Case Study: Model and simulate an existing building and integrate improved & sustainable measures for the building and systems

7Y700 - Sustainable Building and Systems Modeling
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1 Introduction

1.1 Objectives case study

The objective of this case study is to model a building with HAMBASE / Simulink and integrate sustainable measures to improve the energy use or the indoor climate. This is done to gain insight in sustainable building and systems modeling and the evaluation of these systems by estimations and simulations.

1.2 Project approach

To meet the objective, the case study consists of two modeling parts; the existing situation and the new situation including improved and sustainable measures for the building and systems. The model of an existing building will be built from scratch.

First the information for the building modeling is prepared (i.e. number zones; construction details, ventilation, sources, etc.). Then the existing situation is simulated and the energy use is compared with real data from the building. For the second part of the case study the models, needed for the improved measures (i.e. ODEs, S-Functions, Simulink blocks), are collected and/or prepared. The second part of the case study is started with the implementation of the sustainable measures in the existing Simulink model. The models of the measures are fine tuned and after this, conclusions are drawn with respect to the improved situation.

1.3 Building / Apartment

In this study we simulate an apartment that is situated in Roosendaal, that is in the southwest of the Netherlands. It was build in the year 2009. The building consists of two blocks, one block (front side of the building) with five floors and one block (backside of the building) with three floors. The apartment that is used for the modeling is located on the third floor of the block on the backside of the building. The building can be entered through a central hall, the apartments themselves can be entered by a gallery and walkways. Images of the building can be found in appendix 6.1.

The apartment consists of a living room, two bedrooms, a bathroom, a toilet and a technical area/storage. These spaces are connected by a hallway. The living room has two large sliding glass facades. The outer walls are made of bricks with an air gap, insulation, lime stone or concrete and a plaster layer. The inner walls are made of lime stone and a plaster layer or concrete. The floor construction is made of concrete with a laminate covering. The windows of the apartment contain HR++ glazing. The systems that are implemented in the apartment are; a heat recovery system and a boiler with radiators to create a thermal climate. Air is extracted from the living room (kitchen), bathroom, toilet and technical area/storage. Air is supplied in the living room and two bedrooms. Other construction details can be found in the HAMBase file. In Table 1 the location and type of the heat sources can be found.

<table>
<thead>
<tr>
<th>Room</th>
<th>Type</th>
<th>Dimensions [lxhxtype]</th>
<th>Heating power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>convector (2x)</td>
<td>900 x 300</td>
<td>2212</td>
</tr>
<tr>
<td>Living room</td>
<td>radiator</td>
<td>960 x 400 x 21</td>
<td>1234</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>radiator</td>
<td>1440 x 400 x 21</td>
<td>1850</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>radiator</td>
<td>1440 x 400 x 21</td>
<td>1850</td>
</tr>
<tr>
<td>Bathroom</td>
<td>radiator</td>
<td>480 x 900 x 22</td>
<td>1414</td>
</tr>
<tr>
<td>Hallway</td>
<td>radiator</td>
<td>480 x 400 x 10</td>
<td>253</td>
</tr>
</tbody>
</table>

Table 1. Heat sources of the apartment
2 Modeling

2.1 HAMBASE model

In the HAMBASE model we used four climate zones; zone 1 is the living room + kitchen, zone 2 are the two bedrooms, zone 3 is the bathroom and zone 4 are the hallway + toilet + technical area/ storage. Different profiles are used to simulated these zones, there is a distinction between week-days and the weekend. The used MATLAB-file of the model is included in appendix 6.2.

For the validation of the model we used the real gas consumption of the apartment. The simulation period corresponds with the period of the energy bill. Because we only calculated the gas consumption for heating with HAMBASE, we estimated the percentage of gas consumption for cooking and producing hot water as can be seen in Table 2. With this information we compared both gas consumptions and optimized the model. The real gas consumption is approximately 129 m$^3$ and the gas consumption of the HAMBASE model is approximately 134 m$^3$ (see appendix 6.3), from this can be concluded that the model matches the real situation quite good.

<table>
<thead>
<tr>
<th>Period: 19-1-2010 t/m 4-10-2010</th>
<th>Percentage [%]</th>
<th>Gas consumption [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>100</td>
<td>168</td>
</tr>
<tr>
<td>Hot water</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td>Cooking</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Heating (remaining)</td>
<td></td>
<td>129</td>
</tr>
</tbody>
</table>

Table 2. Approximated gas consumption

2.2 Sustainable measures

In this chapter an explanation of the sustainable measures, for the building and systems that we want to integrate, are given. The measures are a solar collector with thermal buffer, floor heating/cooling and an adsorption chiller. The collected solar energy will be used as driven energy in the adsorption chiller and, when possible, for room-heating. A description of these models is given below.

2.2.1 Solar collector with thermal buffer

For the model of the solar collector we adapted an existing model of Ralph van Oorschot (Oorschot, 2010). Therefore we added two extra output variables in the existing Simulink model, Qh_solar (diffuse solar on the horizontal) and Qn_solar (direct normal solar intensity). We changed the model by deleting the embedded MatLab function and replace it by two separate Fcn-functions which calculates outflow temperature and added energy. We also added an Fcn-function which regulates a desirable mass flow through the solar collector, based on incoming solar radiation. The heat will be stored in a thermal buffer. The Simulink model is included in appendix 0.

