Modelling of an adsorption chiller with Modelica

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Abstract

This paper describes the model of an adsorption chiller. The model follows a component modeling approach based on the Modelica Media and Modelica Fluid Library. New models describe the phenomenon of condensing, evaporation and adsorption. A new library has been created to describe the physical properties of adsorption materials. First simulations were performed and are compared to measured data of an existing machine. The simulated curves show good accordance to measured data.

Keywords: thermally driven chiller, adsorption chiller

1   Introduction

Facing a globally increasing cold demand to cover the need of comfort in hot areas and at the same time facing the problem of global warming, the market for thermally driven chillers is increasing. Thermally driven chillers produce cold but are powered by heat instead of mechanical work (electricity). Depending on the application, heat sources with temperatures above 70°C such as solar heat, waste heat or heat of a cogeneration unit can be used.
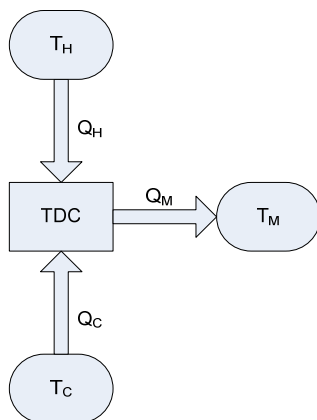

Fig. 1: Thermally driven chiller (TDCs) pump heat from a low temperature heat source at T_C to a middle temperature heat source at T_M and are powered by heat at a temperature level T_H (T_C<T_M<T_H).

Fig. 1 shows the working principle of a thermally driven chiller. It pumps heat from a low temperature heat source at T_C to a middle temperature heat source at T_M powered by heat at a temperature level T_H (T_C<T_M<T_H).
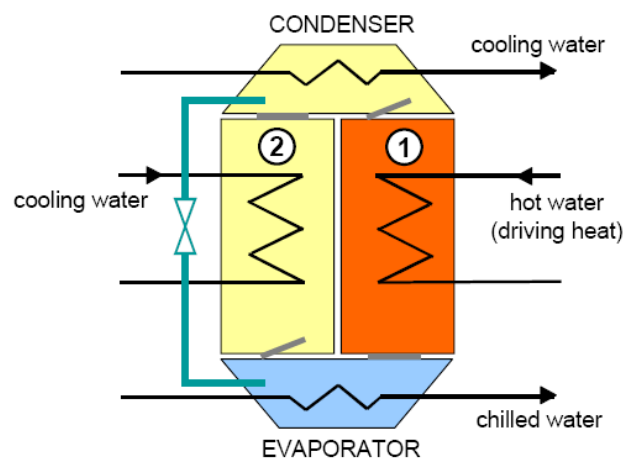

Fig. 2: Scheme of an adsorption chiller with two adsorbers. Cited from [3].

Fig 2 shows the technical implementation of an adsorption chiller. It shows four vacuum vessels for the four main components evaporator, condenser and two adsorbers. Each component contains a heat exchanger that is connected to one of the three heat reservoirs T_C, T_M and T_H as mentioned in Fig 1. The water in the loops is called chilled water, cooling water and hot water, respectively. The components are separated by four flaps that control the vapor flow in the machine. An expansion valve connects the condenser to the evaporator.

At a low pressure and low temperature level refrigerant (here: water) evaporates in the evaporator and passes the flap to the left adsorber (2). Thereby it takes up heat from the chilled water. The left adsorber adsorbs the water vapor at the surface of the adsorbent coating (here: silica gel). The energy released during this exothermal process is passed to the cooling water.

In the meantime the second adsorber (1) at the right side gets desorbed powered by energy of the hot water loop. This occurs at a higher pressure level by heating the adsorbent. The released water vapor passes the flap to the condenser where it condenses and releases energy to the cooling loop. The condensate afterwards passes an expansion valve before reaching the evaporator.

2 Structure of the adsorption chiller model

Fig. 3 shows the Modelica representation of the process described above. The four main components condenser, evaporator and two adsorbers are separated by four flaps. All models are connected via the fluid port of the Modelica Fluid Library [1]. A causal connector represents the expansion valve between condenser and evaporator.
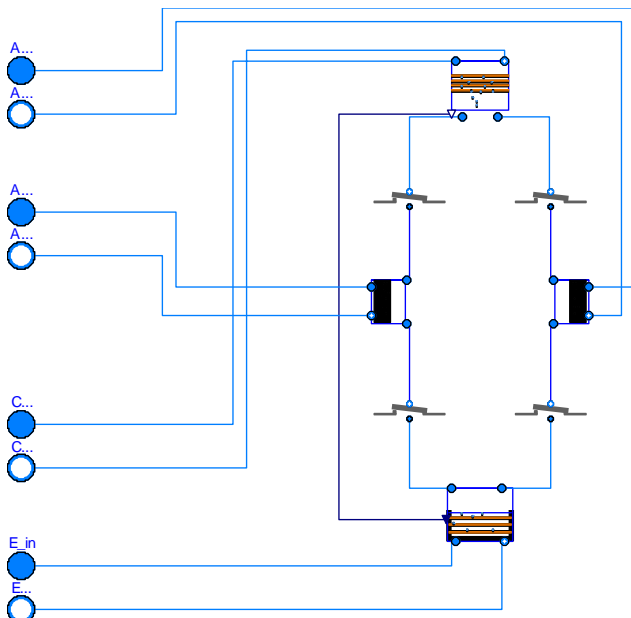

