POLITECNICO DI MILANO

Electronics, Information and Bioengineering Department

Master Degree in Automation Engineering

ZONE TEMPERATURE CONTROL WITH UNDERFLOOR HEATING SYSTEMS FOR RESIDENTIAL BUILDINGS

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Pan Chen

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Abstract

This thesis presents the development of the model of a thermal zone, of a villa and of the underfloor heating radiant panels by using MATLAB environment to build up a simulink model based on parameters from a physical villa. Then we validate our created models by comparing the simulation results with the reference results from Edilclima, a software for the buildings energy consumption calculation. Different control strategies are adopted and tested to achieve both energy saving and to increase human comfort.

Key words: underfloor heating radiant panel, thermal zone model,thermal villa model, zone temperature control, Edilclima, energy saving, human comfort.

1 Introduction

1.1 Energy consumption for space heating situation in the EU and Italy

Nowadays, the residential and commercial sectors use almost 40% of energy consumed in the world [1]; and in European countries, 76% of this energy goes towards comfort control in buildings- heating, ventilation and air conditioning.

The residential sector is one of the four main end uses of energy apart from transportation, industry and the commercial sector. It accounts for about 20% of final energy consumption in the OECD (IEA, 2006). Residential energy consumption has attracted much attention, particularly in relation to efficient use of energy.

In 2003 Italy was responsible for 11.2% of total final energy consumption of the EU-27 and its per capita CO2 emissions were about eight tons. The final energy demand experienced an increase of 21.63% during the period 1990 to 2003 – much stronger than the EU average of 9.19% in the EU-27. This trend, according to some baseline scenario projections is expected to continue in the near future (EC, 2008). The final energy consumption by households has been increasing by 13.8% in the period 1990–2003, less than the EU-27 average of 15.15%. The residential sector accounted for almost 23% of total final energy consumption in Italy in 2003. It was the third largest sector in terms of TFC after transport (33.3%) and industry (38.5%) (Eurostat, 2010).

Space heating represents the single largest electricity end-use for consumers in the residential sector, comprising the electricity consumption of electric boilers, heat pumps, radiators and other electric heating appliances.[2]

The above data shows that by adopting a more efficient energy system for space heating in residential buildings, there will be significant benefit toward saving energy consumption and expenditures.

1.2 Underfloor heating definition and features

Underfloor heating and cooling is a form of central heating and cooling that achieves indoor climate control for thermal comfort using conduction, radiation and convection. The terms radiant heating and radiant cooling are commonly used to describe this approach because radiation is responsible for a significant portion of the resulting thermal comfort peorid. Hower, this usage is technically correct only when radiation composes more than 50% of the heat exchange between the floor and the rest of the space.

Underfloor heating can have a positive effect on the quality of indoor air by facilitating the choice of otherwise perceived cold flooring materials such as tile, slate, terrazzo and concrete. These masonry surfaces typically have very low VOC emissions (volatile organic compounds) in comparison to other flooring options. In conjunction with moisture control, floor heating also establishes temperature conditions that are less favourable in supporting mold, bacteria, viruses and dust mites. By removing the sensible heating load from the total HVAC (Heating, Ventilating, and Air Conditioning) load, ventilation, filtration and dehumidification of incoming air can be accomplished with dedicated outdoor air systems having less volumetric turnover to mitigate distribution of airborne contaminates. There is recognition from the medical community relating to the benefits of floor heating especially as it relates to allergens.

Underfloor radiant systems are evaluated for sustainability through the principles of efficiency, entropy, energy and efficacy. When combined with high performance buildings, underfloor systems operate with low temperatures in heating, high temperatures in cooling in the ranges found typically in geothermal and solar thermal systems. When coupled with these non combustible, renewable energy sources the sustainability benefits include reduction or elimination of combustion and green house gases produced by boilers and power generation for heat pumps and chillers, as well as reduced demands for non renewables and greater inventories for future generations. This has been supported through simulation evaluations and through research funded by the U.S. Department of Energy, Canada Mortgage and Housing Corporation, Fraunhofer Institute as well as ASHRAE.

Low temperature underfloor heating is embedded in the floor or placed under the floor covering. As such it occupies no wall space and creates no burn hazards, nor is it a hazard for physical injuries due to accidental contact leading to tripping and falling. This has been referenced as a positive feature in healthcare facilities including those serving elderly clients and those with dementia. Under similar environmental conditions, heated floors will speed evaporation of wetted floors (showering, cleaning, and spills). Additionally, underfloor heating with fluid filled pipes is useful in heating and cooling explosion proof environments where combustion and electrical equipment can be located remotely from the explosive environment.[4]

1.3 Aim of this paper

The aim of this paper is to create a 19-zone residential villa's thermal model with underfloor radiant panels to heat the building during the winter season (In our study, from 15th Oct. to 15th Apr.). Different control strategies will be tested to achieve both energy consumption reduction and thermal comfort for the users.

In the second chapter we will describe the development of the thermal model of a single zone, with its external and internal variables, and of the underfloor radiant panel model. Then we will build the villa thermal model with 19 zones based on the single zone model.

In the third chapter we will describe the characteristics of the system. The thermal characteristics and physical properties of the building and its external and internal variables, such as outside temperature, solar radiation, ground temperature, air handling unit and internal gains.

In the fourth chapter we will describe the reliability of the thermal model we developed, by comparing the energy consumption from the simulation results and the reference data from Edilclima.

In the fifth chapter we will describe the performance of different control strategies applied to the system.

In the sixth chapter we will describe the evaluation of the results from the previous chapters and come to a conclusion.

2 Thermal model development of single zone, radiant panel and a villa

2.1 A single zone thermal model

The scheme of single zone thermal model in our study shown below. The orientation of the zone is facing South. The zone are composed by the opaque surfaces (walls and ceiling) in dark grey colour, the transparent surface (windows) in blue colour and the pavement in light grey colour. The dimension of our zone is w (width)× h (height) ×l (length). There are several heat exchange types between opaque areas and outside substance (outdoor air or the ground). Similarily, there are several heat exchange types between pavement and outside substance (the ground or another zone's air).

The external and internal inputs of our zone model include outdoor temperature, solar radiation and internal gains.

