MODEL DEVELOPMENT AND CONTROL STRATEGIES FOR A SOLAR SYSTEM COMBINED WITH HEAT PUMP

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ABSTRACT

Buildings consume a considerable amount of energy. This paper presents a model predictive control (MPC) strategy and two conventional control strategies (On-Off and PI) for a solar system assisted by heat Pump. This type of setup is used mainly for domestic hot water and heating purpose. This research is in response to the UK government's commitment to produce 20% of country's energy from renewable sources by 2020. The aim of the controller is to reduce electric consumption and to provide better thermal comfort of the occupants. The MPC controller uses cheaper night time electricity to store heat energy in the water tanks and uses this later in the day, when it is required. The MPC controller also anticipates any future hot day and then tries to use solar radiations to heat up the water. In this paper mathematical model of the heat pump and lumped model of the building is also presented. Three control strategies i.e. MPC, PI and On-Off are compared and it is concluded that model predictive controller provided the best performance.

Keywords: Model predictive controller, Heat Pump, Thermal comfort, Conventional control strategies, Solar radiations.

1. INTRODUCTION

The rapid increase in world's energy use is one of the main concerns of today's world. This energy use has high environmental impacts such as depletion of ozone layer, global warming, climate change etc. According to IEA (International Energy Agency) the primary Energy has grown by 49% in the last two decades (1984-2004) and the CO_2 emission has been increased by 43% (International Energy Agency, 2006). It was also shown by the IEA that there is an average increase of 2% in energy and 1.8% in the CO_2 emissions. All our energy sources are derived from solar energy. Wood, Oil and natural gas were originally produced through photosynthesis and complex chemical reactions. Fossil fuels are the result of chemical reactions in decaying vegetation under high temperatures and pressures over long periods of time (Kreith & Kreider, 1978). The main advantage of solar energy is that it is clean and can be delivered without pollution.

Solar collectors have a wide variety of applications, such as solar water heating, space heating and cooling, solar refrigeration, solar thermal power plants, solar desalination etc. In solar water heating systems the main component is the solar collector, which absorbs energy and transfers it to the working fluid. Integrated collector systems use part of the tank as a solar collector. The disadvantage of this system is the thermal losses from the tank (Kalogirou, 2004). Solar energy systems can be used for hot water generation. In this application a heat exchanger is used between the solar collector and the hot water tank, which allows the use of antifreeze solutions in the solar collector loop (Duffie, & Beckman, 1991).

Air source heat pumps are devices which transfer energy from air at low temperature to a tank at high temperature. The use of a heat pump for space heating and hot water generation is gaining popularity day by day because of its low energy consumption compared to other equipment (Agrawal & Bhattacharyya, 2007), (Rakhesh et al, 2003), (Sakellari & Lundqvist, 2002). The heat pump operates best at low temperature differences, when the coefficient of performance (COP) is high and the required energy low (Zogg et al, 2001).

The solar radiation is not available during night times and on cloudy days. Therefore, solar collectors can be combined with a heat pump in such a way that in times of low solar radiation the heat pump is used instead. The heat pump can also benefit from cheap night time electricity when combined with a thermal storage. The main idea behind using model predictive control in this work is that this control strategy can predict outside weather conditions and occupancy pattern in the building. This strategy also predict any future hot sunny day and then can use maximum free energy during the day i.e. solar energy and also can predict the electricity prices and uses electricity during the night.

Model predictive control (MPC) originated in the late seventies and has developed very considerably. MPC is a class of computer algorithms that utilize process model to predict future outcome/response of a plant. The basic structure of MPC is shown in figure 1. The model gets data from past input and past outputs and combines this data with future inputs. The model then gives predicted output for the time step. This predicted output is combined with reference trajectory to give future errors to the systems. These future errors are then fed into optimizer, which enforces constraints on future predicted outputs and also minimizes the operating cost functions. Optimizers gives future predicted inputs which are fed back into main model. A generic framework of MPC problem in finite-horizon is given by following problem:

$$\mathrm{J}(\mathrm{x_o}) = \min_{\mathrm{u_0,\ldots\ldots,u_{N-1}}} \sum_{\mathrm{k=0}}^{\mathrm{N-1}} \mathrm{l_k}\,(\mathrm{x_k}, \mathrm{u_k}) \quad \text{Cost Function} \qquad \text{(i)}$$

The above equation is the cost function of the problem and is subject to following;

$$(\mathrm{x_k}, \mathrm{u_k}) \in \mathrm{X_k} * \mathrm{U_k} \qquad \text{Constarints} \qquad \text{(ii)}$$

$$\mathrm{x_o} = \mathrm{x} \qquad \text{Current state} \qquad \text{(iii)}$$

$$\mathrm{x_{k+1}} = \mathrm{f}(\mathrm{x_k}, \mathrm{u_k}) \qquad \text{(iv)}$$

In the above equations N is the prediction horizon, X_k and U_k are the sets of constriants for state x_k and inouts u_k respectively at time step k. The cost funtion and constraints are the main components of model predictive control design. The controller uses current state as the initial state for prediction of the future inputs.

2. PLANT DESCRIPTION

The solar assisted heat pump system is installed at the School of Civil and Building Engineering of Loughborough University as an experimental rig. It consists of a solar panel, a heat pump and accumulators.

Solar panels are used for heating when feasible, and the heat pump is used for heating when solar irradiation is insufficient (cloudy weather, night), and it is used for the domestic hot water purposes. The heat pump has a power capacity of 6kW.

The main components of the system are shown in figure 2. In figure 2(a) the heating tank is shown, which encapsulates the hot water tank (not visible). In figure 2(b) the diverter is shown, which diverts the flow from the buffer tank to the heating tank or the hot water tank. Figure 2(c) is the valve which regulates the flow from the buffer tank to the other two tanks. Figure 2(d) is the current controller which controls the heat pump, diverter and valves. The figure 2(e) is the buffer tank which is connected to the heat pump.