For the model of the thermal buffer we use an existing model of Coen Hoogervorst (Hoogervorst, 2010). This existing model has only one input and output flow. We need a buffer with two input and output flows for two separate loops. One loop between the buffer and the solar collector and one between the hot water consumer and the buffer. This consumer could be the adsorption chiller or the floor heating system. So we changed the model to get a buffer which meets these conditions and added an output which visualizes the energy loss from the buffer to the surrounding. The Simulink model is included in appendix 0.
2.2.2 Floor heating/cooling

For the model of the floor heating/cooling we adapt an existing model of Coen Hoogervorst (Hoogervorst, 2010). The changes that we have made to this model are:

- Adding an adapting mass flow through the pipes, based on energy demand and temperature difference between the supply and return water.
- A variable transfer resistance between floor surface and air because our model is also used for floor cooling.
- Expansion from a one zone to a model with four zones.

The Simulink model is included in appendix 6.9.

2.2.3 Adsorption chiller

The development of small scale sorption chillers (2-20kW) is quite new. The Energy research Centre of the Netherlands (ECN) has recently developed an 2.5kW adsorption chiller to enter markets for individual homes and small scale commercial applications. Previously, high driving temperatures were required for the sorption cycles but this product works with driving temperatures of 80-90°C which makes it useful in combination with e.g. solar heat and industrial waste heat. Another big difference with other systems is that this model works with silica gel as a solid, which cannot be pumped from generator to absorber.

The model we made of the adsorption chiller is build from scratch. It is based on the product described above and visualized in Fig. 1. The information we used can be found in the report from the ECN (Bakker & de Boer, 2010).

![Design drawing and picture of the ECN 2.5kW adsorption chiller (Bakker & de Boer, 2010)](image)

Adsorption cooling systems are a closed loop, solid sorbent type. There are two different types of systems which make of use this process: Water / silica gel (or Zeolith) and ammonia / salt systems. Both systems work generally with the same principle but the water / silica gel type is most used commercially. The product of ECN is also of this type.

The system consists of four chambers: two adsorber / desorber chambers, an evaporator and a condenser.

The system is connected to three in- or outputs.

- Chilled water; Cooled water which we use for cooling the apartment.
- Driving heat; Hot water warmed up by a solar collector in our case.
- Cooling water; Water used to disperse the heat from the complete process.
A wet cooling tower or a dry-cooler is commonly used to transfer that energy to the surrounding.

Instead of a conventional compression chiller, the cycle of adsorption chillers is driven by a thermal compressor, based on the sorption reaction of silica gel and water, using heat as driving force. The system cycles the chamber 1 and 2 between adsorbing and desorbing. In case of Fig. 2, chamber 1 is desorbing and chamber 2 is adsorbing. Due to the low pressure, the refrigerant (water) in the evaporator is transferred into the gas phase by taking up the heat from the chilled water, which generates the cooling effect. The silica gel in chamber 2 is adsorbing this refrigerant vapour.

At the same time chamber 1 is regenerated. The refrigerant vapour is being heated and desorbed from the sorbent and condensates by cooling water in the condenser. The condensed refrigerant is transported to the bottom of the machine where it is reused. When the sorption material in chamber 2 is saturated and the sorption material in chamber 1 is dry, the machine automatically reverses the function of the two rooms. The positions of the valves are changed and the cooling water and hot water are reversed in chamber 1 and 2.

![Fig. 2 Schematic of adsorption chiller lay-out (Bakker & de Boer, 2010)](image)

We have build a model with nearly the same performances as depicted in the graph of Fig. 3. The COP and chiller power depends strongly on the inlet temperature of the cooling water. We approximated these values by the linear formulas above the graph. The COP and power also decrease when the chilled water outlet temperature needs to be lower than 15°C. It doesn’t matter in our case study because we use it for floor cooling and it doesn’t need lower temperatures. The temperature of the cooling water strongly depends on the outside air temperature.

![Fig. 3 Chiller performance depends of cooling water temperature (Bakker & de Boer, 2010)](image)
We assumed that we have a dry cooler with a capacity and control that is been able to cool down the cooling water till 9 degrees above the outside temperature. The COP means in this case the ratio between driven heat energy and chilling energy (Pevap). When there is no hot water available above 75°C, it will not function. When outside temperature is rising, the COP will decrease, so the use of heat driven energy increases. Also the demand of cooling power increase because both the energy of the evaporator and driven energy should be eliminate by it. This principle is incorporated in the model. The Simulink model of the adsorption chiller is included in appendix 0.

2.3 Simulink model

In this chapter the whole Simulink model is described. The separate models of the sustainable measures that can be found in paragraph 2.2 are combined to a single Matlab Simulink file which simulates the complete system including the apartment. The separate models can be found in appendices.

2.3.1 Validation Simulink model

For the validation of the Simulink model we compared the gas consumption from the HAMBASE model, which can be found in paragraph 6.2, with the gas consumption of the Simulink model. As can be seen in Table 3 the gas consumptions matches quite good.

<table>
<thead>
<tr>
<th>Period: 19-1-2010 t/m 4-10-2010</th>
<th>Gas consumption [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Really</td>
<td>129</td>
</tr>
<tr>
<td>HAMBASE</td>
<td>134</td>
</tr>
<tr>
<td>Simulink</td>
<td>126</td>
</tr>
</tbody>
</table>

Table 3. Comparison gas consumption HAMBASE and Simulink

The used Simulink model, without the improved and sustainable measures, is included in appendix 6.6.

2.3.2 Control and coupling

In this paragraph there is an explanation of how the Simulink models of the various components are linked with each other and how these models are coupled with the HAMBASE model. The HAMBASE model receives the cooling and heating capacities, of every room, from the Simulink model. The output data of the HAMBASE model are the indoor conditions of the four zones, the outdoor conditions and the diffuse solar radiation and the direct normal solar intensity.