The thermal energy balance for our zone model were based on:

- The heat exchange between the zone air and outdoor air through the walls;
- The heat exchange between the zone air and the ground through the walls;
- The heat exchange between the zone air and the pavement;
- The heat exchange between the pavement and the ground;
- The radiation energy received by both pavement and zone air through transparent surface;
- The radiation energy received by opaque surface increase the temperature of walls resulting in zone temperature variation;
- The heat exchange between fresh air from Air Handling Unit and zone space;

- The heat brought by internal gains;
- The heat brought by terminals, in our case, the underfloor radiant panels.

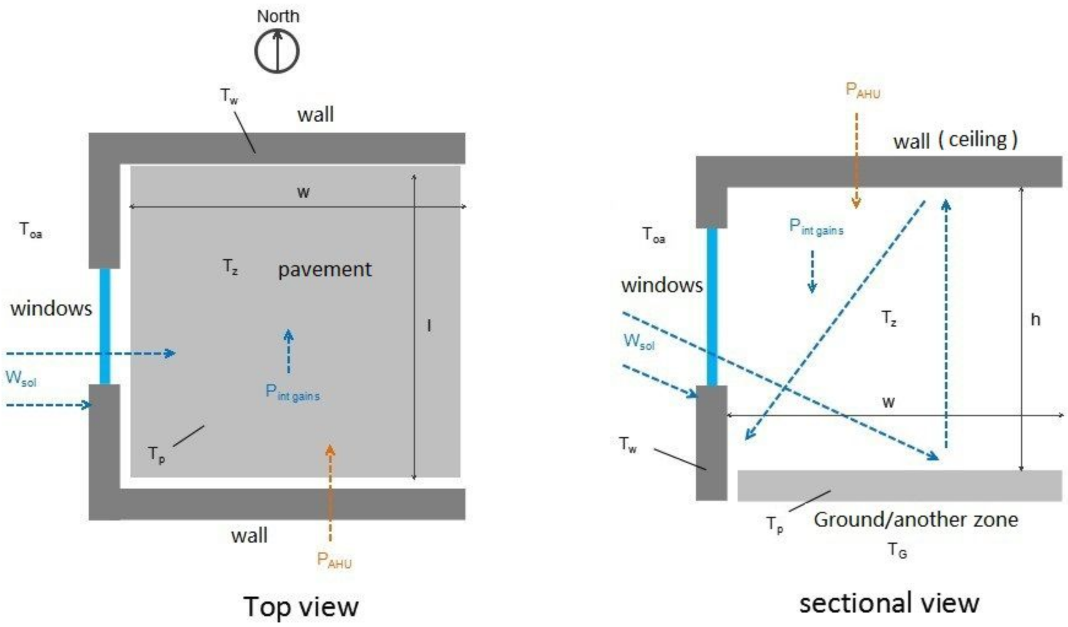

Figure 2.1 Scheme of the single zone model.

State variables:

- Zone temperature: T_Z [°C];
- Walls (includes ceiling) temperature: Tw [°C];
- Pavement (includes furniture) temperature: Tp [°C].

External and internal inputs:

- Temperature of outside air: Toa [°C];
- Solar radiation (divided by facade, opaque and transparent surfaces): Wsol,i [W/m^2], i= N, S, W, E;
- Internal gains: Pintgains [W/m^2];
- Temperature of the ground: TG [°C];
- Supply air mass flow (AHU): msa [kg/s];

- Supply air temperature (AHU): Tsa [°C] (In our case, Tsa= Toa);
- Ground temperature: TG [°C].

Manipulated variables:

- Heat flux from terminals: P_{TERM} [W].

Energy balance equations:

$$C_{wc}\dot{T}_W = U_{wceO}(T_{oa}-T_W)+U_{wci}(T_Z-T_W)+\underbrace{\frac{\alpha_w R_{e\_wall}}{R_{e\_wall}+R_{wall}}}_{kwall}\cdot\sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{op,i}+\frac{1}{2}Ksol,tr\cdot\sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{tr,i}+U_{weG}(T_G-T_W)$$

$$C_Z\dot{T}_Z = U_{wci}(T_W-T_Z)+U_{win}(T_{oa}-T_Z)+U_{pavi}(T_P-T_Z)+\underbrace{\overbrace{\dot{m}_{sa}c_{pa}}^{U_{sa}}(T_{oa}-T_Z)}_{P_{AHU}}+P_{\text{int}\,gains}$$

$$C_p\dot{T}_P = U_{pavi}(T_Z-T_P)+\frac{1}{2}\underbrace{(1-FF)\cdot ggl\cdot F_{sm}}_{K_{sol,tr}}\cdot\sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{tr,i}+U_{pavG}(T_G-T_P)+P_{TERM}$$

Model parameters:

- Walls (include ceiling) thermal capacity: C_{wc} [J/K];
- Zone air mass thermal capacity: C_Z [J/K];
- Pavement thermal capacity: C_P [J/K];
- External wall convective resistance: R_{e_wall} [K/W];
- Wall convective resistance: R_{wall} [K/W];
- External convective conductance of walls (ceiling) with open air: U_{wceO} [W/K];
- Internal convective conductance of walls (ceiling): U_{wci} [W/K];
- External convective conductance of walls (ceiling) with ground: U_{weG}[W/K];
- Convective conductance of transparent surface: U_{win} [W/K];

- Air- pavement convective transmittance: U_{pavi} [W/K];
- Pavement- ground convective transmittance: U_{pavG} [W/K];
- Convection conductance of supply air: U_{sa} [W/K];
- Coefficient of solar radiation affect on opaque area: Kwall [#];
- Coefficient of solar radiation affect on transparent area: $K_{sol,tr}$ [#];
- Opaque area of façade i: $S_{op,i}$ [m^2], i= N, S, W, E;
- Transparent area of façade i: $S_{tr,i}$ [m^2], i= N, S, W, E;
- Windows solar protection shading factor: F_{sm} [#];
- Windows solar factor: ggl [#];
- Windows frame factor: FF [#];
- Walls solar radiation absorbance coefficient: α_w [#];
- Air specific heat: cpa [J/KgK].