A general schematic diagram of the plant is shown in figure 3. In figure 3 the main components of the system can be observed. The heat pump is connected to the buffer tank. The plant uses two different energy sources: the solar collector and the electric air source heat pump. Both of these can be used together or separately for the heating tank.

The mixing valve M1 allows water to flow from the buffer tank (heat pump tank) into the heating tank or hot water tank, while the diverter D1 diverts the flow to either or both of these tanks. The valve M2 allows water to bring energy into the heating tank or to take it back to the solar collectors.

The objective for the system is to supply hot water for heating and domestic hot water at the required temperatures. The control object is to minimize the cost of electric energy for the heat pump. If the solar irradiation is low the heat pump can be used, but the desired solution is to operate the heat pump during the night when the energy tariffs are low. The preferred energy is of course solar energy. Since the solar radiation cannot be controlled, it is considered as a measured disturbance here.

3. SYSTEM DESCRIPTION

The main components of the system are described here.

a. Accumulation system

The accumulation system consists of three tanks. The hot water tank is inside the heating tank. The heating tank is 450L and hot water tank is 300L of capacity. The third tank is the buffer tank and is 300L. It is connected to the heat pump and supplies hot water to other two tanks when it is required.

b. Solar Collector

Solar collectors are used to collect sole radiations and to raise the temperature of water of the heating tank. It uses solar energy to raise the water temperature and is the primary energy source of the system. It consists of 2 flat plate collectors 2m^2 in area each.

c. Heat Pump

The installed heat pump uses air as a heat source. It is the auxiliary source of the energy for the heating tank, but it is the main (only) energy source for the hot water tank. The heat pump is directly connected to the buffer tank. The rated electric power of the heat pump is 6kW.

The system variables are shown in figure 4.

d. Manipulated variables

- M1 allows the connection between buffer tank and other two tanks.
- M2 allows the heating tank and solar collector.
- D1 diverts flow to either hot water tank or heating tank
- Heat pump On/Off switch
- Heater On/Off Switch to heat the indoor environment.

e. Output Variables:

- All tank temperatures
- Solar collector output temperature or useful energy from the collector.
- Energy consumed by the heat pump

f. System disturbances

- Outside Environmental temperature
- Solar irradiations
- Domestic hot water consumption
- Tanks temperature

g. Building:

The building under consideration is a two rooms building; a hall and a bedroom. The hall has a south facing and a window on the south face. The dimensions of both the rooms are 4.27*4.57 and 2.44m high. The schematic layout of the building is shown in figure 5. The design data for the location of Birmingham is used for the calculation of the heating load and is taken from CIBSE (Chartered Institute of Building Services Engineers) guidelines. The building schematic and properties of the construction are given in figure 5 and table 1 respectively.

4. MATHEMATICAL MODELLING OF THE SYSTEM

The mathematical model of the whole system is developed and implemented in Simulink.

a. Heat Pump

A heat pump is a device that transfers thermal energy from a lower temperature (Source) to a higher temperature (Sink). It reverses the natural flow of thermal energy. The operating cycle of heat pump is shown in figure. It consists of four components;

- a compressor,
- a condenser,
- an expansion valve, and
- an evaporator.

The condenser is used to convert the refrigerant from its gaseous state into the liquid form, while the evaporator is used to convert the refrigerant from liquid to gaseous state. The refrigerant in its gaseous state is pressurised in the compressor. It is compressed by extra mechanical work (W_{net}). This high pressurised and high temperature fluid is then fed into condenser where it releases its heat (Q_{out}) and changes into liquid. Then, it enters into the expansion valve and changes into low pressure and low temperature liquid. In this state the refrigerant is fed into the evaporator, where it gains energy (Q_{in}) and changes it into gaseous state. Detailed information can be found in (Moran & Shapiro, 2006).

The efficiency of the heat pump is calculated by its coefficient of performance (COP). COP is the ratio of the heat transferred to the amount of the work done to the compressor.

$$\mathrm{COP} = \mathrm{K} * \frac{\mathrm{T_{c,out}}}{(\mathrm{T_{c,out}} - \mathrm{T_{e,out}})} \tag{A}$$

Where K is the efficiency coefficient of the compressor and is assumed as 0.4. Below the focus is on the dynamic heat pump model developed in (Van Schijndel et al, 2003). The heat pump under study is an air source heat pump. Figure 6 shows the operating cycle and two external cycles. The air cycle is attached to the evaporator while the water cycle is attached to the condenser. It is assumed that the temperature of liquid leaving the condenser denoted as $T_{c,out}$ at point 1 is equal to the temperature of the water going into the water tank denoted as $T_{w\_tank\_in}$ (buffer tank). Similarly it is also assumed that the temperature of the refrigerant feeding into the evaporator denoted by $T_{e,in}$ at point 2 is equal to the temperature of air coming into the evaporator denoted by Tair_in.

On the basis of these assumptions we have;

$T_{c,out} = T_{w\_tank\_in}$ and $T_{e,in} = T_{air\_in}$

Based on equation 1, further approximation of COP has been done by (Moran & Shapiro, 2006).

$$\mathrm{COP} = \dot{\mathrm{Q}}_{\mathrm{out}} / \mathrm{W}_{\mathrm{net}} \tag{1}$$

From equation 1;

$$\dot{\mathrm{Q}}_{\mathrm{out}} = \dot{\mathrm{W}}\mathrm{COP} \tag{2}$$

The energy balance gives:

$$\dot{\mathrm{Q}}_{\mathrm{out}} = \dot{\mathrm{W}} + \dot{\mathrm{Q}}_{\mathrm{in}} \tag{3}$$

$$\dot{\mathrm{Q}}_{\mathrm{in}} = \dot{\mathrm{W}}(\mathrm{COP} - 1) \tag{4}$$

The rate of heat energy gained by the evaporator from the air cycle is given by (Yan et al, 2007);

$$\dot{\mathrm{Q}}_{\mathrm{e}} = \dot{\mathrm{m}}_{\mathrm{e1}} \mathrm{C}_{\mathrm{r}} (\mathrm{T}_{\mathrm{e,in}} - \mathrm{T}_{\mathrm{e,out}}) \tag{5}$$