The cooling and heating capacities that the HAMBASE model receives from the Simulink model are realized as follows:

For every zone a proportional integral control (PI) is created which is based on measured indoor temperatures and a set point model. In this model it is possible to simply enter the desired day / night temperature, the temperature on weekdays and the temperature in the weekend. Based on this data, the desired cooling or heating capacity is determined. The heating power is limited by a constant maximum. The cooling capacity is limited by the power that the adsorption chiller can generate. This power is related to the availability of hot water from the solar collector or boiler (> 75 °C) and the temperature of the cooling water for heat dissipation. The temperature of the cooling water for heat dissipation is related to the outside temperature and determines both the COP value as the maximum capacity of the cooler.

Now a desired capacity is available that can be returned to the zones, which initially are limited by the generators of heating and cooling. For the distribution of the cooling power priorities of the four zones are allocated. For example, the first priority are the bedrooms followed by the living room and kitchen.
After the determination of the priority the cooling and heating capacities are ‘transported’ to the floor heating model in which it is converted into an inlet water temperature and mass flow through the pipes. The floor heating model contains the properties of the construction. The model then calculates the parameters of the floor surface temperature and power output to the air in each zone. There exists a delay between the required power and the real power output. The power output can also be limited by the capacity of the floor heating system. These cooling and heating powers are now input parameters of the HAMBASE model and this cycle will constantly repeat itself.

Of course, the heating power is not limited by the heat generated in the solar collectors. To simulate the proportion of heating power, generated by solar energy, with respect to the total heating power requested, the following control strategy is set up: If there is heating power requested and the water in top of the buffer is more than 35 °C, than the requested energy is extracted from the buffer. The water will be returned to the buffer with a temperature difference of at least 10 °C (variable mass flow). The temperature difference increases at higher outlet temperatures.

3 Results

Before continuing with the models they are validated using the gas consumption of the apartment. First the gas consumption of the HAMBASE model is compared with the real gas consumption. After this the gas consumption of the Simulink model is compared with the gas consumption of the HAMBASE model to verify the correct settings of all temperature controllers. Both gas consumptions match quite good with the real gas consumption.

Because of the size and the complexity (S-functions etc.) of the Simulink model we did not use the same simulation period as we used in the HAMBASE model. We only simulated two periods with extreme outdoor conditions, namely: seventeen summer days (2-7-2010 till 19-7-2010) and seventeen winter days (15-1-2010 till 1-2-2011). The simulation period is not the same, therefore we can’t use this period to indicate the total contribution of the solar collector to the heating system and savings potential of the gas consumption to the real situation. Fig. 4 shows the temperature of the winter period. It can be seen that the desired set points (see appendix 6.11) of the zones are reached.

Some other simulation results, like relative humidity, of the winter period simulated with Simulink are included in the appendices.

In Fig. 5 (left) it can be seen that the indoor temperature of the existing situation during the summer reaches undesirable high temperatures. An important sustainable measure that we implemented in the Simulink model is the adsorption chiller (see 2.2.3). Fig. 5 (right) shows that the indoor temperatures
decreases and reaches more comfortable conditions. We simulated the situation without cooling with the basic version of the Simulink model (see appendix 6.6), the heating system is different and that’s why the temperature pattern, during heating from initial condition, is not equal. This heating period is not realistic in this period and is therefore not relevant.

Some other simulation results of the summer period are included in the appendices.

4 Conclusion

The objective of this case study was to model a building with HAMBASE / Simulink and integrate sustainable measures to improve the energy use or the indoor climate. Due to the shorter simulation period we don’t have specific results for the energy savings over the total period. The results do show that there will be a contribution of the solar collector to the heating demand, which results in a reduction of the gas consumption.

Besides this energy saving, the simulations show that the adsorption chiller in combination with the solar collector are sustainable improvements that provide more comfortable indoor temperatures during summer period.

We used a collector area of 30 m², buffer volume of 250 litre and the specifications of the adsorption chiller developed by ECN. The current model can still be optimized by using our simulation results, for example the ratios between the parameters above, mass flows of the systems, set points etc.

The combination of adsorption chiller, solar collector with thermal buffer and floor cooling/heating is realistic, because they don’t function without each other and the system temperatures fit together. In the model we use an optimal mass flow over the solar collector, mostly in practice both mass flow and outlet temperatures are less optimal. When looking at the Simulink model it is possible to change the S-functions in embedded Matlab functions, this will increase the simulation speed.
5 References


6 Appendices

6.1 Images building

Figure 1. Impression building

Figure 2. Orientation and plan building
Figure 3. Impression apartment used for modeling

Figure 4. West façade (front side of apartment)
Figure 5. South façade (right side of apartment)

Figure 6. East facade (backside of apartment)
Figure 7. Floor plan of apartment used for modeling
6.2 HAMBASE model building

% Appartement (with adjusted standard wavo_output)
% Location: Roosendaal
% Date: 10-5-2011
% ---------------------------------------------------------------
% HAMBASE
% % HEAT And Moisture Building And Systems Evaluation
% ---------------------------------------------------------------
% BUILDINGref
% % Based on:
% % Startexample1

clear all
close all

% -----------------------------------
% PART 1 : THE CALCULATION PERIOD
% -----------------------------------
% % FORMAT BAS.Period=[yr,month,day,ndays]
% % BAS.Period=[2010,1,19,259];
% BAS.Period=[2010,1,1,365];
% % BAS.DSTime(1,:)=[year,starting month,day,ending month,day];
% BAS.DSTime=0;