State-space continuous form derived from energy balance equations:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases}$$

Where:

$$\begin{bmatrix} \dot{T}_W \\ \dot{T}_Z \\ \dot{T}_P \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{1}{C_{WC}}(U_{wce}+U_{wci}+U_{weG}) & \frac{1}{C_{WC}}U_{wci} & 0 \\ \frac{1}{C_Z}U_{wci} & -\frac{1}{C_Z}(U_{wci}+U_{win}+U_{pavi}+U_{sa}) & \frac{1}{C_Z}U_{pavi} \\ 0 & \frac{1}{C_P}U_{pavi} & -\frac{1}{C_P}(U_{pavi}+U_{pavG}) \end{bmatrix}}_{A} \bullet \begin{bmatrix} T_W \\ T_Z \\ T_P \end{bmatrix} +$$

$$+\underbrace{\begin{bmatrix} b11 & b12 & b13 & b14 & b15 & b16 & b17 & b18 & b19 \\ b21 & b22 & b23 & b24 & b25 & b26 & b27 & b28 & b29 \\ b31 & b23 & b33 & b34 & b35 & b36 & b37 & b38 & b39 \end{bmatrix}}_{B} \bullet \begin{bmatrix} T_{oa} \\ W_{sol,N} \\ W_{sol,S} \\ W_{sol,W} \\ W_{sol,E} \\ W_{sol,ceil} \\ T_G \\ P_{int\,gains} \\ P_{TERM} \end{bmatrix}$$

The terms of matrix B list as:

$$b11 = \frac{1}{C_{WC}} \mathrm{U}_{wceO}$$

$$b12 = \frac{1}{C_{WC}} (k_{wall} S_{op,N} + \frac{1}{2} K_{sol,tr} S_{tr,N})$$

$$b13 = \frac{1}{C_{WC}} (k_{wall} S_{op,\mathrm{S}} + \frac{1}{2} K_{sol,tr} S_{tr,\mathrm{S}})$$

$$b14 = \frac{1}{C_{WC}} (k_{wall} S_{op,\mathrm{W}} + \frac{1}{2} K_{sol,tr} S_{tr,W})$$

$$b15 = \frac{1}{C_{WC}} (k_{wall} S_{op,\mathrm{E}} + \frac{1}{2} K_{sol,tr} S_{tr,\mathrm{E}})$$

$$b16 = \frac{1}{C_{WC}} k_{wall} S_{op,\mathrm{ceil}}$$

$$b17 = \frac{1}{C_{WC}} U_{weG}$$

$$b18 = 0$$

$$b19 = 0$$

$$b31 = 0$$

$$b32 = \frac{1}{2C_P} K_{sol,tr} S_{tr,N}$$

$$b33 = \frac{1}{2C_P} K_{sol,tr} S_{tr,\mathrm{S}}$$

$$b34 = \frac{1}{2C_P} K_{sol,tr} S_{tr,\mathrm{W}}$$

$$b35 = \frac{1}{2C_P} K_{sol,tr} S_{tr,\mathrm{E}}$$

$$b36 = \frac{1}{2C_P} K_{sol,tr} S_{tr,\mathrm{ceil}}$$

$$b37 = \frac{1}{C_P} U_{pavG}$$

$$b38 = 0$$

$$b39 = \frac{1}{C_P}$$

$$b21 = \frac{1}{C_Z} (\mathrm{U}_{win} + \mathrm{U}_{sa})$$

$$b22 = 0$$

$$b23 = 0$$

$$b24 = 0$$

$$b25 = 0$$

$$b26 = 0$$

$$b27 = 0$$

$$b28 = \frac{1}{C_Z} S_{pavi}$$

$$b29 = 0$$

2.2 Radiant panel thermal model

The underfloor radiant panel, which is a loop of pipes installed under the floor that allow hot water to recirculate between the floor and the boiler. Different loop layouts will affect the performance of thermal diffusion and surface temperature quality. There has a strong relationship between the performance of radiant panels with characteristics of flooring resistances, conductivities of surrounding mass, tube spacings, depths, fluid temperatures and so on.

According to EU standard EN1264[5], the underfloor radiat panel can be modelled as follow:

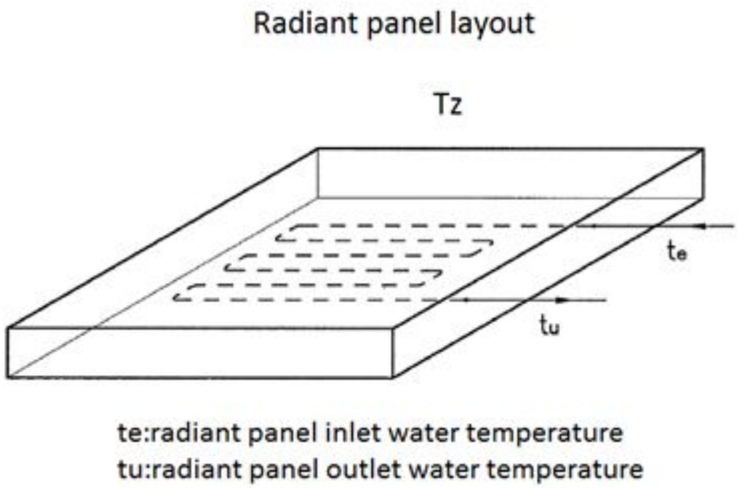

Figure 2.2 Scheme of underfloor radiant panel

The formula of upward heat flow from the radiant panel is presented:

$$Q = S \cdot \Delta t \cdot B \cdot F_P \cdot F_I \cdot F_M \cdot F_D = \alpha \cdot \Delta t;$$
$$\alpha = S \cdot B \cdot F_P \cdot F_I \cdot F_M \cdot F_D;$$
$$\Delta t = \frac{(te - tu)}{In\frac{(te - tu)}{tu - T_Z}}; \qquad (1)$$

- Upwards heat flow from the panel: Q [W];
- Surface of the panel: S [m^2];
- Inlet temperature of the panel: te [°C];
- Outlet temperature of the panel: tu [°C];
- Temperature of the heated zone: T_Z [°C];
- Pipeline factor: B [W/m^2K];
- Floor thermal resistance factor: FP [#];
- Axles spacing factor: FI [#];
- Screed factor: FM [#];
- External diameter of the pipeline factor: FD [#].

The formula of total heat flow from radiant panel presented as:

$$Q_t = (te - tu) \cdot G \cdot 1.16 \qquad (2)$$

- Total heat flow: Qt [W];
- Water mass flow in the panel: G [l/h].

The formula of water mass flow of the panel presented as:

$$G = \frac{Q}{(te - tu) \cdot 1.16}\left[1 + \frac{\frac{1}{a} + R_P + \frac{s_m}{\lambda_m}}{R_s} + \frac{S \cdot (T_Z - ts)}{Q \cdot R_s}\right] \qquad (3)$$

- $a = 10.8$ [W/m^2K];
- Floor thermal resistance: R_P [m^2K/W];
- Screed width: s_m [m];
- Screed thermal conductivity: λ_m [W/m^2K];
- Thermal resistance of the floor under the panel: R_S [m^2K/W];

- Temperature of the zone under the floor: ts [°C].