And the thermodynamics of the evaporator are

$$\mathrm{C}_{\mathrm{e}} \mathrm{m}_{\mathrm{e}} \dot{\mathrm{T}}_{\mathrm{e,out}} = \dot{\mathrm{Q}}_{\mathrm{e}} - \dot{\mathrm{Q}}_{\mathrm{in}} \tag{6}$$

$$\mathrm{C}_{\mathrm{e}} \mathrm{m}_{\mathrm{e}} \dot{\mathrm{T}}_{\mathrm{e,out}} = \dot{\mathrm{Q}}_{\mathrm{e}} - \dot{\mathrm{W}}\,(\mathrm{COP} - 1) \tag{7}$$

For the condenser the heat transferred in the water cycle is

$$\mathrm{C}_{\mathrm{e}} \mathrm{m}_{\mathrm{e}} \dot{\mathrm{T}}_{\mathrm{e,out}} = \dot{\mathrm{Q}}_{\mathrm{e}} - \dot{\mathrm{W}}\,(\mathrm{COP} - 1) \tag{8}$$

$$\dot{\mathrm{Q}}_{\mathrm{c}} = \dot{\mathrm{m}}_{\mathrm{c1}} \mathrm{C}_{\mathrm{r}} (\mathrm{T}_{\mathrm{c,out}} - \mathrm{T}_{\mathrm{c,in}}) \tag{9}$$

Similarly from the dynamics of condenser,

$$\mathrm{C_c m_c \dot{T}_{c,out} = \dot{Q}_{out} - \dot{Q}_c} \tag{10}$$

$$\mathrm{C_c m_c \dot{T}_{c,out} = \dot{W}COP - \dot{Q}_c} \tag{11}$$

Rearranging these equations leads to

$$\mathrm{\dot{T}_{e,out=}} \frac{\mathrm{\dot{m}_{e1} C_r T_{e,in} - \dot{m}_{e1} C_r T_{e,out} - (COP - 1)\dot{W}}}{\mathrm{C_e m_e}} \tag{B}$$

$$\mathrm{\dot{T}_{c,out=}} \frac{\mathrm{\dot{m}_{c1} C_r T_{c,in} - \dot{m}_{c1} C_r T_{c,out} + COP * \dot{W}}}{\mathrm{C_c m_c}} \tag{C}$$

Equations A, B and C are used as a heat pump model which is implemented in Simulink.

From above equations it can be concluded that the COP of the heat pump depends on the outside air temperature and the condenser outflow temperature. The heat pump operates between two different mediums (air and water), which have very different heat capacities. Air has less capacity than water, and for this reason the mass flow rate on the evaporator side is assumed higher than on the condenser side. The COP results found from the above equation did not match with the limited data that was available from the manufacturer as shown in the figure 7. Therefore the above model of heat pump was not suitable for this study.

In the second method to calculate the COP of the heat pump four other factors are considered i.e. α, β, $u_T P$ and $u_\mathrm{E} P$. Whereas α thermal efficiency coefficient of compressor, β is the recovery of losses into heat, $u_T P$ is the thermal coefficient on condenser side and $u_\mathrm{E} P$ is the thermal coefficient on evaporator side. $u_T P$ and $u_\mathrm{E} P$ incorporates the resistances of air and water on cold and hot mediums of the heat pump. The COP equation will be given by following equations;

$$\mathrm{COP} = \alpha \left(\frac{T_H}{T_H - T_C} \right) + \beta \tag{12}$$

By taking air and water resistances into account;

$$\mathrm{T_H - T_C = T_T - T_E + (u_T + u_E)P * COP - u_E P} \tag{13}$$

By Simplifying the above equation we have;

$$\mathrm{(u_T + u_E)P * COP^2 + (T_T - T_E - u_E P - \beta(u_T + u_E)P - \alpha u_T P)COP - \alpha T_T - \beta(T_T - T_E - u_E P) = 0} \tag{14}$$

The above quadratic equation can be solved for COP. In the figure 8 different calculations are shown with different values of α, β and $u_E P$ and one calculation by taking inverse of ideal COP and manufacture's COP and plotting them against each other. The results given by plot of inverse of ideal COP and manufacture's COP gives better results than the others and is considered as the heat pump model.

b. Solar Collector Model

Flat plate collector is used to heat up the heating tank. The useful energy from the solar panel is calculated by using the mathematical model proposed by (Duffie, & Beckman, 1991). The energy used in the solar panel is solar energy. The solar radiation is captured by the solar panel and used to heat up water. With a solar radiation I (W/m^2) covering the solar panel of an area Ac (m^2), the energy received by the solar collector is given by;

$$Q_r = I.A_c \qquad (15)$$

It is known that not all of energy received by the solar collector is used to raise the temperature of water, since some of the radiation is reflected back in to the sky. Only part of the radiation is absorbed by the solar plate. The conversion factor τα indicates the percentage of solar radiations which is absorbed by the solar collector and transmitted into the cover of panel. Therefore the energy received by solar collector is given by;

$$Q_r = \tau\alpha(I.A_c) \qquad (16)$$

There is also an energy loss from the solar collector surface when the temperature of solar panel is higher than the surroundings. This loss is given by;

$$Q_l = U_L A_c (T_c - T_a) \qquad (17)$$

Therefore the rate of useful energy gained by the solar collector is given by;

$$Q_U = Q_{r-} Q_l = \tau\alpha(I.A_c) - U_L A_c (T_c - T_a) \qquad (18)$$

The useful energy is also measured by the amount of the energy carried by the fluid;

$$Q_U = mC_p(T_o - T_i) \qquad (19)$$

It is difficult to define the average collector temperature in equation (15), therefore a factor called “the collector heat removal factor (F_R)” is given by the following equation;

$$F_{R=}\frac{mC_p(T_o - T_i)}{A_c\,[\tau\alpha I - U_L(T_c - T_a)]} \qquad (20)$$

The useful energy from the collector is measured by multiplying F_R with Q_U. The useful energy is;

$$Q_U = F_R A_c\,[\tau\alpha I - U_L(T_c - T_a)] \qquad (21)$$

The above equation is called “Hottel-Whillier-Bliss equation” and is used as a collector model in Simulink. The values of F_R* τα is taken as 0.68 and value of F_RU_L is 4.90 (W/m2)/^{O}C.

c. Energy equations

In this section the different heat transfer equations will be presented. The equations are based on energy balance and energy flow. By assuming an average temperature equal to T_b, T_h and T_H for buffer tank, heating tank and hot water tank respectively.