Fig. 3: Modelica representation of the adsorption chiller main components.

2.1 Functional Component Models

All main components used in the model have a similar design. Fig. 4 shows the graphical representation of the condenser.

The model mainly uses components from the Modelica Fluid Library. The ports at the top lead to the hydraulic connections (here cold water). The golden box in the middle represents a finned heat exchanger which is described below. As a first approximation, the heat transfer coefficient describing the condensation of water vapor at the heat exchangers surface is assumed to be constant. Therefore, a constant thermal conductor taken from the Modelica Standard Library connects the heat exchanger to a condensing model. In the condensing model simple heat and mass conservation equations are taken into account. Within this model, no mass and energy storage takes place. All condensate is released to the water outlet connector which is a causal output connector and was especially designed for this purpose. Opposed to the standard Modelica Fluid connector it only transmits flow variables (m_flow, H_flow) but no state variables (p, h), since the later change during the expansion process in the expansion valve.
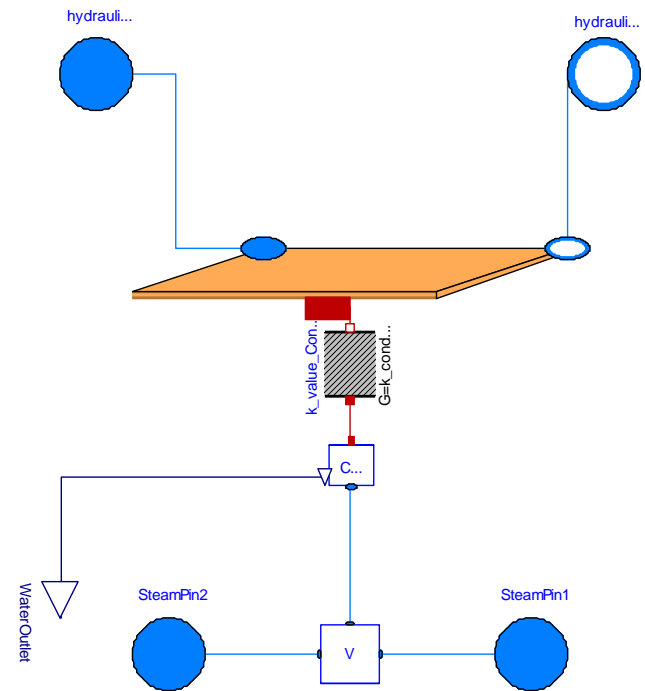

Fig. 4: Graphical Modelica representation of the condenser.

The models for the evaporator and the adsorber have the same structure as the condenser but the condensing model is replaced by an evaporation model and an adsorption model, respectively.

The evaporation model in the evaporator contains basically the same heat and mass conservation equations as the condensing model, but additionally heat and mass is stored to describe the refrigerant pool that covers the heat exchanger. Moreover, the connector for the condensate is defined as input as a counterpart to the condenser.

The adsorption model contains fundamental heat and mass conservation equations with internal storage to describe the adsorption process. The load $x = f(p,T)$ describes the amount of refrigerant that is adsorbed by the adsorbent

$$x = \frac{m_{refrigerant}}{m_{adsorbent}}$$

In equilibrium the load only depends on temperature and pressure at the adsorbent surface. The specific adsorption enthalpy h_{ad} as well as the equilibrium relation $x = f(p, T)$ are defined in the adsorption material package described below. However, the speed of adsorption is described as a simple linear relation between driving pressure and mass flow

$$\dot{m} = \beta(p_{sat} - p)$$

where p_{sat} is the saturation pressure for the refrigerant in the adsorbent, p is the vapor pressure in the vessel and $\dot{m}$ is the mass flow of refrigerant into or out of the adsorbent. β is an effective diffusion coefficient that describes the kinetics and so for is a fit parameter [2].