Given the inlet temperature of the water in the panel te and the water mass flow G, using (1), (2) and (3) we can calculate the outlet temperature tu. Starting from (3):

$$G=\frac{Q}{(te-tu)\cdot 1.16}[1+\frac{\frac{1}{a}+R_P+\frac{s_m}{\lambda_m}}{R_s}+\frac{S\cdot(T_Z-ts)}{Q\cdot R_s}]$$

$$G=\frac{Q}{(te-tu)\cdot 1.16}[1+\frac{\frac{1}{a}+R_P+\frac{s_m}{\lambda_m}}{R_s}]$$

$$let,\beta=\frac{1}{1.16}[1+\frac{\frac{1}{a}+R_P+\frac{s_m}{\lambda_m}}{R_s}]$$

$$G=\frac{Q}{(te-tu)}\beta$$

The term $\frac{S\cdot(T_Z-ts)}{Q\cdot R_S}$ been cancelled because we assume T_Z equals to t_s.

By substituting (1) in (3):

$$G=\frac{\alpha\cdot\Delta t}{(te-tu)}\beta$$

$$G=\frac{\alpha\cdot\frac{te-tu}{In\frac{(te-tu)}{(tu-T_Z)}}}{(te-tu)}\beta$$

$$G=\frac{\alpha\cdot\beta}{In\frac{(te-tu)}{(tu-T_Z)}}$$

$$In\frac{(te-tu)}{(tu-T_Z)}=\frac{\alpha\cdot\beta}{G}$$

$$\frac{(te-tu)}{(tu-T_Z)}=e^{\frac{\alpha\cdot\beta}{G}}$$

$$let,k=e^{\frac{\alpha\cdot\beta}{G}}$$

$$tu=\frac{te+k\cdot T_Z}{k+1}$$

Therefore, the upwards heat from the panel can be calculated from (1):

$$Q = \alpha \cdot \frac{(te - tu)}{In\dfrac{(te - tu)}{tu - T_Z}}$$

$$Q = \alpha \cdot \frac{(te - tu)}{Ink}$$

$$Q = \frac{G}{\beta} \cdot \frac{k}{k+1} \cdot (te - T_Z)$$

$$Q = \frac{G}{\beta} \cdot \frac{e^{\frac{\alpha \cdot \beta}{G}}}{e^{\frac{\alpha \cdot \beta}{G}} + 1} \cdot (te - T_Z)$$

The heat flow of radiant panel thermal model could be presented as follow,

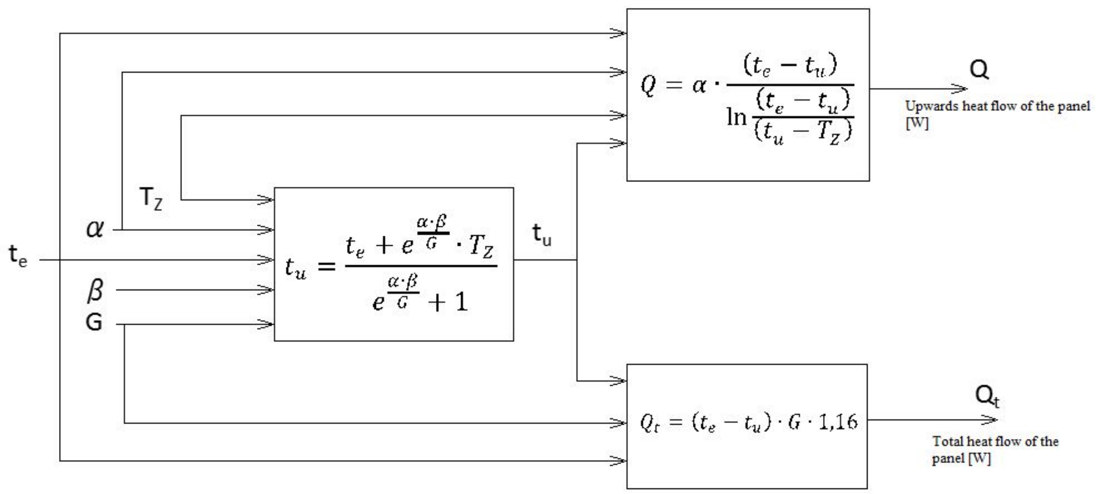

Figure 2.3 Energy flow path of underfloor radiant panel

Thermal model of the floor:

$$C_p \dot{T}_P = \underbrace{U_{pavi}(T_Z - T_P)}_{Q_P} + \underbrace{\frac{1}{2}(1 - FF) \cdot ggl \cdot F_{sm} \cdot \sum_{i = N,S,W,E,Ceil} W_{sol,i} S_{tr,i}}_{Q_{SOL}} + \underbrace{U_{pavG}(T_G - T_P)}_{Q_G} + \underbrace{P_{TERM}}_{Q}$$

where:

$$P_{TERM} = Q = \frac{G}{\beta} \cdot \frac{e^{\frac{\alpha \cdot \beta}{G}}}{e^{\frac{\alpha \cdot \beta}{G}} + 1} \cdot (te - T_Z)$$