The heat transferred from the heat pump into the buffer tank is;

$$\dot{Q}_{out} = \dot{W}COP \qquad (22)$$

Where $\dot{Q}_{out}$ is the energy output from the condenser and $\dot{W}$ is the power input. The heat transfer between buffer tank and hot water tank is given by;

$$\dot{Q} = \dot{m}C_p\,(T_b - T_H) \qquad (23)$$

There is an energy use caused by the withdrawal of hot water, as cold water is fed into the tank. It is assumed that the cold water has a temperature of 15 ^{O}C and the hot water tank temperature is 55^{O}C. The heat transfer between the buffer tank and the heating tank is;

$$\dot{Q} = \dot{m}C_p\,(T_b - T_h) \qquad (24)$$

The solar energy input in the solar tank is given in the equation 21.

d. Building Modelling

Following is the modelling of the building using Simulink and equations used to develop the building model. All the external walls and roof are considered of same construction. The building is modelled as lumps because it takes into account the time changing behaviour of the building.

It is assumed that there are two modes of heat transfer to and through the wall i.e. one dimensional conduction and convection. The 1-D conduction heat transfer can be derived by using Fourier’s law given by equation 25.

$$q_{cond} = -kA\frac{dT}{dt} \qquad (25)$$

In above equation $\frac{dT}{dt}$ is the rate of change of temperature, k is the thermal conductivity and A is the area of the heat transfer section.

The heat transfer between solid and gas or liquid is known as convection and can be described by the equation 26.

$$q_{conv} = hA(T_1 - T_2) \qquad (26)$$

In figure 9 a typical wall divisions are shown, Ti is the inside temperature, T1 is the temperature of first layer, ………,T_N is of the N^{th} layer and T_o is the outside temperature.

The heat transferred from indoor air to the wall can be summarized in the following equation;

$$q_{conv} = q_{cond} + q_{stored} \qquad (27)$$

q_{stored} is the stored heat energy inside the wall layer or heat energy of lumped capacitance.

$$\frac{dT_i}{dt} = \frac{h_i(T_{in} - T_i) - \frac{k_i}{L_i}(T_i - T_{i+1})}{c_{p,i}\rho_i L_i} \qquad (28)$$

$$\text{in above equation } i = 1$$

For middle layers;

$$\frac{k_i}{L_i}(T_{i-1} - T_i) = \frac{k_{i+1}}{L_{i+1}}(T_i - T_{i+1}) + \frac{dT_i}{dt}\left(c_{p,i}\rho_i L_i + c_{p,i+1}\rho_{i+1}L_{i+1}\right) \qquad (29)$$

$$\text{where } i = 2, 3, \ldots\ldots, (N-1)$$

For outer layer the equation will be;

$$h_{out}(T_i - T_{out}) = \frac{k_i}{L_i}(T_{i-1} - T_i) + \frac{dT_i}{dt}\left(c_{p,i}\rho_i L_i\right) \qquad (30)$$

Each wall layer is modelled separately in Simulink.

5. SIMULATION RESULTS

The water consumption is considered as a measured disturbance, which can be predicted in advance by using model predictive control. The data is taken from (Defra, 2008) and is shown in the figure 10. The figure 11 shows the temperature of tank 1 (Buffer tank). The reference signal is a step signal and it is set as to use night time electricity and to store the heat energy during night. As can be seen that the model predictive controller gives better results. The MPC performance tracking of the reference signal is superior than the PI and on-off controllers. The model predictive controller takes less time to reach to the set point than other two control strategies, also there is less fluctuations in the MPC controlled temperature readings.

The second simulation was performed to find out whether the heat pump is using the night time electricity when the electricity cost is lower. Three days were simulated, two with low radiation rates and the third day with high radiation level. In figure 12 the red graph is the radiations in kW/m^2 and heat pump signal is shown by blue curve. It is evident that controller was shifting the load to the night. The first two days are cloudy days with low radiation level. In the first two days the controller has used the heat pump during the day to meet the hot water and heating demand of the building. In the third day the controller has predicted a very hot sunny day and the heat pump use during the day is almost zero and the heat pump was switched off during most of the third day. The heat pump was used during the night and also on the third day when the radiations level was high the controller did not switched ON the heat pump and the energy was supplied through the solar thermal collector. Another simulation was performed with one cold day and two hot days i.e. low solar radiations day and high solar radiations day respectively. This simulation was performed to find out the weather prediction ability of the model predictive controller. In the figure 13 the heat pump is using more electricity during the first day and very little on day two and three. It does uses more electrical energy during the night. The controller predicts the upcoming hot days and it can be seen that at the beginning of day 2 and 3 the use of heat pump is minimized by the controller. it can be concluded that the controller did predicted the weather changes and used very less electrical energy on two hot days as compared to the cold day.

6. CONCLUSIONS

A model of a heating and hot water system consisting of a heat pump and a solar panel has been developed. Initial simulations are performed using Loughborough weather data. It is concluded that model the system is working according to the expectations and a good match of the heat pump is also found. A detailed building model is also presented.

