4 The energy roof system

An energy roof collector is cooled by a heat pump in such a way that the surface temperature will often be below the ambient air temperature. This has the advantage that cover plates are superfluous and that besides a maximum of solar energy, also energy is gained from cooling the ambient air, from latent heat of the air and from rain. In the Netherlands the winters are mild and humid with little sunshine, so the system is very promising. In the past four years, several configurations of an energy roof with a focus on the convective heat recovery from ambient air, have been investigated at the GEO test site of the University [1]. The heat storage (TES) is located at the cold side of the heat pump so instead of heat loss even heat gain is possible. In this paper the system is only used as a demonstration of modeling in the SimuLink environment. The system is not the realistic one but a simplified for this purpose. In figure 4 an outline is given of the simplified energy roof system.

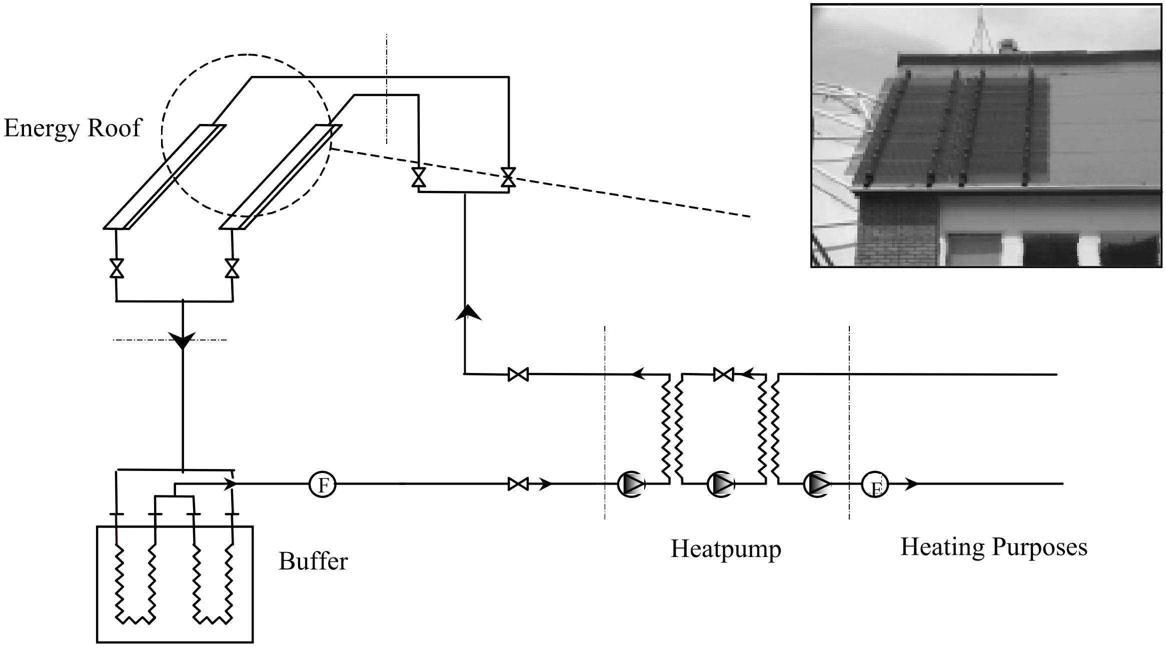

Figure 4. The energy roof system.

The system has two identical roof surfaces, one facing south and one facing north. This give the opportunity to investigate whether an energy roof facing north, without direct solar radiation, is cost effective. Circulating the cooling fluid through the energy roof charges the water buffer. Discharging the buffer is accomplished by passing the cooling fluid through the heat pump. (In the real system charging and discharging can be done at the same time, when the energy roof is extracting heat from outside and there is a simultaneous heat demand from the dwelling). Up to now, it may be concluded that cost-efficient application of a heat pump in a dwelling is best achieved by bivalent systems. The capacity of the heat pump is limited then to about 30% of the total required maximal heating capacity.