The energy balance of the floor that heated by radiant panel, drawn as,

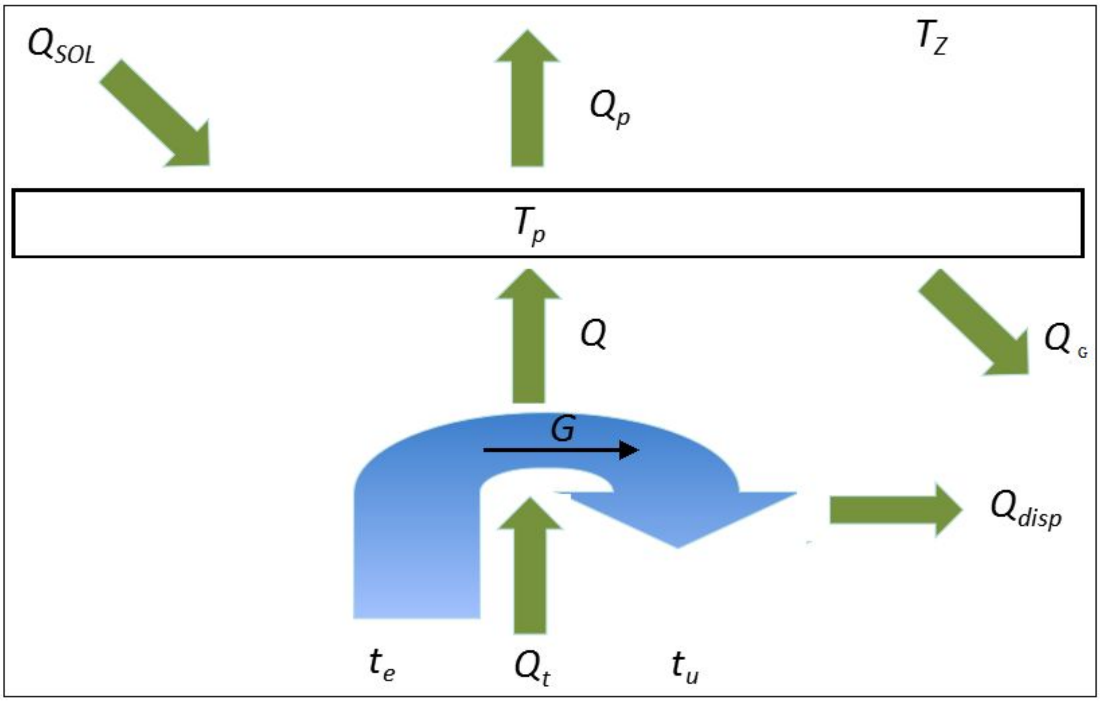

Figure 2.4 Energy balance of thermal model of the floor

2.3 Thermal model of a single zone with radiant panels heating

The thermal model of a single zone with radiation panels heating could achieved by substuiting P_{TERM} of the single zone model with the equation from radiant panel model,

$$P_{TERM} = Q = \frac{G}{\beta} \frac{e^{\frac{\alpha \cdot \beta}{G}}}{1 + e^{\frac{\alpha \cdot \beta}{G}}} \cdot (t_e - T_Z),$$

which we have new model of floor:

$$C_p \dot{T}_P = \underbrace{U_{pavi}(T_Z - T_P)}_{Q_P} + \underbrace{\frac{1}{2}(1 - FF) \cdot ggl \cdot F_{sm} \cdot \sum_{i = N,S,W,E,Ceil} W_{sol,i} S_{tr,i}}_{Q_{SOL}} + \underbrace{U_{pavG}(T_G - T_P)}_{Q_G} + \underbrace{P_{TERM}}_{Q}$$

From the equation above, we could notice a direct effect of T_Z on P_{TERM} which means if the given te stay constant, P_{TERM} will depend on the value of T_Z. In that case, when comes a disturbance on temperature T_Z, the energy P_{TERM} from underfloor radiant panel will be change in real time which will brings a error to our model. In order to remove this effect, a new state variable T_Z' will be introduced into our model. Where T_Z' is a delayed T_Z with time constant τ (In our study, τ= 300 [s]).

Written as:

$$\dot{T}_Z' = \frac{1}{\tau}T_Z - \frac{1}{\tau}T_Z'$$

As the new model of floor revised with T_Z:

$$C_p\dot{T}_P = U_{pavi}(T_Z - T_P) + \underbrace{\frac{1}{2}(1-FF)\cdot ggl\cdot F_{sm}}_{K_{sol,tr}}\cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{tr,i} + U_{pavG}(T_G - T_P) + \underbrace{\frac{G}{\beta}\frac{e^{\frac{\alpha\cdot\beta}{G}}}{e^{\frac{\alpha\cdot\beta}{G}}+1}}_{hcoeff}(te - T_Z')$$

Then the model of the single zone with radiant panels heating can be written as:

$$C_{wc}\dot{T}_W = U_{wceO}(T_{oa} - T_W) + U_{wci}(T_Z - T_W) + \underbrace{\frac{\alpha_w R_{e\_wall}}{R_{e\_wall} + R_{wall}}}_{kwall}\cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{op,i} + \frac{1}{2}Ksol,tr\cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{tr,i} + U_{weG}(T_G - T_W)$$

$$C_Z\dot{T}_Z = U_{wci}(T_W - T_Z) + U_{win}(T_{oa} - T_Z) + U_{pavi}(T_P - T_Z) + \underbrace{\dot{m}_{sa}c_{pa}(T_{oa} - T_Z)}_{P_{AHU}} + P_{\text{int}\,gains}$$

$$C_p\dot{T}_P = U_{pavi}(T_Z - T_P) + \underbrace{\frac{1}{2}(1-FF)\cdot ggl\cdot F_{sm}}_{K_{sol,tr}}\cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{tr,i} + U_{pavG}(T_G - T_P) + \underbrace{\frac{G}{\beta}\frac{e^{\frac{\alpha\cdot\beta}{G}}}{e^{\frac{\alpha\cdot\beta}{G}}+1}}_{hcoeff}(te - T_Z')$$

$$\dot{T}_Z' = \frac{1}{\tau}T_Z - \frac{1}{\tau}T_Z'$$

In state-space form:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases}$$

Where,

$$A=\begin{bmatrix} -\frac{1}{C_{WC}}(\mathrm{U}_{wce}+\mathrm{U}_{wci}+\mathrm{U}_{weG}) & \frac{1}{C_{WC}}\mathrm{U}_{wci} & 0 & 0 \\ \frac{1}{C_Z}\mathrm{U}_{wci} & -\frac{1}{C_Z}(\mathrm{U}_{wci}+\mathrm{U}_{win}+U_{pavi}+\mathrm{U}_{sa}) & \frac{1}{C_Z}U_{pavi} & 0 \\ 0 & \frac{1}{C_P}U_{pavi} & -\frac{1}{C_P}(U_{pavi}+U_{pavG}) & -\frac{1}{C_P}hcoeff \\ 0 & \frac{1}{\tau} & 0 & -\frac{1}{\tau} \end{bmatrix}_{4\times 4}$$

$$B=\begin{bmatrix} b11 & b12 & b13 & b14 & b15 & b16 & b17 & b18 & b19 \\ b21 & b22 & b23 & b24 & b25 & b26 & b27 & b28 & b29 \\ b31 & b32 & b33 & b34 & b35 & b36 & b37 & b38 & b39 \\ b41 & b42 & b43 & b44 & b45 & b46 & b47 & b48 & b49 \end{bmatrix}_{4\times 9}$$