Model predictive control proved to have good performance than the other control strategies. From this paper it is also concluded that model predictive gave better reference tracking capability and also uses night time electricity efficiently. Model predictive control also shifted load to the night to save some energy and store heat energy during the night. However, the model predictive control needs some extra effort and getting the accurate model of the system is the crucial part of the controller. Once the model of the system is found, the controller tuning is much easier than the PI controller.

In future these three control strategies will be tested for different environmental conditions and energy consumption will be analysed. All these control strategies will be implemented to on the basis of thermal comfort of the indoor environment. The cost function used in this paper is a quadratic cost function and did not used the heat pump during the night time as it was expected. In future a linear weight for this formulation will be analysed. The linear programming (LP) gives totally different results than the quadratic programming problem (QP). The LP method always gives solutions at the intersection of the constraints whereas QP solutions can be on intersection of constraints, on a single constraint or off constraints. It is expected that for this problem LP method is more suitable to get better use of heat pump and to shift the building heating and hot water loads to the night. Model predictive control strategy also depends on the right selection of input and output weights i.e. how much to penalized the input or output of the system if it deviates from the limits or set point. The effect of different weights will be analysed in near future.

7. ACKNOWLEDGMENT

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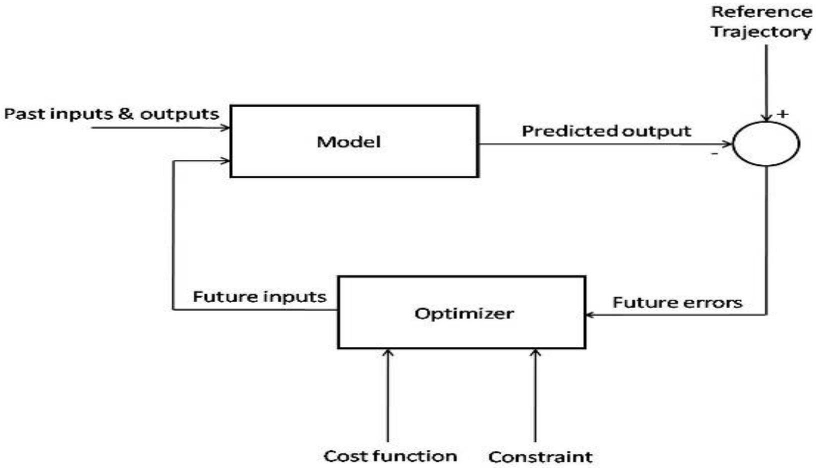

Fig 1. Basic Structure of MPC (Source Camacho et al., 1998)

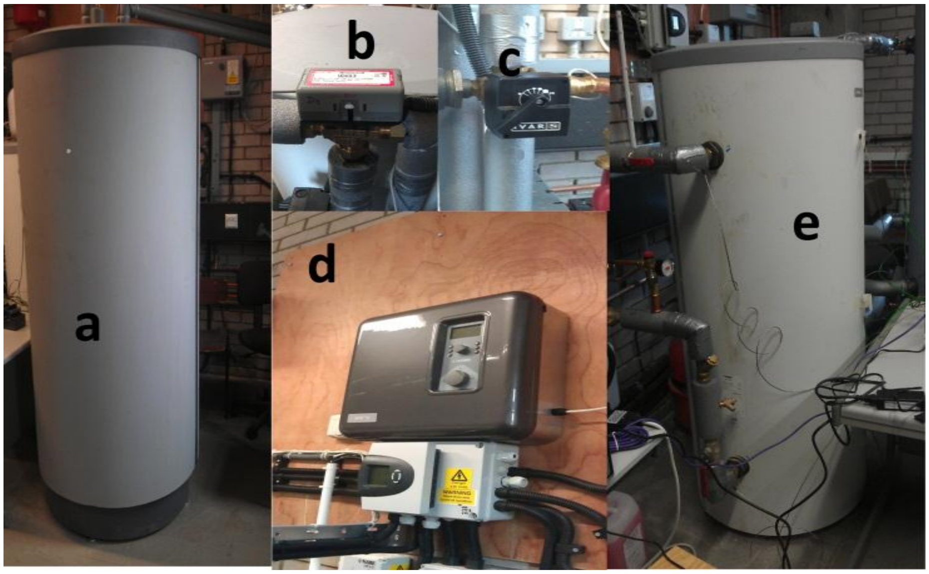

Fig 2. Heat pump combined solar system. (a) Heating Tank (b) Diverter (c) Valve (d) Controller and (e) Buffer tank