% -----------------------------------
% PART 2 : THE BUILDING
% -----------------------------------
% % FORMAT BAS.Vol{zonenumber}=volume (m3);
% BAS.Vol{1}= 68.0; %slaapkamer1+2
% BAS.Vol{2}= 130.8; %woonkamer+keuken
% BAS.Vol{3}= 20.5; %badkamer
% BAS.Vol{4}= 64.2; %gang+toilet+berging/techniek
% % ** CONSTRUCTION COMPONENTS DATA **
% % BAS.Con{conID}=[Ri, d1,matID,..., dn,matID, Re, ab, eb].
% BAS.Con{1} = [0.13, 0.013,370, 0.150,235, 0.110,409, 0.040,003,
% 0.100,232, 0.04, 0.9, 0.9];
% BAS.Con{2} = [0.13, 0.013,370, 0.150,342, 0.110,409, 0.040,003,
% 0.100,232, 0.04, 0.9, 0.9];
% BAS.Con{3} = [0.13, 0.250,342,
% 0.13, 0.5, 0.9];
% BAS.Con{4} = [0.13, 0.010,261, 0.070,235, 0.010,370,
% 0.13, 0.5, 0.9];
% BAS.Con{5} = [0.13, 0.010,370, 0.150,235, 0.010,370,
% 0.04, 0.9, 0.9];
% BAS.Con{6} = [0.13, 0.010,366, 0.370,316, 0.200,453, 0.005,601,
% 0.07,638, 0.04, 0.8, 0.9];
% BAS.Con{7} = [0.13, 0.010,366,
% 0.1, 0.6, 0.9];
% BAS.Con{8} = [0.13, 0.008,518, 0.007,474, 0.200,312, 0.010,366,
% 0.1, 0.6, 0.9];
% BAS.Con{9} = [0.13, 0.040,585,
% 0.04, 0.8, 0.9];
BAS.Con{10} = [0.13, 0.040, 0.505, 0.13, 0.6, 0.9];

% 1: pleisterlaag, kalkzandsteen, insulation, air gap, brick (external wall)
% 2: pleisterlaag, concrete, insulation, air gap, brick (external wall)
% 3: heavy concrete (internal wall)
% 4: tiles, kalkzandsteen, pleisterlaag (internal wall, badkamer)
% 5: pleisterlaag, kalkzandsteen, pleisterlaag (internal wall small)
% 6: roof construction
% 7: floor construction (tussen onderburen in berging) zeil, beton, vezel spuitlaag plafond
% 8: floor construction (tussen onderburen) laminaatvloer, isolatiematten, beton, vezel spuitlaag plafond
% 9: exterior door Kunststof (PVC?)
% 10: interior door Spaanderplaat

% ** GLAZING SYSTEMS DATA**
% BAS.Glas{glaID} = [Uglas, CFR, ZTA, ZTAW, CFrw, Uglasw]
BAS.Glas{1} = [1.4, 0.047, 0.65, 0.072, 0.116, 1.4];
BAS.Glas{2} = [1.4, 0.047, 0.65, 0.65, 0.047, 1.4];

% Glazing 1 HR++ glazing with interior sunblinds
% Glazing 2 HR++ glazing

% ** ORIENTATIONS **
% BAS.Or{orID} = [beta, gamma];
BAS.Or{1} = [90.0, 13.0]; % south wall rechter zijgevel
BAS.Or{2} = [90.0, -77.0]; % east wall achtergevel
BAS.Or{3} = [90.0, 103.0]; % west wall tussengevel
BAS.Or{4} = [0.0, 0.0]; % horizontal roof

% ** SHADOWING DATA**
% Changing below '0' into '1' below, gives a drawing of the obstacle geometry for ShaID.
if 1==0
    shaID=1;
    figure(1)
    shaddrawf1101(BAS.shad,shaID);
end

% I. EXTERNAL WALLS
% BAS.wallex{exID} = [zonenr, surf, conID, orID, bridge]
BAS.wallex{1} = [1, 15.3, 2, 1, 0]; % south wall rechter zijgevel slaapk. 1
BAS.wallex{2} = [2, 21.7, 2, 1, 0]; % south wall rechter zijgevel woonkamer
BAS.wallex{3} = [1, 24.0, 1, 2, 0]; % east wall achtergevel woonkamer
BAS.wallex{4} = [1, 24.0, 1, 3, 0]; % west wall tussengevel slaapkamers
BAS.wallex{5} = [4, 7.8, 1, 3, 0]; % west wall tussengevel gang
BAS.wallex{6} = [2, 54.5, 6, 4, 0]; % horizontal roof (boven woonkamer)
BAS.wallex(7) = [1, 28.5, 6, 4, 0]; % horizontal roof (boven slaapkamers)
BAS.wallex(8) = [3, 8.5, 6, 4, 0]; % horizontal roof (boven badkamer)
BAS.wallex(9) = [4, 28.5, 6, 4, 0]; % horizontal roof (boven gang, wc, berging)
BAS.wallex(10) = [4, 2.5, 9, 3, 0]; % west wall voordeur in gang

% II. WINDOWS IN EXTERNAL WALLS
% BAS.window(winID) = [exID, surf, glaID, shaID]
BAS.window(1) = [3, 5.3, 1, 0];
BAS.window(2) = [3, 5.3, 1, 0];
BAS.window(3) = [4, 2.6, 1, 0];
BAS.window(4) = [4, 2.6, 1, 0];
BAS.window(10) = [5, 0.5, 2, 0]; % raam voordeur

% III. CONSTANT TEMPERATURE WALLS

% IV ADIABATIC EXTERNAL WALLS
% BAS.wallia{iaID} = [zonenr, surf, conID]
BAS.wallia(1) = [2, 8.5, 3]; % scheiding woonkamer met keuken buren
BAS.wallia(2) = [4, 30, 3]; % scheiding gang/berging met buren
BAS.wallia(3) = [4, 12.8, 5]; % scheiding gang/berging met schacht
BAS.wallia(4) = [2, 54.5, 8]; % scheiding vloer met onderburen (onder woonkamer)
BAS.wallia(5) = [1, 28.5, 8]; % scheiding vloer met onderburen (onder slaapkamers)
BAS.wallia(6) = [3, 8.5, 8]; % scheiding vloer met onderburen (onder badkamer)
BAS.wallia(7) = [4, 28.5, 8]; % scheiding vloer met onderburen (onder gang, wc, berging)