The terms of matrix B list as:

$$b11=\frac{1}{C_{WC}}\mathrm{U}_{wceO}$$

$$b12=\frac{1}{C_{WC}}(k_{wall}S_{op,N}+\frac{1}{2}K_{sol,tr}S_{tr,N})$$

$$b13=\frac{1}{C_{WC}}(k_{wall}S_{op,\mathrm{S}}+\frac{1}{2}K_{sol,tr}S_{tr,\mathrm{S}})$$

$$b14=\frac{1}{C_{WC}}(k_{wall}S_{op,\mathrm{W}}+\frac{1}{2}K_{sol,tr}S_{tr,W})$$

$$b15=\frac{1}{C_{WC}}(k_{wall}S_{op,\mathrm{E}}+\frac{1}{2}K_{sol,tr}S_{tr,\mathrm{E}})$$

$$b16=\frac{1}{C_{WC}}k_{wall}S_{op,\mathrm{ceil}}$$

$$b17=\frac{1}{C_{WC}}U_{weG}$$

$$b18=0$$

$$b19=0$$

$$b21=\frac{1}{C_Z}(\mathrm{U}_{win}+\mathrm{U}_{sa})$$

$$b22=0$$

$$b23=0$$

$$b24=0$$

$$b25=0$$

$$b26=0$$

$$b27=0$$

$$b28=\frac{1}{C_Z}S_{pavi}$$

$$b29=0$$

$$d31=0$$

$$d32=\frac{1}{2C_P}K_{sol,tr}S_{tr,N}$$

$$d33=\frac{1}{2C_P}K_{sol,tr}S_{tr,\mathrm{S}}$$

$$d34=\frac{1}{2C_P}K_{sol,tr}S_{tr,\mathrm{W}}$$

$$d35=\frac{1}{2C_P}K_{sol,tr}S_{tr,\mathrm{E}}$$

$$d36=\frac{1}{2C_P}K_{sol,tr}S_{tr,\mathrm{ceil}}$$

$$d37=\frac{1}{C_P}U_{pavG}$$

$$d38=0$$

$$d39=\frac{1}{C_P}hcoeff$$

$$d41=0$$

$$d42=0$$

$$d43=0$$

$$d44=0$$

$$d45=0$$

$$d46=0$$

$$d47=0$$

$$d48=0$$

$$d49=0$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4\times 4}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{4\times 9}$$

2.4 Thermal model of the villa

When we build our thermal model of villa, the room quantity and the behaviour of each room are based on the physical villa which will be introduced at chapter 3. The thermal model of the villa consists of 18 heated zones and 1 unheated zone. When we consider two heated zone next to each other, we assume the zone temperatures are the same, so that there will not be heat exchange through the wall or the pavement between them. But when considering a heated zone next to an unheated zone, there exist a continuous heat exchange through the wall or the pavement between the zones. In this case, we need to add the thermal coupling terms in the state space matrix A of the villa model.

2.4.1 Heat exchange between a heated zone and a unheated zone

Wall-wall heat exchange

There is a wall in between a heated zone 1 and an unheated zone 2. There exists a heat transfer from zone 1 to zone 2 through the wall by convection. When we consider the heat exchange between two zones, we model the conductive transmittance of Uwall= Uz1z2 [W/m^{2}K].

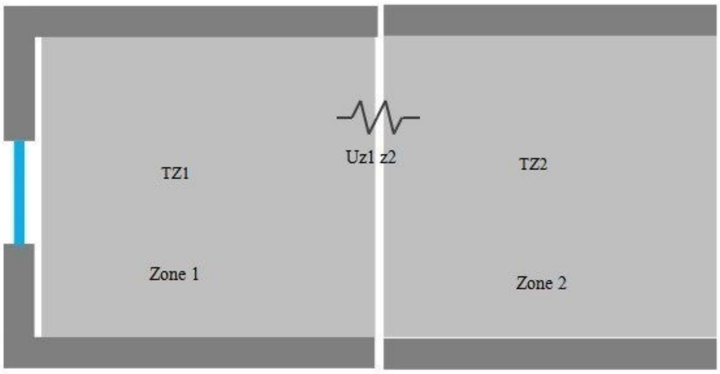

Figure 2.5 Scheme of wall-wall heat exchange

The resulting A matrix of the state-space form is a block diagonal matrix.

Some terms in and out of the diagonal are added for modeling the thermal interactions.

Here are the revised air energy balance equation for each zone:

$$C_{Z1}\dot{T}_{Z1} = U_{wci}\big|_{Z1}(T_{W1}-T_{Z1}) + U_{win}\big|_{Z1}(T_{oa}-T_{Z1}) + U_{pavi}\big|_{Z1}(T_{P1}-T_{Z1}) + \underbrace{\dot{m}_{sa1}c_{pa}(T_{oa}-T_{Z1})}_{P_{AHU|Z1}}$$
$$+P_{\text{int}\,gains}\big|_{Z1} + U_{Z1Z2}(T_{Z2}-T_{Z1})$$

$$C_{Z2}\dot{T}_{Z2} = U_{wci}\big|_{Z2}(T_{W2}-T_{Z2}) + U_{win}\big|_{Z2}(T_{oa}-T_{Z2}) + U_{pavi}\big|_{Z2}(T_{P2}-T_{Z2}) + \underbrace{\dot{m}_{sa2}c_{pa}(T_{oa}-T_{Z2})}_{P_{AHU|Z2}}$$
$$+P_{\text{int}\,gains}\big|_{Z2} + U_{Z1Z2}(T_{Z1}-T_{Z2})$$

We rewrite the A matrix of these two zones,

$$A=\begin{bmatrix}
a_{11}\big|_{Z1} & a_{12}\big|_{Z1} & a_{13}\big|_{Z1} & a_{14}\big|_{Z1} & 0 & 0 & 0 & 0 \\
a_{21}\big|_{Z1} & a_{22}\big|_{Z1}-\frac{1}{C_{Z1}}U_{Z1Z2} & a_{23}\big|_{Z1} & a_{24}\big|_{Z1} & 0 & \frac{1}{C_{Z1}}U_{Z1Z2} & 0 & 0 \\
a_{31}\big|_{Z1} & a_{32}\big|_{Z1} & a_{33}\big|_{Z1} & a_{34}\big|_{Z1} & 0 & 0 & 0 & 0 \\
a_{41}\big|_{Z1} & a_{42}\big|_{Z1} & a_{43}\big|_{Z1} & a_{44}\big|_{Z1} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & a_{11}\big|_{Z2} & a_{12}\big|_{Z2} & a_{13}\big|_{Z2} & a_{14}\big|_{Z2} \\
0 & \frac{1}{C_{Z2}}U_{Z1Z2} & 0 & 0 & a_{21}\big|_{Z2} & a_{22}\big|_{Z2}-\frac{1}{C_{Z2}}U_{Z1Z2} & a_{23}\big|_{Z2} & a_{24}\big|_{Z2} \\
0 & 0 & 0 & 0 & a_{31}\big|_{Z2} & a_{32}\big|_{Z2} & a_{33}\big|_{Z2} & a_{34}\big|_{Z2} \\
0 & 0 & 0 & 0 & a_{41}\big|_{Z2} & a_{42}\big|_{Z2} & a_{43}\big|_{Z2} & a_{44}\big|_{Z2}
\end{bmatrix}_{8\times 8}$$