The collector of the test site consists of a very simple perforated plate designed primarily for convective heat transfer. The measurements of [1] are used for the determination of the constants in the component models. The physics of it are not considered in this paper. The empirical models are:

- Heat pump model:

$$\begin{cases} \mathrm{COP} = \mathrm{k} \cdot \dfrac{0.5 \cdot \mathrm{T_{cin}} + 0.5 \cdot \mathrm{T_{cout}} + 273.15}{(0.5 \cdot \mathrm{T_{cin}} + 0.5 \cdot \mathrm{T_{cout}}) - (0.5 \cdot \mathrm{T_{vin}} + 0.5 \cdot \mathrm{T_{vout}})} \\ \mathrm{C_c} \dfrac{\mathrm{dT_{cout}}}{\mathrm{dt}} = \mathrm{F_{cin}} \cdot \mathrm{cw} \cdot (\mathrm{T_{cin}} - \mathrm{T_{cout}}) + \mathrm{COP} \cdot \mathrm{Ehp} \\ \mathrm{C_v} \dfrac{\mathrm{dT_{vout}}}{\mathrm{dt}} = \mathrm{F_{vin}} \cdot \mathrm{cw} \cdot (\mathrm{T_{vin}} - \mathrm{T_{vout}}) - (\mathrm{COP} - 1) \cdot \mathrm{Ehp} \end{cases} \tag{4}$$

Where T is temperature [^{o}C], COP Coefficient of Performance [-], k heat pump efficiency determined from the measurements at the GEO test site, (k=0.4), cw specific heat capacity of water, C heat capacity (C_V=C_c≈10^5 J/K),], t time[s], F mass flow [kg/s], Ehp heat pump electric power supply (1200 W). Subscript c means water at the condenser, v water at the evaporator, in, incoming, out, outgoing.

- Energy roof model:

$$\mathrm{C_r} \frac{\mathrm{dT_{rout}}}{\mathrm{dt}} = \mathrm{F_{rin}} \cdot \mathrm{cw} \cdot (\mathrm{T_{rin}} - \mathrm{T_{rout}}) + \mathrm{k1} \cdot \mathrm{Esolar} - \mathrm{k2} \cdot (\frac{\mathrm{T_{rin}} + \mathrm{T_{rout}}}{2} - \mathrm{T_e}) \tag{5}$$

Where Esolar irradiance [W/m^2], k1 and k2 empirical determined factors (k1=0.8 m^2 and k2=125 W/K). Subscript r means water at energy roof, e exterior.

- Thermal energy storage

$$m \cdot cw \cdot \frac{dT_{bout}}{dt} = F_{bin} \cdot cw \cdot T_{bin} - F_{bout} \cdot cw \cdot T_{bout} \tag{6}$$

Where m is the mass of storage [kg], Subscript b means water in TES.

Parameter evaluation of the systems

With the parameters found from the measurements the calculated performance of the components is compared with measurements. The input for the models are: the measured incoming and outgoing mass flows, incoming water temperatures, the external temperature and the irradiance on the inclined surface. In the first 4 figures of figure 5 it is show that the models of the components predict the outgoing water temperatures well.

Simulation of the total system with a preliminary simple control strategy

The external temperature and the irradiance on the inclined surface are used as input for the simulation of the complete system of figure 6. The next simulated temperatures are given for a 48 hours period: Incoming and outgoing water temperatures of the evaporator and condenser, outgoing water temperature of the energy roof and internal and external air temperatures (see figure 5, bottom). There are substantial differences between the calculated values and the measured ones (not shown). This is probably due to a different control. More research is needed for this.