% V. INTERNAL WALLS BETWEEN AND IN ZONES
% BAS.wallin{inID} = [zonenr1, zonenr2, surf, conID]
BAS.wallin(1) = [1, 1, 6.9, 5]; % tussen slaapkamers
BAS.wallin(2) = [1, 4, 10.4, 5]; % slaapkamers > gang
BAS.wallin(3) = [1, 4, 6.9, 3]; % slaapkamer 2 > gang
BAS.wallin(4) = [4, 4, 7.7, 5]; % toiletwandjes
BAS.wallin(5) = [1, 2, 8.5, 5];
% slaapkamer 1 > woonkamer
BAS.wallin(6) = [3, 1, 1.1, 4];
% badkamer > slaapkamer 1
BAS.wallin(7) = [3, 4, 12.9, 4]; % badkamer > gang
BAS.wallin(8) = [3, 2, 14.0, 4];
% badkamer 2 > woonkamer
BAS.wallin(9) = [4, 2, 1, 5]; % gang > woonkamer
BAS.wallin(10) = [2, 4, 6.3, 3]; % woonkamer > berging
BAS.wallin(11) = [4, 4, 3.3, 5]; % gang > berging
BAS.wallin(11) = [4, 4, 3.8, 5]; % meterkast
BAS.wallin(12) = [4, 2, 2.3, 5]; % deur
gang > woonkamer
BAS.wallin(13) = [1, 4, 4.6, 5]; %2 deuren slaapkmr>gang
BAS.wallin(14) = [3, 4, 2.3, 5]; %deur badkamer>gang

%-------------------------------------------------------------------------
% PART 3: profiles for internal sources, ventilation, sunblinds and free
% cooling
% ------------------------------------------------------------------------
% **PROFILES**
% Woonkamer+keuken
% proID=1 Gangbare profiel voor woonkamer (overdag beide aan het werk)
BAS.Ers(1) = 300;
BAS.dayper(1) = [17, 23];
BAS.vvmin(1) = [0.3, 0.3];
BAS.vvmax(1) = [2, 2];
BAS.Tfc(1) = [25, 25];
BAS.Gint(1) = [1.1e-4, 0];
BAS.Tsetmin(1) = [22, 17];
BAS.Tsetmax(1) = [100, 100];
BAS.RVmin(1) = [-1, -1];
BAS.RVmax(1) = [101, 101];

% proID=2 Weekendprofiel voor woonkamer (hele dag thermostaat op 21gr.)
BAS.Ers(2) = 300;
BAS.dayper(2) = [9, 23];
BAS.vvmin(2) = [0.3, 0.3];
BAS.vvmax(2) = [2, 2];
BAS.Tfc(2) = [25, 25];
BAS.Gint(2) = [2.7e-5, 0];
BAS.Tsetmin(2) = [22, 17];
BAS.Tsetmax(2) = [100, 100];
BAS.RVmin(2) = [-1, -1];
BAS.RVmax(2) = [101, 101];

% Badkamer
% proID=3 Gangbare profiel voor badkamer (overdag beide aan het werk)
BAS.Ers(3) = 300;
BAS.dayper(3) = [17, 23];
BAS.vvmin(3) = [0.3, 0.3]; [%[ 0.3, 0.3 ]];
BAS.vvmax(3) = [0.3, 0.3]; [%[ 0.3, 0.3 ]];
BAS.Tfc(3) = [100, 100];
BAS.Tsetmin(3) = [22, 17]; [%[ 24, 18 ]];
BAS.Tsetmax(3) = [100, 100];
BAS.RVmin(3) = [-1, -1];
BAS.RVmax(3) = [101, 101];

% proID=4 Weekendprofiel voor badkamer
BAS.Ers(4) = 300;
BAS.dayper(4) = [9, 23];
BAS.vvmin(4) = [0.3, 0.3]; [%[ 0.3, 0.3 ]];
BAS.vvmax(4) = [0.3, 0.3]; [%[ 0.3, 0.3 ]];
BAS.Tfc(4) = [100, 100];
BAS.Qint(4) = [15, 0];

Eindhoven University of Technology
% Slaapkamers
% proID=5 Gangbare profiel (overdag beide aan het werk)
BAS.Ers{5} = 300;
BAS.dayper{5} = [ 8, 17, 23 ];
BAS.vvmin{5} = [ 0.3, 0.3, 0.3 ];
BAS.vvmax{5} = [ 2, 2, 2 ];
BAS.Tfc{5} = [ 25, 25, 25 ];
BAS.Qint{5} = [ 0, 0, 130 ];
BAS.Gint{5} = [ 0, 0, 3.2e-5 ];
BAS.Tsetmin{5} = [ 17, 17, 17 ];
BAS.Tsetmax{5} = [ 100, 100, 100 ];
BAS.RVmin{5} = [ -1, -1, -1 ];
BAS.RVmax{5} = [ 101, 101, 101 ];

% proID=6 Weekendprofiel voor slaapkamers
BAS.Ers{6} = 300;
BAS.dayper{6} = [ 9, 17, 23 ];
BAS.vvmin{6} = [ 0.3, 0.3, 0.3 ];
BAS.vvmax{6} = [ 2, 2, 2 ];
BAS.Tfc{6} = [ 25, 25, 25 ];
BAS.Qint{6} = [ 0, 0, 130 ];
BAS.Gint{6} = [ 0, 0, 3.2e-5 ];
BAS.Tsetmin{6} = [ 17, 17, 17 ];
BAS.Tsetmax{6} = [ 100, 100, 100 ];
BAS.RVmin{6} = [ -1, -1, -1 ];
BAS.RVmax{6} = [ 101, 101, 101 ];