We name the added terms of matrix A with $A_{coupling1}$

$$A_{coupling1} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{C_{Z1}}U_{Z1Z2} & 0 & 0 & 0 & \frac{1}{C_{Z1}}U_{Z1Z2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_{Z2}}U_{Z1Z2} & 0 & 0 & 0 & -\frac{1}{C_{Z2}}U_{Z1Z2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{8\times 8}$$

Ceiling-pavement heat exchange

There is a pavement in between a heated zone (on top of Figure 2.6) and an unheated zone. There exists a heat transfer from the pavement (T_{p1}) of zone 1 to the air of zone 2 by convection. When we consider the heat exchange between two zones, we model the conductive transmittance of pavement as Upavi [W/m^{2}K].

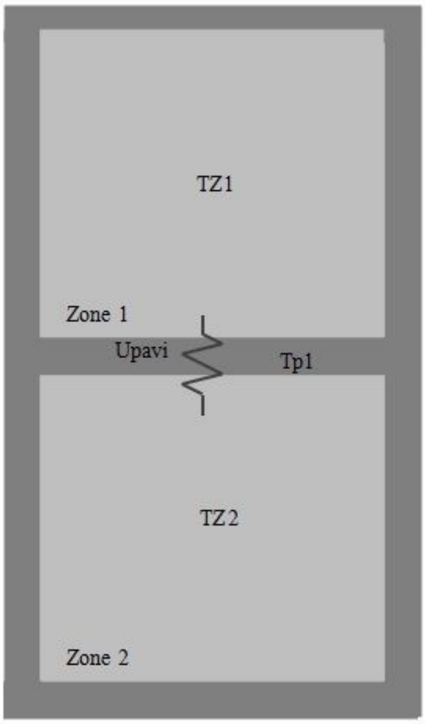

Figure 2.6 Scheme of Ceiling-pavement heat exchange

Some terms in and out of the diagonal are added for modeling the thermal interactions.

Here are the revised energy balance equation for each zone:

$$C_{p1}\dot{T}_{P1} = U_{pavi}\big|_{Z1}(T_{Z1}-T_{P1}) + \frac{1}{2}\underbrace{(1-FF)\cdot ggl\cdot F_{sm}}_{K_{sol,tr}\big|_{Z1}} \cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i}S_{tr,i1}$$

$$+U_{pavG}\big|_{Z1}(T_G-T_{P1}) + \underbrace{\frac{G}{\beta}\frac{e^{\frac{\alpha\cdot\beta}{G}}}{e^{\frac{\alpha\cdot\beta}{G}}+1}}_{hcoeff\big|_{Z1}}(te1-T'_{Z1}) + U_{pavi}(T_{Z2}-T_{P1})$$

$$C_{Z2}\dot{T}_{Z2} = U_{wci}\big|_{Z2}(T_{W2}-T_{Z2}) + U_{win}\big|_{Z2}(T_{oa}-T_{Z2}) +$$
$$U_{pavi}\big|_{Z2}(T_{P2}-T_{Z2}) + \underbrace{\dot{m}_{sa2}c_{pa}(T_{oa}-T_{Z2})}_{P_{AHU}\big|_{Z2}} + P_{\text{int}\,gains}\big|_{Z2} + U_{pavi}(T_{P1}-T_{Z2})$$

Here is the A matrix of these two zones,

$$A=\begin{bmatrix}
a_{11}\big|_{Z1} & a_{12}\big|_{Z1} & a_{13}\big|_{Z1} & a_{14}\big|_{Z1} & 0 & 0 & 0 & 0\\
a_{21}\big|_{Z1} & a_{22}\big|_{Z1} & a_{23}\big|_{Z1} & a_{24}\big|_{Z1} & 0 & 0 & 0 & 0\\
a_{31}\big|_{Z1} & a_{32}\big|_{Z1}-\frac{1}{C_{p1}}U_{pavi} & a_{33}\big|_{Z1} & a_{34}\big|_{Z1} & 0 & \frac{1}{C_{p1}}U_{pavi} & 0 & 0\\
a_{41}\big|_{Z1} & a_{42}\big|_{Z1} & a_{43}\big|_{Z1} & a_{44}\big|_{Z1} & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & a_{11}\big|_{Z2} & a_{12}\big|_{Z2} & a_{13}\big|_{Z2} & a_{14}\big|_{Z2}\\
0 & \frac{1}{C_{Z2}}U_{pavi} & 0 & 0 & a_{21}\big|_{Z2} & a_{22}\big|_{Z2}-\frac{1}{C_{Z2}}U_{pavi} & a_{23}\big|_{Z2} & a_{24}\big|_{Z2}\\
0 & 0 & 0 & 0 & a_{31}\big|_{Z2} & a_{32}\big|_{Z2} & a_{33}\big|_{Z2} & a_{34}\big|_{Z2}\\
0 & 0 & 0 & 0 & a_{41}\big|_{Z2} & a_{42}\big|_{Z2} & a_{43}\big|_{Z2} &
\end{bmatrix}_{8\times 8}$$

We name the added terms of matrix A with $A_{coupling2}$

$$A_{coupling2}=\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & -\frac{1}{C_{p1}}U_{pavi} & 0 & 0 & 0 & \frac{1}{C_{p1}}U_{pavi} & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \frac{1}{C_{Z2}}U_{pavi} & 0 & 0 & 0 & -\frac{1}{C_{Z2}}U_{pavi} & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}_{8\times 8}$$

2.4.2 State space representation of the villa model

State-space form of villa model:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases}$$

Where,

$$x = [T_{W1} \quad T_{Z1} \quad T_{P1} \quad T_{Z1}^{'} \quad T_{W2} \quad T_{Z2} \quad T_{P2} \quad T_{Z1}^{'} \quad \bullet \quad \bullet \quad \bullet \quad T_{W19} \quad T_{Z19} \quad T_{P19} \quad T_{Z19}^{'}]_{1\times 76}^{T}$$

$$u = [T_{oa} \quad W_{sol,N} \quad W_{sol,S} \quad W_{sol,W} \quad W_{sol,E} \quad W_{sol,Ceil} \quad TG \quad P_{\text{int}\,gains} \quad te1 \quad te2 \quad \bullet \quad \bullet \quad \bullet \quad te19]_{1\times 27}^{T}$$

First step, based on the single zone model, we will build a total of 19 single zone models, from zone 1 to zone 19.