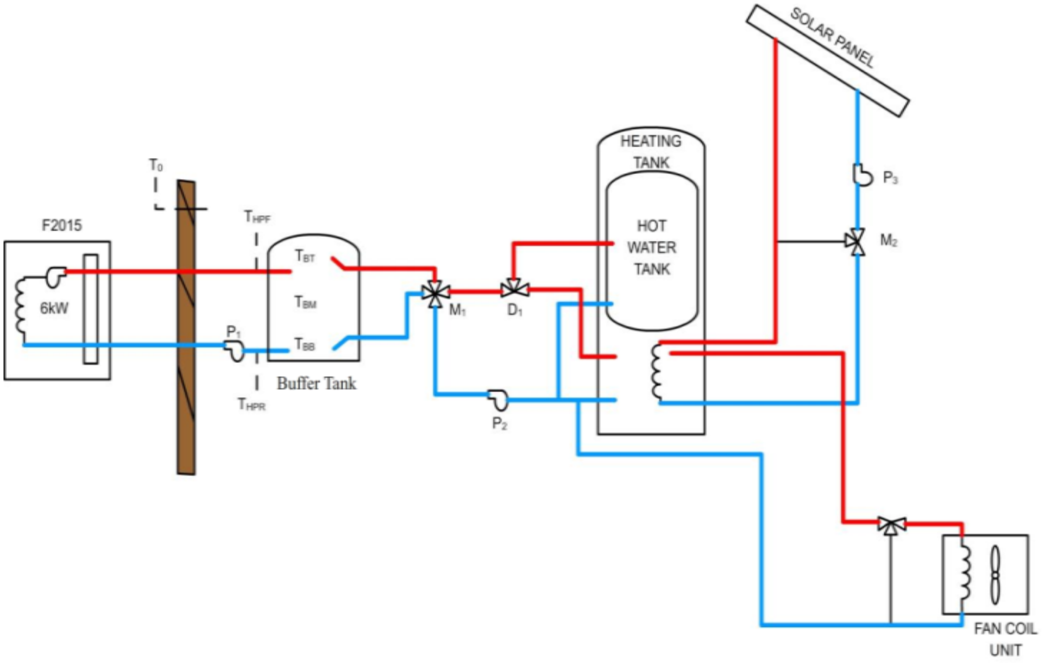

Fig 3. Plant Scheme

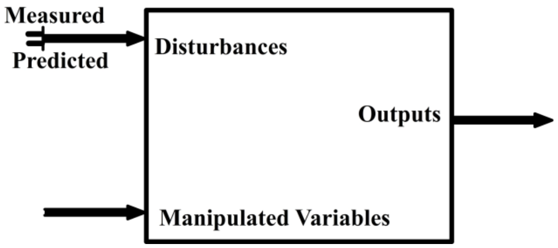

Fig 4: Inputs, Disturbances and Outputs

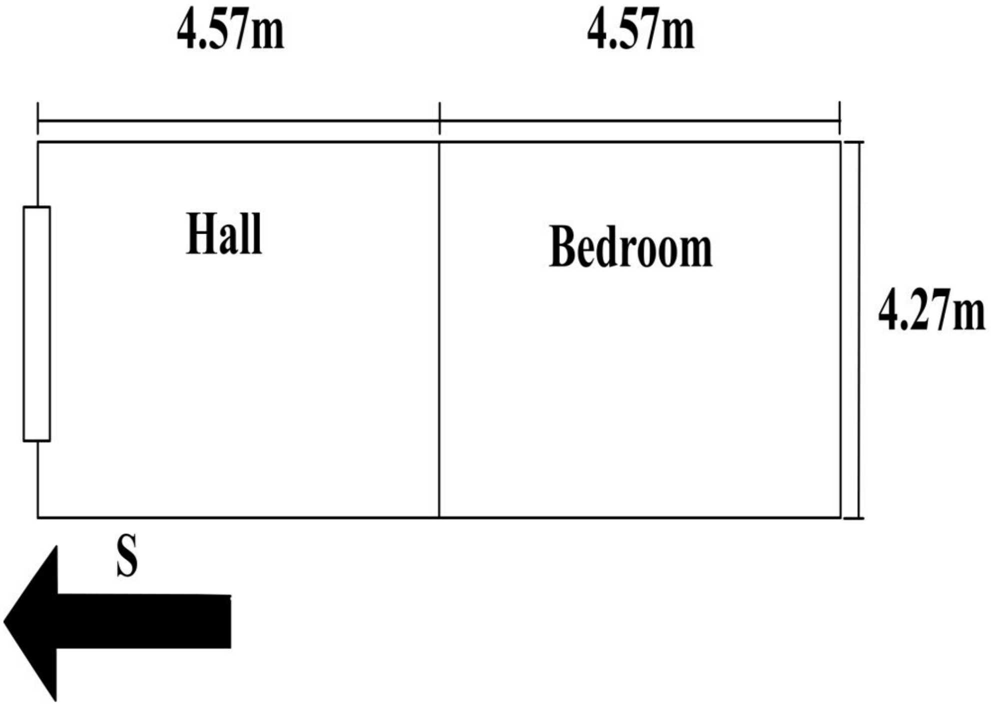

Fig 5. House plan

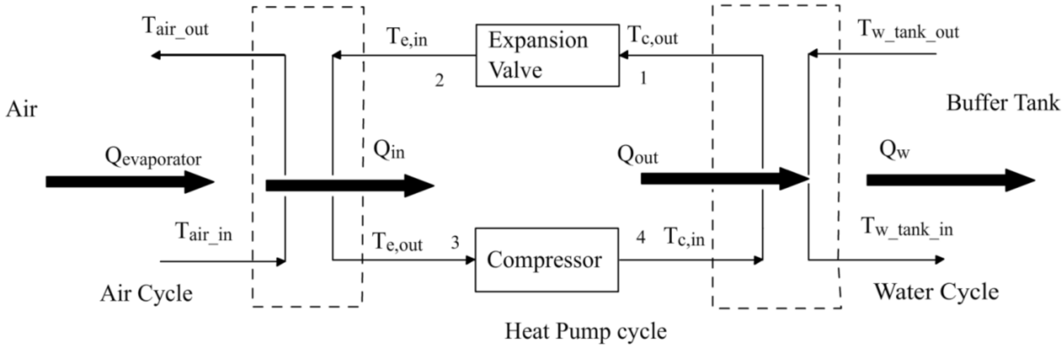

Fig 6. Schematic Diagram of heat Pump

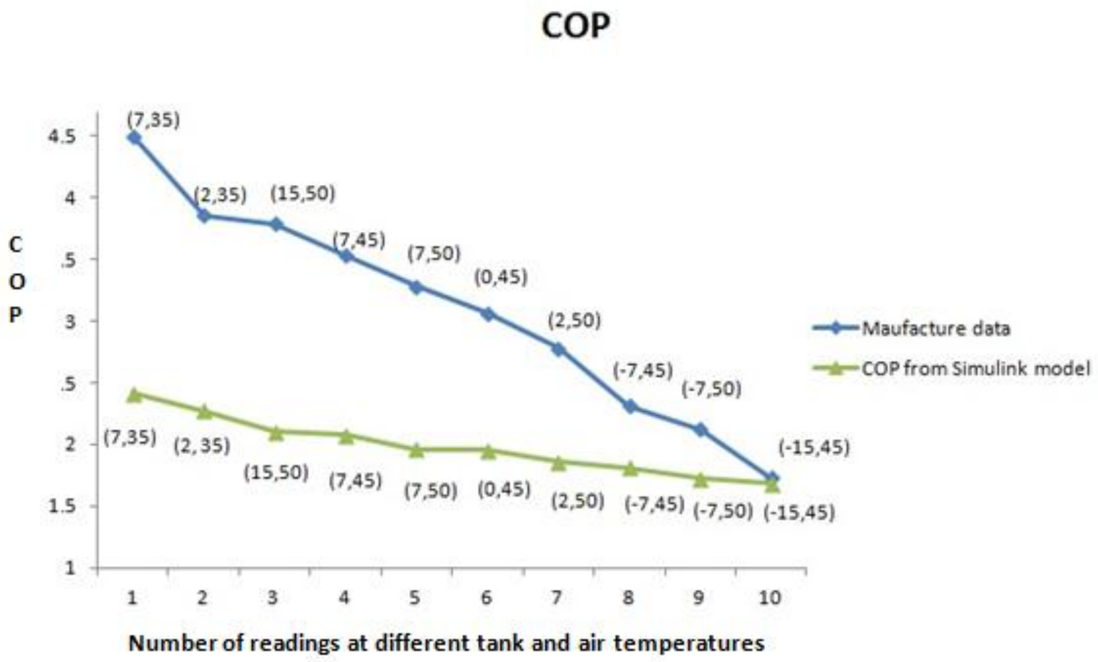

Fig 7. Heat Pump COP Model 1