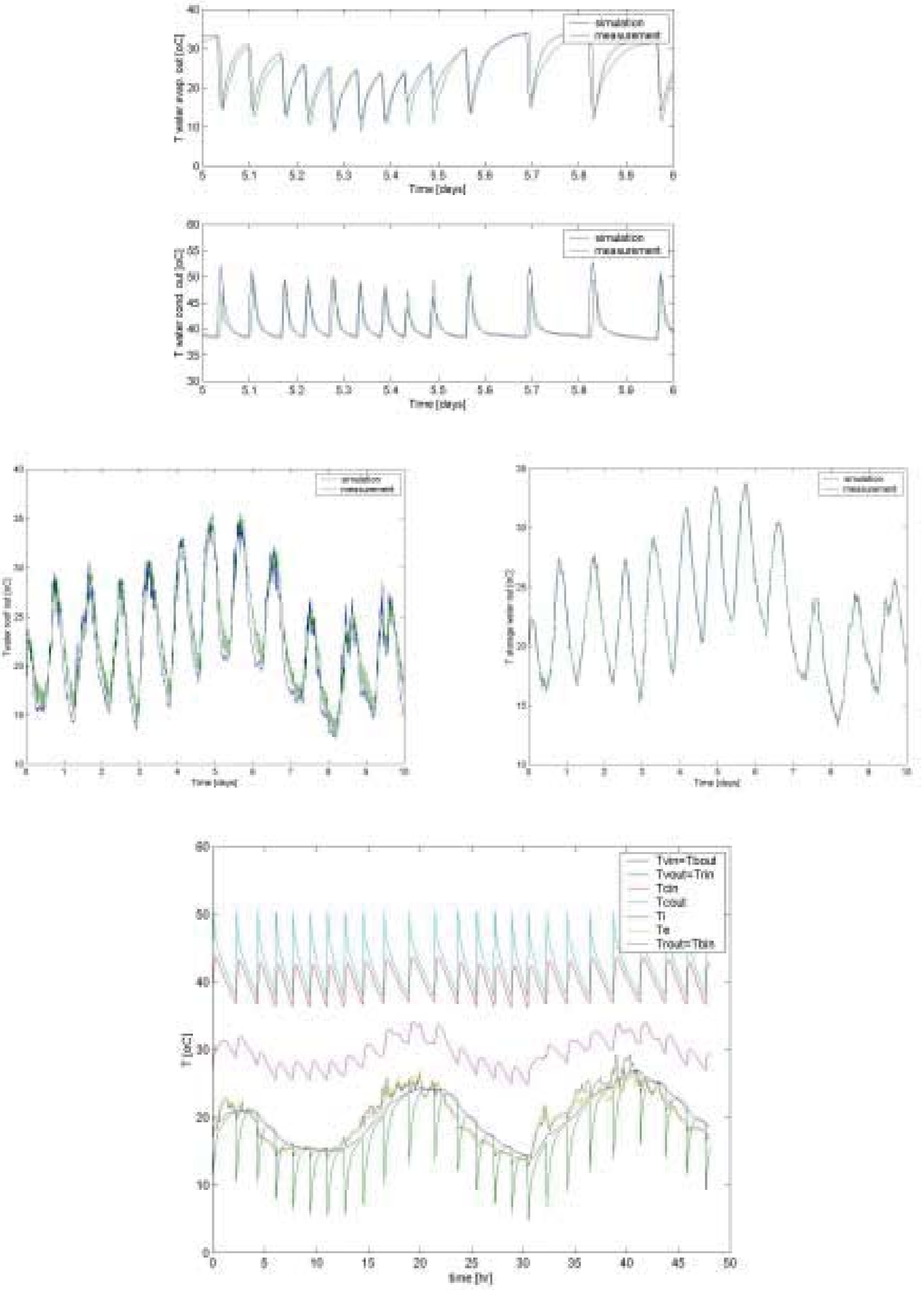

Figure 5. Simulation (blue) and measurement (green) of the outgoing water temperature of: the evaporator (top), condenser (second), the energy roof (third left) and TES (third right) and simulation of the total system (bottom)

In figure 6 the complete energy roof system connected to the building zone model in SimuLink is presented. The control strategy is simple. All mass flows are kept constant (0.02 kg/s) and heat pump is controlled by the internal temperature and an on/off switch (Relay).

