dP_{tank}}}{\mathrm{dt}} + \mathrm{V_{tank}} \cdot \frac{\mathrm{d\rho_{tank}}}{\mathrm{dh_{tank}}} \cdot \frac{\mathrm{dh_{tank}}}{\mathrm{dt}} = \mathrm{\dot{m}_{liq,down,i=N}} + \mathrm{\dot{m}_{v,down,i=N}} - \mathrm{\dot{m}_{pump}} \tag{9}$$

$$\frac{\mathrm{dP_{ref}}}{\mathrm{dt}} = \frac{\mathrm{\dot{m}_{pump}} - \sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{\dot{m}_{Bed,i}} - \mathrm{\dot{m}_{liq,down,i=N}} - \sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{V_{ref,i}} \cdot \frac{\mathrm{d\rho_{ref,i}}}{\mathrm{dh_{ref,i}}} \cdot \frac{\mathrm{dh_{ref,i}}}{\mathrm{dt}}}{\sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{V_{ref,i}} \cdot \frac{\mathrm{d\rho_{ref,i}}}{\mathrm{dP_{ref}}}} \tag{10}$$

Energy balance from equation (1) represents temperature of the inert material inside the phase-change chamber ($\mathrm{T_{inert,i}}$), calculated with the overall heat transfer coefficient from inert material to refrigerant ($\mathrm{UA_{ref\rightarrow inert}}$), its temperature difference with the refrigerant temperature ($\mathrm{T_{ref,i}}$), and the inert material heat capacity ($\mathrm{(M\cdot c)_{inert,i}}$). Equation (2) depicts the mass balance for the refrigerant layer considering the incoming flowrate ($\mathrm{\dot{m}_{top,i}}$), vapor to the adsorption bed ($\mathrm{\dot{m}_{Bed,i}}$), and exiting vapor and liquid flowrates ($\mathrm{\dot{m}_{v,down,i}}$, and $\mathrm{\dot{m}_{liq,down,i}}$, respectively). Variation of refrigerant density ($\mathrm{\rho_{ref,i}}$) with pressure and enthalpy is also highlighted, along with the refrigerant’s volume in layer “i” ($\mathrm{V_{ref,i}}$). Equation (3) represents the refrigerant’s energy balance on layer “i”, with the heat transferred from inert material to refrigerant ($\mathrm{Q_{ref\rightarrow inert}}$). Following this, equation (4) presents the energy balance of the wet sorbent material for calculating its temperature $\mathrm{T_{sw,i}}$, considering the heat exchanged to the internal bed’s heat exchanger ($\mathrm{Q_{Bed\rightarrow HTF,i}}$), adsorption bed’s heat exchanger heat capacity ($\mathrm{(M\cdot c)_{Bed,HX,i}}$), mass of silica gel on layer “i” ($\mathrm{M_{s,i}}$), and the link between wet sorbent enthalpy ($\mathrm{h_{sw,i}}$) with water uptake and temperature. The energy balance from equation (5) calculates the adsorption bed’s heat transfer fluid temperature ($\mathrm{T_{HTF,i}}$) with its heat capacity ($\mathrm{(M\cdot c)_{HTF,i}}$), and flowrate ($\mathrm{\dot{m}_{HTF}}$), while equation (6) calculates the water uptake variation with the time constant (τ) and water uptake in equilibrium conditions ($\omega_{\mathrm{eq_i}}$). For the heat exchanger, equation (7) determines the refrigerant's outlet enthalpy ($h_{HX,out}$) with the pump's flowrate ($\dot{m}_{pump}$), exchanged heat (Q_{HX}), and heat exchanger's mass (M_{HX}). Finally, equations (8) and (9) are the refrigerant's tank energy and mass balances respectively, written to calculate the tank's pressure (P_{tank}) and enthalpy (h_{tank}), highlighting the variation of liquid refrigerant density (ρ_{tank}) with pressure and enthalpy, along with the tank's volume (V_{tank}). Equation (10) presents an overall balance for the calculation of P_{ref}. The first preliminary results related to the adsorption bed's internal fluid heat transfer rate and refrigerant's pressure are shown in Figure 2a and 2b, respectively.

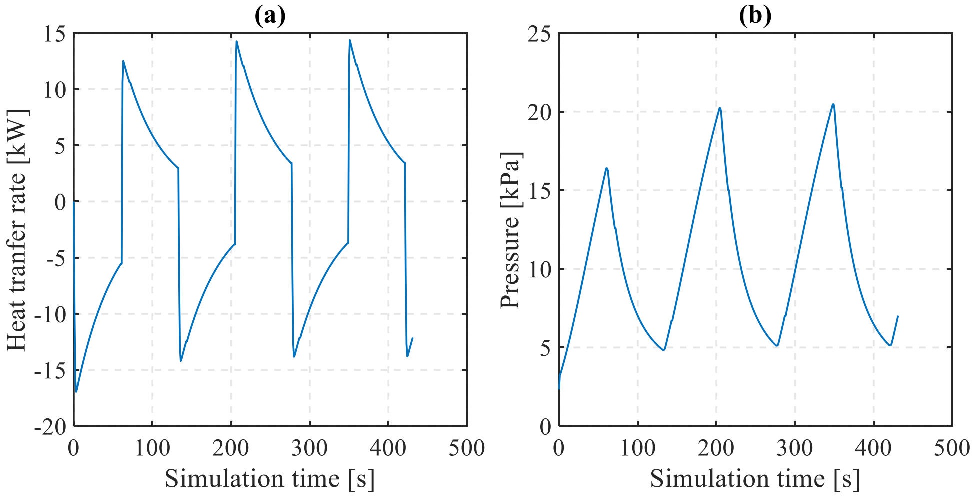


Figure 2. Preliminary results: (a) $Q_{Bed\rightarrow HTF}$ (b) P_{ref}

For this initial simulation, 10 layers were considered, with adsorption/desorption phases lasting for 60 seconds, and heat recovery phases 10 seconds. As seen in Figure 2a and 2b, initial results of the preliminary model correspond to the expected behaviour of the machine, with the refrigerant's pressure going from low to high pressure as the machine switches from adsorption to desorption, and the adsorption's bed internal heat transfer fluid carrying away the heat of adsorption and providing the heat of desorption. However, current work is focused on ongoing simulations and prototype laboratory tests for the model's validation.

Summary/Conclusions

A lumped-parameter preliminary model for a novel rack-integrated adsorption chiller is presented, focusing on the model's concept and initial results. The model solves 10 differential equations governing the energy and mass balances of various components, with 5 equations representing variables for each node/layer in the discretized adsorption bed and phase-change chamber. Preliminary results exhibit expected behaviour, and new simulations and prototype laboratory tests are ongoing for the model's validation.

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