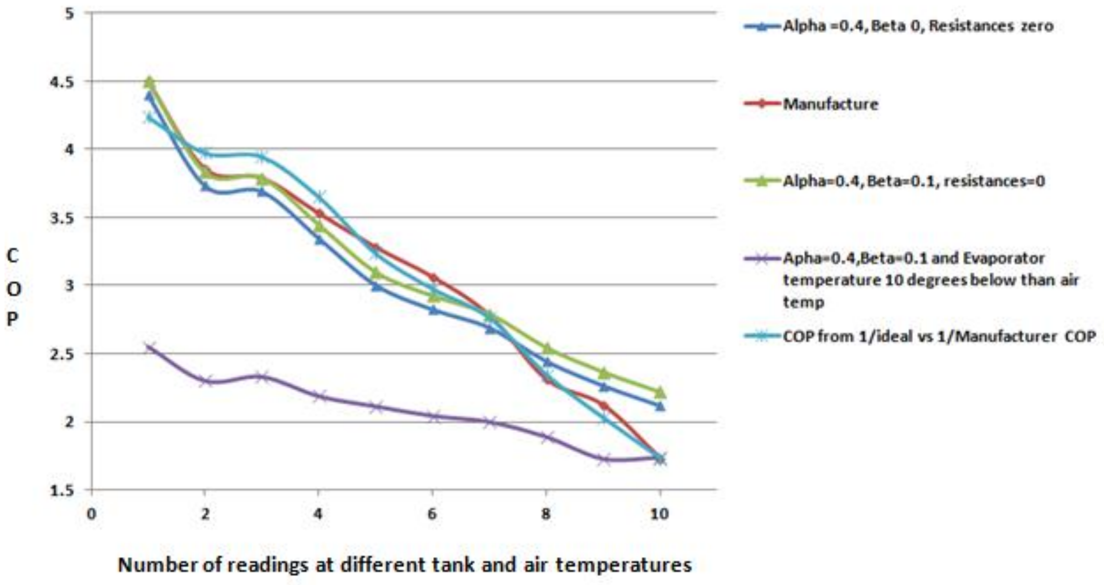

Fig 8. Heat Pump COP Model

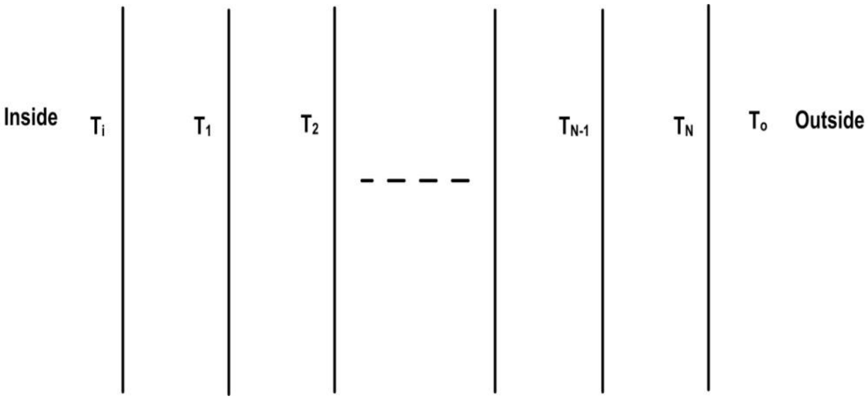

Fig 9. Wall divisions

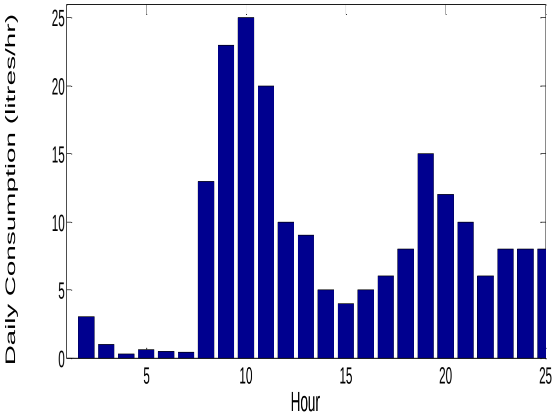

Fig 10. Water daily consumption

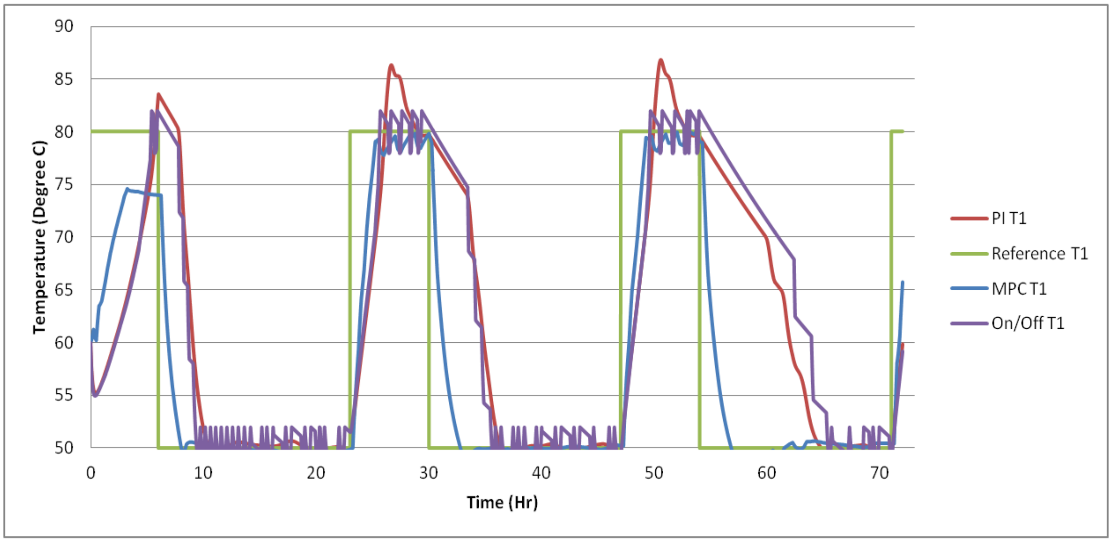

Fig 11. Step response of the controller for buffer tank

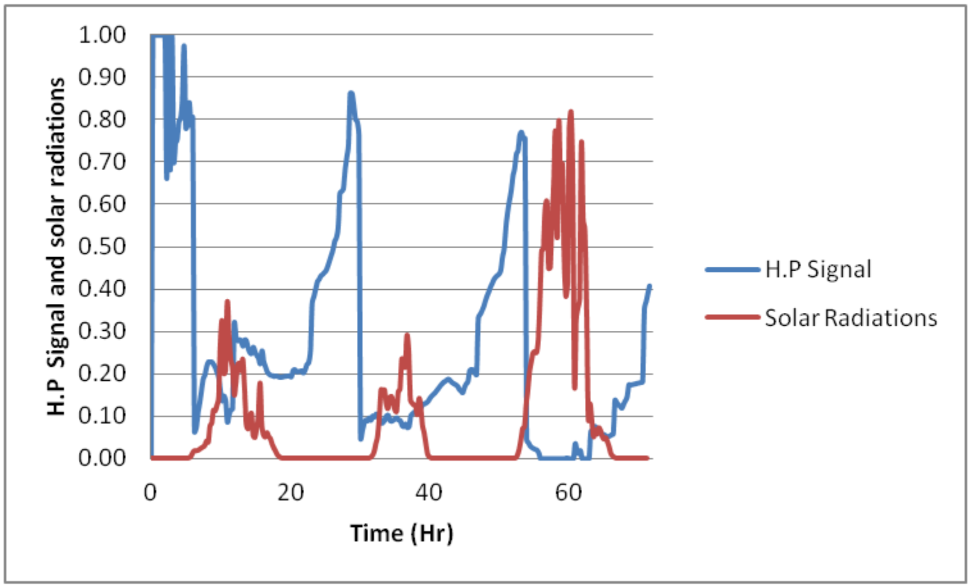

Fig 12. Use of night time electricity