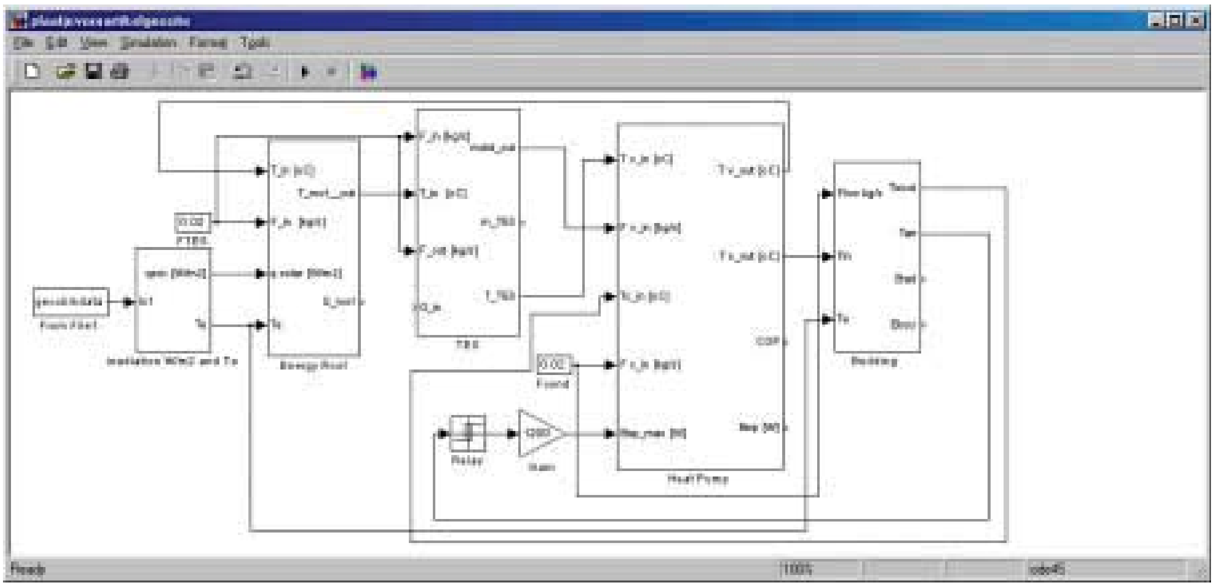

Figure 6. The complete energy roof system in SimuLink.

5 Conclusions

The next applications of System (S-) functions in SimuLink for building systems component simulation are evaluated:

- A hybrid (continuous/discrete) building zone model capable of simulating the thermal and hygric indoor climate. The main advantages of this model are: a) the dynamics of the building systems of time scales less than an hour are accurately simulated, b) the model becomes time efficient. The building zone model is validated with the ASHRAE test [4] and shows a good agreement
- Continuous models of a heat pump, an energy roof and a TES (Thermal Energy Storage). The main advantages of this approach are: a) a clear relation between mathematical model (system of Ordinary Differential Equations (ODEs)) and computer code in the S-functions, b) the state of art ODE solvers of MatLab give accurate solutions. The models are compared with measurements and show a good agreement.
- A complete energy roof and building model containing all the above mentioned components with a preliminary simple control strategy. Future models will include more advanced control strategies in order to get more realistic simulation results and to validate the complete model.

The evaluation illustrates the powerful and flexible nature of Matlab/SimuLink for simulating building systems models.

6 References

[1] J. de Jong, A.W.M. van Schijndel, C.E.E. Pernot, Evaluation of a low temperature energy roof and heat pump combination, Int. Building Physics Conference Eindhoven, 18-21 Sept. 2000

[2] M.H. de Wit, H.H. Driessen, 1988. ELAN A Computer Model for Building Energy Design. Building and Environment, Vol.23, No 4, pp.285-289

[3] The Mathworks Inc., Simulink version 2, 1997.

[4] ASHRAE, Standard method of test for the evaluation of building energy analysis computer programs, standard 140-2001, 2001.

[5] M.H. de Wit: WAVO, a simulation model for the thermal and hygric performance of a building, Univ. of Tech. Eindhoven, group FAGO, 2001

7 Appendix

A complete example how to model a system of ODEs with an S-function of Simulink is shown for the heat pump model. The first step is to define the input-output definition of the model. This is presented in Table III.