% Zone 4
% proID=7 Gangbare profiel (overdag beide aan het werk)
BAS.Ers{7} = 300;
BAS.dayper{7} = [ 17, 23 ];
BAS.vvmin{7} = [ 0.3, 0.3 ];
BAS.vvmax{7} = [ 2, 2 ];
BAS.Tfc{7} = [ 25, 25 ];
BAS.Qint{7} = [ 100, 20 ];
BAS.Gint{7} = [ 0, 0 ];
BAS.Tsetmin{7} = [ 17, 17 ];
BAS.Tsetmax{7} = [ 100, 100 ];
BAS.RVmin{7} = [ -1, -1 ];
BAS.RVmax{7} = [ 101, 101 ];

% proID=8 Weekendprofiel voor zone 4
BAS.Ers{8} = 300;
BAS.dayper{8} = [ 9, 23 ];
BAS.vvmin{8} = [ 0.3, 0.3 ];
BAS.vvmax{8} = [ 2, 2 ];
BAS.Tfc{8} = [ 25, 25 ];
BAS.Qint{8} = [ 60, 10 ];
BAS.Gint{8} = [ 0, 0 ];
BAS.Tsetmin(8) = [ 17, 17 ];
BAS.Tsetmax(8) = [ 100, 100 ];
BAS.RVmin(8) = [ -1, -1 ];
BAS.RVmax(8) = [ 101, 101 ];

% THE PROFILES OF THE BUILDING
BAS.weekfun{zonenr} = [upnrm, upnrtue, upnrd, upnfrh, upnfr, upnsat, upnrsun];
BAS.weekfun{1} = [5, 5, 5, 5, 5, 6, 6];
BAS.weekfun{2} = [1, 1, 1, 1, 1, 2, 2];
BAS.weekfun{3} = [3, 3, 3, 3, 3, 4, 4];
BAS.weekfun{4} = [7, 7, 7, 7, 7, 8, 8];

% PART 4 : Heating, cooling, humidification, dehumidification

% FORMAT BAS.Plant{zonenr} = [heating capacity [W], cooling capacity [W],
% humidity capacity [kg/s], dehumidification capacity [kg/s]]
BAS.Plant{1} = [3700, 0, 0, 0];
BAS.Plant{2} = [5658, 0, 0, 0];
BAS.Plant{3} = [1414, 0, 0, 0];
BAS.Plant{4} = [300, 0, 0, 0];

% FORMAT BAS.convfac{zonenr} = [CFh, CFset, CFint ];
BAS.convfac{1} = [0.8, 1, 0.5 ];
BAS.convfac{2} = [0.8, 1, 0.5 ];
BAS.convfac{3} = [0.8, 1, 0.5 ];
BAS.convfac{4} = [0.8, 1, 0.5 ];

% FORMAT BAS.heatexch{zonenr} = [etaww, Twws];
BAS.heatexch{1} = [0.9 22];
BAS.heatexch{2} = [0.9 22];
BAS.heatexch{3} = [0.9 22];
BAS.heatexch{4} = [0.9 22];

% FORMAT BAS.furnishings{zonenr} = [fbv, CFfbi];
BAS.furnishings{1} = [1, 0.2];
BAS.furnishings{2} = [1, 0.2];
BAS.furnishings{3} = [1, 0.2];
BAS.furnishings{4} = [1, 0.2];

%*************** END OF INPUT**************************%

%(voor eventueel het invoeren van extra info, zie handleiding)
%Inputextra0309

% De functie 'Hambasefun0309' controleerd op mogelijke fouten bij de invoer:
[Control, Profiles, InClimate, InBuil] = Hambasefun0309(BAS);

% De functie 'Wavox0209' is het bestand met de berekeningen welke de
uitkomsten transporteert naar een uitkomstenmap 'output.mat':
[Output, Control, Elan] = Wavox0209(Control, Profiles, InClimate, InBuil);

% De functie 'Wavox0209' is het bestand met de berekeningen welke de
uitkomsten transporteert naar een uitkomstenmap 'output.mat':
Wavooutput
6.3 **Energy consumption existing building**

![Graph showing energy consumption](image)

**Figure 8.** Simulated gas consumption and heating power
6.4 Data indoor climate existing situation

**Figure 9.** Simulated indoor temperature (four zones) and outdoor temperature existing situation

**Figure 10.** Simulated indoor relative humidity (four zones) and outdoor relative humidity existing situation
Figure 11. Climate Evaluation Chart Zone 1 existing situation

Figure 12. Climate Evaluation Chart Zone 2 existing situation
Figure 13. Climate Evaluation Chart Zone 3 existing situation

Figure 14. Climate Evaluation Chart Zone 4 existing situation
6.5 *Data indoor climate improved situation (winter + summer period)*

Figure 15. Simulated temperature (four zones) improved situation winter period

Figure 16. Simulated indoor temperature (four zones) improved situation summer period
Figure 17. Simulated (outdoor) relative humidity (four zones) improved situation winter period

Figure 18. Simulated (outdoor) relative humidity (four zones) improved situation summer period
6.6 *Simulink model without improved and sustainable measures*
6.7 Simulink model solar collector
Simulink model thermal buffer, coupled with floor heating and chiller
6.9 Simulink model floor heating/cooling

Thermal floor system
Inputs are:
- water supply temp, massflow, air temp
- In zones and transfer resistance between air and floor surface.
Outputs are:
- Surface temps, Q inside above and under the floor, pipe temp and return temperature.