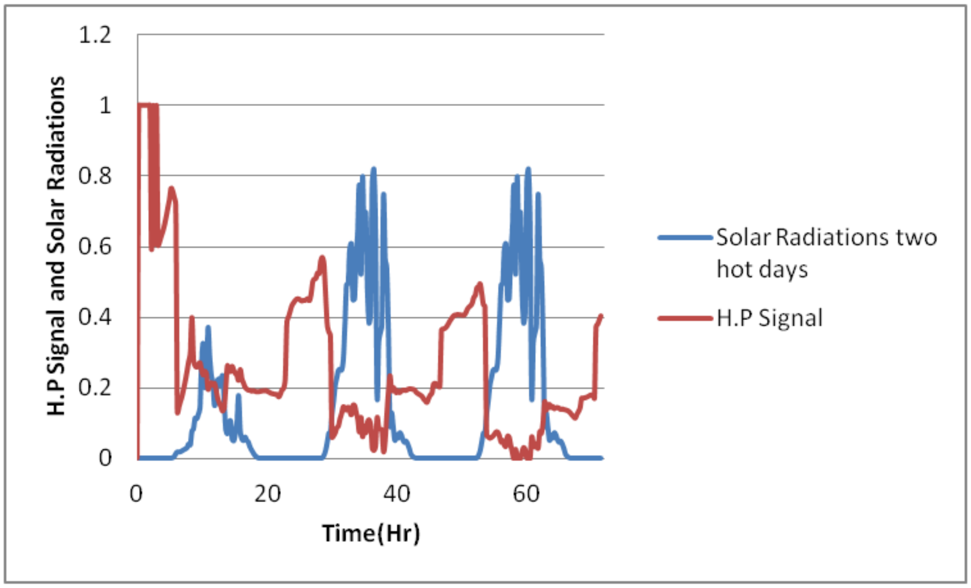

Fig 13. Weather prediction

Table 1. House model specifications

Wall/Roof		Thickness (m)	Thermal conductivity (W/m.K)	Density (kg/m^3)
	Brick	0.1	0.84	1700
	Polystyrene	0.0795	0.034	35
	Concrete	0.1	0.51	1400
	Plaster	0.013	0.025	900
Partition Wall				
	Gypsum	0.025	0.25	900
	Air	0.1	0.15 (Resistance) m^{2}K/W	1.204
	Gypsum	0.025	0.25	900