Table III. The input-output definition of the heat pump model

Variable name	**Input (u) / Output (y)**	**Description**
T_{vin}	u(1)	Incoming water temperature at the evaporator [^oC]
F_{vin}	u(2)	Incoming mass flow at the evaporator [kg/s]
T_{cin}	u(3)	Incoming water temperature at the condenser [^oC]
F_{cin}	u(4)	Incoming mass flow at the condenser [kg/s]
Ehp	u(5)	Electrical power supply [W]
k	u(6)	efficiency [-]
T_{vout}	y(1)	Outgoing water temperature at the evaporator [^oC]
T_{cout}	y(2)	Outgoing water temperature at the condenser [^oC]
COP	y(3)	Coefficient Of Performance [-]

The second step is to formulate a mathematical model by a system of ODEs. This is done using (4). The third step is to implement the mathematical model into a (S)ystem function, a programmatic description of a dynamic system. Details about this subject can be found in [3]. Figure 7 shows the program code of the S function and the final SimuLink model.

```
function [sys,x0,str,ts] = wpsfun2(t,x,u,flag)
%WPSFUN2 Heat pump
%u(1)=Tvin [oC], u(2)=Fvin [kg/s], u(3)=Tcin [oC],
%u(4)=Fcin [kg/s], u(5)=Ehp [W], u(6)=k [-]
%y(1)=Tvout [oC] (=x(1)), y(2)=Tcout [oC] (=x(2))
%y(3)=COP
switch flag,
  case 0,
    [sys,x0,str,ts]=mdlInitializeSizes;
  case 1,
    sys=mdlDerivatives(t,x,u);
  case 3,
    sys=mdlOutputs(t,x,u);
  case { 2, 4, 9 },
    sys=[];
end
function [sys,x0,str,ts]=mdlInitializeSizes
sizes.NumContStates  = 2; % Number of Cont. states
sizes.NumDiscStates  = 0; % Number of Disc. states
sizes.NumOutputs     = 3; % Number of Outputs
sizes.NumInputs      = 6; % Number of Inputs
x0  = [10; 10];          % Initial values
function sys=mdlDerivatives(t,x,u)
   Tvm=(u(1)+x(1))/2;
   Tcm=(u(3)+x(2))/2;
   COP=u(6)*(273.15+Tcm)/(Tcm-Tvm);
   Cc=200000;Cv=200000;cv=4200;cc=4200;
  xdot(1)=(1/Cv)*(u(2)*cv*(u(1)-x(1))-(COP-1)*u(5));
   xdot(2)=(1/Cc)*(u(4)*cc*(u(3)-x(2))+COP*u(5));
   sys = [xdot(1); xdot(2)];
function sys=mdlOutputs(t,x,u)
   Tvm=(u(1)+x(1))/2;
   Tcm=(u(3)+x(2))/2;
   COP=u(6)*(273.15+Tcm)/(Tcm-Tvm);
   sys = [x(1); x(2); COP];
```

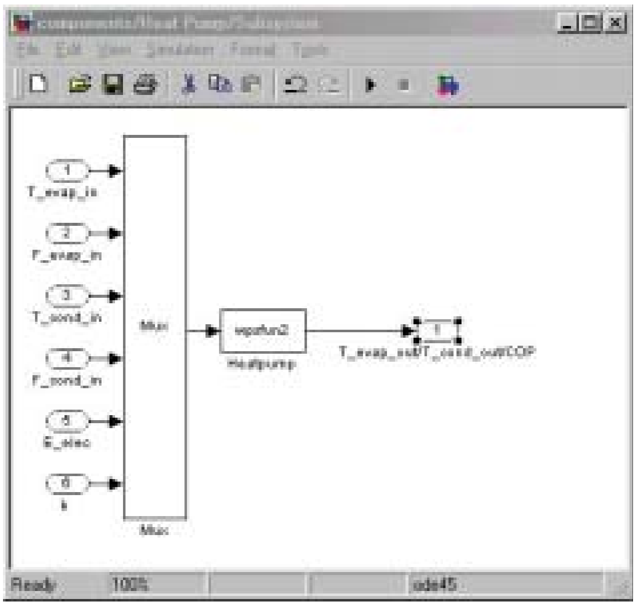

Figure 7. The code of the heat pump model used at the S function (upper) and the final Simulink model (lower).