[Diagram of Simulink model for floor heating/cooling]
6.10 Simulink model adsorption chiller
6.11 Simulink model of the zone temperature controllers and used setpoints.
6.12 Simulink model of in and outputs HAMBase file and heat energy registration.
In this section more data out of the winter simulation period were presented. Keep in mind that the data presented during the first simulation days are usually incorrect because the influence of the initial condition of the construction is too large.

**Fig. 7** Outdoor temperature [°C]

**Fig. 8** Zone temperatures [°C]
Fig. 9 Relative humidity outdoor

Fig. 10 Relative humidity in the zones
De outlet temperature of the buffer is not the same as the inlet temperature of the thermal floor system. The last one is limited by 35 degrees Celsius.
Because the mass flow depends on the incoming solar radiation, the outlet temperature stays quite high by small sun power.
Below the inlet temperatures of the floor heating system were presented. They strongly depend on the set point temperatures of the zones.

Fig. 15 Zone heating contributed by solar energy [W]

Fig. 16 Inlet temperature of thermal Floor system of zone 1
Fig. 17 Inlet temperature of thermal Floor system of zone 2

Fig. 18 Inlet temperature of thermal Floor system of zone 3

Fig. 19 Inlet temperature of thermal Floor system of zone 4
Fig. 20: Floor heating energy demand [W]

Fig. 21: Energy delivered to the air by floor surface of zone 1 [W]
Fig. 22 Energy delivered to the air by floor surface of zone 2 [W]

Fig. 23 Energy delivered to the air by floor surface of zone 3 [W]

Fig. 24 Energy delivered to the air by floor surface of zone 4 [W]
6.14 *Simulation results of the Simulink model during summer period.*

In this section more data out of the summer simulation period were presented. Keep in mind that the data presented during the first simulation days are usually incorrect because the influence of the initial condition of the construction is too large.

![Outdoor temperature graph](image)

*Fig. 25 Outdoor temperature [°C]*

![Indoor zone temperatures graph](image)

*Fig. 26 Indoor zone temperatures [°C]*
Fig. 27 Relative humidity outdoor

Fig. 28 Relative humidity into the zones
Fig. 29 Hot water temperature on top of the buffer [°C]

Fig. 30 Outlet temperature of buffer or inlet temp. of the solar collector [°C]
Fig. 31 Outlet temperature of the collector to the buffer [°C]

Fig. 32 Driven energy demand of the adsorption chiller [W]
Fig. 33 Massflow between buffer and adsorption chiller [kg/s]

Fig. 34 Inlet temperatures of the thermal floor system zone 1 [°C]
Fig. 35 Inlet temperatures of the thermal floor system zone 2 [°C]

Fig. 36 Inlet temperatures of the thermal floor system zone 3 [°C]

Fig. 37 Inlet temperatures of the thermal floor system zone 4 [°C]
Fig. 38 Zone floor system cooling energy demand [W]

Fig. 39 Energy delivered to the air by floor surface of zone 1 [W]
Fig. 40 Energy delivered to the air by floor surface of zone 2 [W]

Fig. 41 Energy delivered to the air by floor surface of zone 3 [W]
The total extracted thermal energy during this period into the zones by cooling is:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Cooling energy [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>106.5</td>
</tr>
<tr>
<td>Zone 2</td>
<td>165.6</td>
</tr>
<tr>
<td>Zone 3</td>
<td>0.94</td>
</tr>
<tr>
<td>Zone 4</td>
<td>10.14</td>
</tr>
<tr>
<td>Total</td>
<td>283.3</td>
</tr>
</tbody>
</table>

Fig. 42 Energy delivered to the air by floor surface of zone 4 [W]
Development of a new 2.5 kW adsorption chiller for heat driven cooling

E.J. Bakker

R. de Boer
DEVELOPMENT OF A NEW 2.5KW ADSORPTION CHILLER
FOR HEAT DRIVEN COOLING

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SUMMARY
Besides (better) utilisation of available solar heat or waste heat, and thereby reduction of fossil fuel consumption, sorption cooling offers several other advantages compared to conventional compression cooling. Such as reduction of summer peaks in the electricity grid, natural refrigerants, and less noise & maintenance. Sorption cooling in itself is not a new development. However, the development of small scale sorption chillers (2-20kW) is new. This development allows sorption cooling to enter the markets for individual homes, small collective systems and small commercial applications. A second trend is gradual reduction of the driving temperatures of the sorption cycles allowing more solar and waste heat to be used. This article describes the design and performance of a new, innovative 2.5kW adsorption chiller, developed by ECN. For this chiller ECN is currently searching for suited commercial parties, for production and commercialization.

INTRODUCTION
Sorption cooling is a technology that uses heat to generate cooling. Compared to conventional compression cooling, sorption cooling offers several advantages, e.g.:
- Using heat instead of electricity reduces peaks on the electricity grids in the summer.
- Many sorption cycles are based on natural refrigerants.
- Using thermal compression reduces noise levels and maintenance requirements.

In recent years several companies have started development of small capacity sorption chillers, with cooling power below 20 kW, as was shown at the IEA.
Heat Pump Conference 2008 in Zürich. Some of these efforts have already led to commercial products. With these new developments the market for thermally driven cooling in single family homes and small commercial applications is opening up. A second trend is gradual reduction of the driving temperatures of sorption cycles to well under 100°C (typically 80-90°C). This allows for an increase in the use of e.g. solar heat and industrial waste heat (via district heating systems).

Triggered by the national potential of waste heat (e.g. from industry) and renewable heat (e.g. from the sun) the Energy research Centre of the Netherlands (ECN) has initiated development of sorption cooling technology several years ago. As a working pair silica gel – water was chosen, a choice that has proven successful so far.