2.2   Finned Heat Exchanger Model

Fig. 5 shows a graphical representation of a finned heat exchanger model. It is a simple model consisting of different heat capacities for fins and tubes and a constant heat transfer coefficient model that represents the heat transfer from the hydraulic medium in the pipe to the pipe's wall. The pipe model from the Modelica Fluid Library is applied.
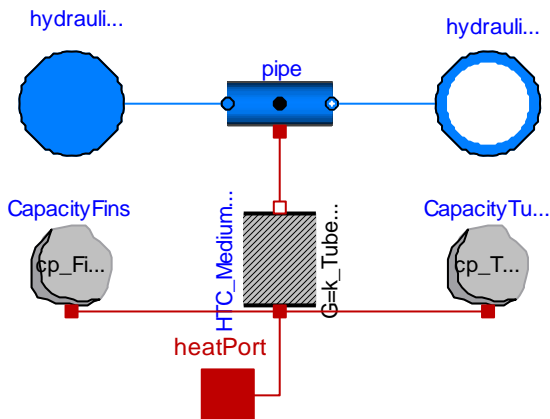

Fig. 5: Modelica representation of a simple finned heat exchanger.

2.3   Adsorption chiller piping model

Fig. 6 shows a graphical representation of the adsorption chiller piping. The purpose of the piping is to distribute the flow of the three loops for hot water, cooling water and chilled water to the four main components.

The connections to the hot water, cooling water and chilled water loops are shown on the left side. The connections to the four vessels from Fig. 3 are on the right side. The single valve in the lower right

controls the distribution of the cooling water between condenser and cooled adsorber. From a hydraulic point of view both vessels are arranged in parallel.
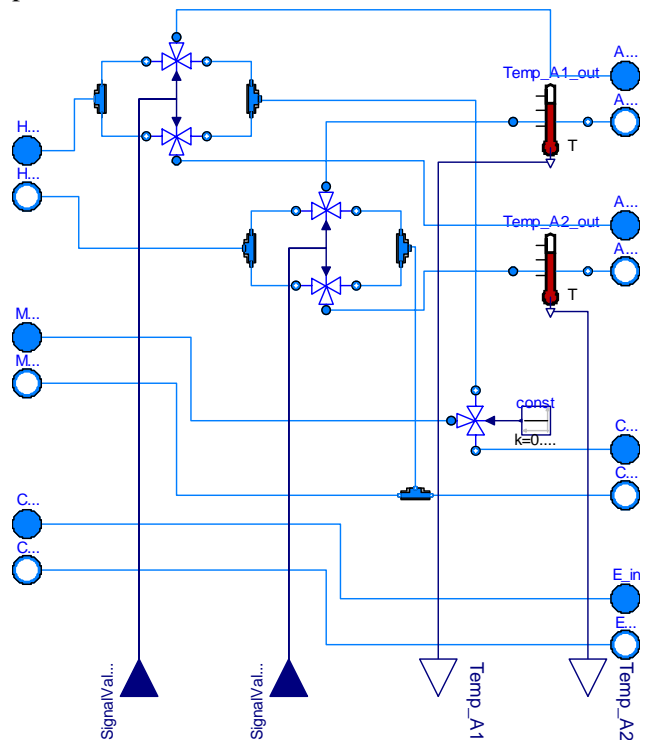

Fig. 6: Modelica representation of the piping of the adsorption chiller.

The two three-way-valves in the upper left of Fig. 6 control the forward flow of hot water and cooling water. Either the one or the other adsorber is connected to the hot water loop and cold water loop, respectively. Similarly, the two three-way-valves in the middle control the reverse flow. An external controller connected via the control connector at the bottom controls the valves. In order to improve the efficiency of the chiller the reverse flow valves are switched according to the temperatures in the reverse flow of the adsorbers. The warmer outlet flow is connected to the hot water and the colder outlet flow to the cooling water. Therefore, temperatures at the adsorber outlets are delivered to the controller. Switching of the valves in reverse flow occurs at a later time than switching of the valves in forward flow.

3   Adsorption Material Properties

At Fraunhofer ISE different adsorption materials are measure and characterized. The material package in the adsorber model is therefore defined as replaceable and simulation can be performed with different materials.

3.1 Description of the adsorption physics

According to Dubinin's theory [4] the physical equilibrium between temperature, pressure and load in the adsorber can be described by knowing only one function

$$W = f(A)$$

in which $[W] = \frac{m^3}{kg}$ is the adsorption volume onto the adsorbent surface that describes how much vapor can be adsorbed. Therefore, it is proportional to the load

$$x = \rho \cdot W$$

where ρ is the density of the refrigerant in the liquid adsorbed state. The adsorption potential $[A] = \frac{J}{kg}$ describes the conditions of pressure and temperature charactering adsorption process and is defined as

$$A = R \cdot T \cdot \ln \frac{p_{refrigerant}}{p}$$

with specific gas constant R, saturation pressure of the pure refrigerant $p_{refrigerant}$ and saturation pressure p of the refrigerant in the adsorbed state. Also the adsorption enthalpy h_{ad} is derived from the characteristic material equation:

$$h_{ad} = h_v + A - T \cdot \alpha \left(\frac{\partial A}{\partial \ln W} \right)_T$$

Here h_v is the specific evaporation enthalpy of the refrigerant and α is the linear thermal expansion coefficient of refrigerant in the adsorbed state.

3.2 Implementation of adsorption data in Modelica

The implementation of the adsorption material properties in Modelica follows Dubinin's theory to describe all parameters with the $W = f(A)$ relation. In practice, for the specific adsorption enthalpy also the derivative $\frac{\partial W}{\partial A}$ is needed since Modelica cannot perform this transformation. Therefore, three functions are needed to describe the properties of a material:

The first function describes the relation between W and A (which may contain piecewise-defined functions), the second function gives the according derivative and the third function contains the needed coefficients. The first two functions therefore are extended by the coefficient function.

Each material package is then extended by a partial base class package. In this partial package all physical adsorption properties as described above are calculated.

So far, all implemented adsorption materials work with water as refrigerant but in principle it is possible to extend the package to the physical properties of other adsorption pairs like methanol/activated carbon.

4 Preliminary results and discussion

Simulations with real measured data as input have been performed in order to compare the model with a real machine. As working water according to the IAPWS-formulation from the Modelica Media Library and pair silica gel from the adsorption materials package are used. Measurement data come from the SorTech SKA PT 402 chiller. Data for temperature and mass flow at the inlets of the adsorption machine are given as inputs for the simulation from the measurement. Weight of adsorbent and heat capacities are given as parameters. Moreover, switching times for forward valves in the adsorption chiller piping are set manually, whereas reverse flow valves are switched by the controller as described above.

Fig. 7 compares measured data with the simulated results. It shows the measured temperatures at the inlet and outlet of the hot water, cooling water and chilled water loops versus time. Moreover, simulated results at the outlets are shown.
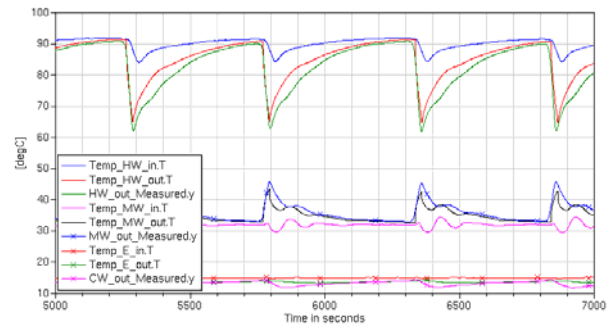

Fig. 7: Comparison between measured and simulated data. Temp_HW_in.T, Temp_MW_in.T and Temp_E_in.T are input data for the inlets of the adsorption chiller. Temp_HW_out.T, Temp_MW_out.T and Temp_E_out.T are simulated temperature values at the chiller's outlets. HW_out_Measured.y, MW_out_Measured.y and CW_out_Measured.y are measured outlet temperatures.

A half cycle needs approximately about 500s. After this time adsorption or desorption, respectively, stops and the valves in the piping model are switched to change operation mode. Therefore, a complete ad-

sorption/desorption cycle needs about 1000s. The peaks especially in the hot and cooling water loop are caused by this switching process.

The simulated curves show good accordance to the measured data. After the switching process the simulated output temperature from the hot water loop (Temp_HW_out.T) and measured data (HW_out_measured.y) start from a similar temperature and converge against the same final desorption temperature.

The same is true for the simulated and measured values (Temp_MW_out.T) and (MW_out_measured.y), respectively, in the cooling water loop.

In both loops the simulated temperature differences after the switching process are smaller than the measured values. This might indicate that the switching in the reverse flow valves of the SKA PT 402 happens to soon.

Inlet temperatures actually were supposed to be constant temperatures but the test bench for the chiller was not able to handle the high power requirement which resulted in oscillating inlet temperatures. For example the middle temperature level Temp_MW_in.T shows a double overshoot in the time interval 5800s-5900s. The model can handle this fluctuation. At the outlet Temp_MW_out.T and MW_out_measured.y both show a reaction to the fluctuation. But since the model does not include the length of the pipes between adsorber and thermometer the simulated reaction happens before the real measured events.

5   Conclusion

A simulation model for an adsorption chiller on a component approach has been implemented in Modelica. Even though it consists of simple equations for heat and mass transfer it already shows good accordance to measured data. It demonstrates the principle functions of the adsorption chiller and shows reaction to dynamic changes.

Moreover a package for different adsorption materials has been designed according to Dubinin's Theory.

New measurements will also contain pressure data in the adsorption machine, with this data it will be possible to calibrate the free parameters in the model which are currently only first approximations.

Acknowledgment

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