**WORKING PRINCIPLE ADSORPTION COOLING**

Just like a conventional compression chiller, an adsorption chiller uses a cycle where a refrigerant condenses at high pressure/temperature and evaporates at low pressure/temperature. However, this cycle is not driven by a mechanical compressor but by a thermal compressor, based on the sorption reaction of silica gel and water, using heat as driving force. Dry silica gel (a porous, glass-like solid) attracts and adsorbs water vapour, until it’s saturated. Then it needs to be regenerated: heating the silica gel releases the water vapour at a pressure that allows it to condense at ambient temperatures. Then the cycle of adsorption and desorption can be repeated.

This cycle is not unlike absorption cycles (with e.g. LiBr-solution), however there are 2 important differences: 1. the silica gel can be regenerated efficiently at lower driving temperatures and 2. the silica gel is a solid that can not be pumped from generator to absorber. The silica gel is applied on heat exchangers which are supplied intermittently with hot and cooling water. The adsorption cycle is a batch process and for quasi-continuous cooling at least 2 silica gel beds (reactors) are needed, operating in counter-phase.
The lowest possible chilled water temperature of this adsorption cycle is about 4°C, making it perfectly suited for air-conditioning and chilled water systems in the built environment and in industry.

![Diagram of adsorption chiller lay-out]

*Figure 1: Schematic of adsorption chiller lay-out*

**DESIGN 2.5kW ADSORPTION CHILLER**

Within the European project PolySMART (www.polysmart.org), ECN has developed a small-scale adsorption chiller, using silica gel - water as working pair, which will be tested and demonstrated. Starting point for this chiller is to supply sufficient cooling power for a modern single family house (2.5kW). For the size, a common (challenging!) standard for household appliances is used: a 60x60cm footprint (height is about 100cm).

In the design of this chiller compact light-weight aluminium heat exchangers from the automotive industry are used to apply the silica gel, creating a large surface while maintaining low weight and volume. For the same reason this type of heat exchanger is also used for the condenser and for the evaporator. Figure 2 shows the lay-out of the new chiller: the evaporator at the bottom, two silica gel reactors above the evaporator and on top the condenser.

Water vapour flows at low pressure from the evaporator (creating a cooling effect) and is adsorbed in one of the two silica gel reactors (adsorption phase). At the same time, water vapour flows from the other reactor to the condenser (desorption phase) at higher pressure. Between these components special check
valves have been placed to prevent the water vapour from flowing back. This (low pressure) process requires that the system does not contain any other gases or vapours besides water vapour and that all components are hermetically sealed. The water from the condenser flows back to the evaporator via a condensate return line. The flow for heating and cooling of the silica gel is controlled by 8 valves, which intermittently supply both reactors. To control these valves and to monitor temperatures and pressures, a PLC unit is included in the chiller.

![Design drawing and picture of the ECN 2.5kW adsorption chiller](image)

**Figure 2: Design drawing and picture of the ECN 2.5kW adsorption chiller**

**ADSORPTION CHILLER PERFORMANCE**

The adsorption chiller has been tested in an ECN laboratory, with the facilities to control flows and temperatures for hot, cooling and chilled water. Hot, cooling and chilled water temperatures strongly influence the chillers' performance. As nominal operating conditions the following inlet temperatures are set: 80°C, 30°C and 15°C respectively.

Under these conditions the influence of cycle time on thermal performance has been determined. The cycle time is the duration of a complete cycle of heating up and cooling down of one reactor. Figure 3 shows the cooling power (left axis) and Coefficient of Performance (right axis, ratio of cooling power and driving heat).

\[
COP = \frac{Q_{\text{evaporator}}}{Q_{\text{heatsource}}}
\]
The graph shows that cycle times under 6 minutes are not useful, because both cooling power and COP show a decrease (because this short cycle time does not allow all silica gel to go through the complete temperature cycle). At increasing cycle times (>10 minutes) a decrease in cooling power is compensated by an increase in efficiency (because less changes between heating and cooling of a reactor means less thermal losses).

Figure 3: Influence of cycle time on thermal performance of the adsorption chiller

Figure 4 shows the influence of the cooling water and chilled water inlet temperature on the chillers' performance. Chiller performance clearly benefits from "high temperature cooling" and relatively low cooling water temperatures. When designing a complete (solar) cooling system these influences have to be taken into consideration.
Figure 4: Influence of cooling water (left) and chilled water (right) inlet temperature

The laboratory tests show that the ambitious design specifications for this prototype have been achieved. Nearly 2.5kW cooling power can be produced with a very compact chiller (power density of about 7kW/m³) at a very respectable COP.

OUTLOOK

This 2.5kW chiller has recently been installed in one of the research houses at the ECN premises in Petten, The Netherlands. These research houses are not inhabited, but nearly all aspects of user behaviour is simulated (such as domestic hot water use, internal heat production, and humidity and CO₂ production), offering a realistic but controlled test environment.

Within the framework of the PolySMART project, this chiller will be driven by a small cogeneration unit (microCHP), creating a unique micro-trigeneration system. For heat rejection a standard dry cooler is used. This configuration will be tested until the summer of 2010. Intention is to create a follow-up demo project
with a solar cooling configuration. The thermal power of this chiller fits well with Stirling-based microCHP (or small-scale solar collector systems) for individual residences. When applied in combination with measures to reduce "overheating" in summer (e.g. solar shading, night ventilation), it's expected 2.5kW cooling is sufficient to provide a comfortable indoor temperature. Especially if this cooling power can be used completely, when necessary, to tackle a commonly reported comfort problem (in Dutch residences): overheating of bedrooms.

Parallel to this "field test", development of the 2.5kW sorption chiller continues, to turn it into a commercial product. Current emphasis is on redesign for manufacturability. For both production and commercialization ECN is currently looking for interested and suited commercial companies, to form a consortium that will transform the current prototype into a commercial product.