Villa matrix A is contain 19 zones' matrices $A|_{Zn}$, each zone has a form like:

$$A|_{Zn} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}_{4\times 4}, n = 1,2...19.$$

So the villa matrix A has dimension equals to 76×76, with the form of:

$$A = A_{diag} + A_{coupling}$$

Where

$$A_{diag} = \begin{bmatrix} A|_{Z1} & & & \\ & A|_{Z2} & & \\ & & \bullet & \\ & & & A|_{Z19} \end{bmatrix}$$

$$A_{coupling} = A_{coupling1}|_{Zn} + A_{coupling2}|_{Zn}, n = 1,2,\cdots 19.$$

Where matrices $A_{coupling1}$ and $A_{coupling2}$ depend on the zone to zone heat exchange, which metioned on chapter “2.4.1 Heat exchange between a heated zone and a unheated zone”.

For villa matrix B, as the parameters of first 8 input variables are the same for all 19 zones, the parameters of te different with each zone, so we could build up our matrix B in the form:

$$B = \begin{bmatrix}
b_{11}|_{Z1} & b_{12}|_{Z1} & b_{13}|_{Z1} & b_{14}|_{Z1} & b_{15}|_{Z1} & b_{16}|_{Z1} & b_{17}|_{Z1} & b_{18}|_{Z1} & 0 & 0 & \bullet & 0 \\
b_{21}|_{Z1} & b_{22}|_{Z1} & b_{23}|_{Z1} & b_{24}|_{Z1} & b_{25}|_{Z1} & b_{26}|_{Z1} & b_{27}|_{Z1} & b_{28}|_{Z1} & 0 & 0 & \bullet & 0 \\
b_{31}|_{Z1} & b_{32}|_{Z1} & b_{33}|_{Z1} & b_{34}|_{Z1} & b_{35}|_{Z1} & b_{36}|_{Z1} & b_{37}|_{Z1} & b_{38}|_{Z1} & b_{39}|_{Z1} & 0 & \bullet & 0 \\
b_{41}|_{Z1} & b_{42}|_{Z1} & b_{43}|_{Z1} & b_{44}|_{Z1} & b_{45}|_{Z1} & b_{46}|_{Z1} & b_{47}|_{Z1} & b_{48}|_{Z1} & 0 & 0 & \bullet & 0 \\
b_{11}|_{Z2} & b_{12}|_{Z2} & b_{13}|_{Z2} & b_{14}|_{Z2} & b_{15}|_{Z2} & b_{16}|_{Z2} & b_{17}|_{Z2} & b_{18}|_{Z2} & 0 & 0 & \bullet & 0 \\
b_{21}|_{Z2} & b_{22}|_{Z2} & b_{23}|_{Z2} & b_{24}|_{Z2} & b_{25}|_{Z2} & b_{26}|_{Z2} & b_{27}|_{Z2} & b_{28}|_{Z2} & 0 & 0 & \bullet & 0 \\
b_{31}|_{Z2} & b_{32}|_{Z2} & b_{33}|_{Z2} & b_{34}|_{Z2} & b_{35}|_{Z2} & b_{36}|_{Z2} & b_{37}|_{Z2} & b_{38}|_{Z2} & 0 & b_{39}|_{Z2} & \bullet & 0 \\
b_{41}|_{Z2} & b_{42}|_{Z2} & b_{43}|_{Z2} & b_{44}|_{Z2} & b_{45}|_{Z2} & b_{46}|_{Z2} & b_{47}|_{Z2} & b_{48}|_{Z2} & 0 & 0 & \bullet & 0 \\
\bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
b_{11}|_{Z19} & b_{12}|_{Z19} & b_{13}|_{Z19} & b_{14}|_{Z19} & b_{15}|_{Z19} & b_{16}|_{Z19} & b_{17}|_{Z19} & b_{18}|_{Z19} & 0 & 0 & \bullet & 0 \\
b_{21}|_{Z19} & b_{22}|_{Z19} & b_{23}|_{Z19} & b_{24}|_{Z19} & b_{25}|_{Z19} & b_{26}|_{Z19} & b_{27}|_{Z19} & b_{28}|_{Z19} & 0 & 0 & \bullet & 0 \\
b_{31}|_{Z19} & b_{32}|_{Z19} & b_{33}|_{Z19} & b_{34}|_{Z19} & b_{35}|_{Z19} & b_{36}|_{Z19} & b_{37}|_{Z19} & b_{38}|_{Z19} & 0 & 0 & \bullet & b_{39}|_{Z19} \\
b_{41}|_{Z19} & b_{42}|_{Z19} & b_{43}|_{Z19} & b_{44}|_{Z19} & b_{45}|_{Z19} & b_{46}|_{Z19} & b_{47}|_{Z19} & b_{48}|_{Z19} & 0 & 0 & \bullet & 0
\end{bmatrix}_{76\times 27}$$

Villa matrix C is a unit matrix with dimension equals to 76×76:

$$C = \begin{bmatrix}
1 & & & & \\
 & 1 & & & \\
 & & \bullet & & \\
 & & & 1 & \\
 & & & & 1
\end{bmatrix}_{76\times 76}$$

$$D = ZEROS(76,27)$$

3 Case study

3.1 Introduction and description of the villa

The physical villa building in our study is made of two floors with a total of 19 zones. The first floor contains a total of 14 zones: one entrance, one kitchen, two living rooms, two bathrooms, four bedrooms, three hallways and one set of stairs. The basement floor contains 5 zones: one garage, two storage areas, one laundry and one hallway. There are stairs connecting all floors, we consider it as a zone located at first floor. All zones were installed with underfloor radiant panels for heating except for the garage. On first floor, the outside walls of peripheral zones face open air. On the basement floor, there is the outside wall of west facade facing open air; the other 3 facades contact with the ground.

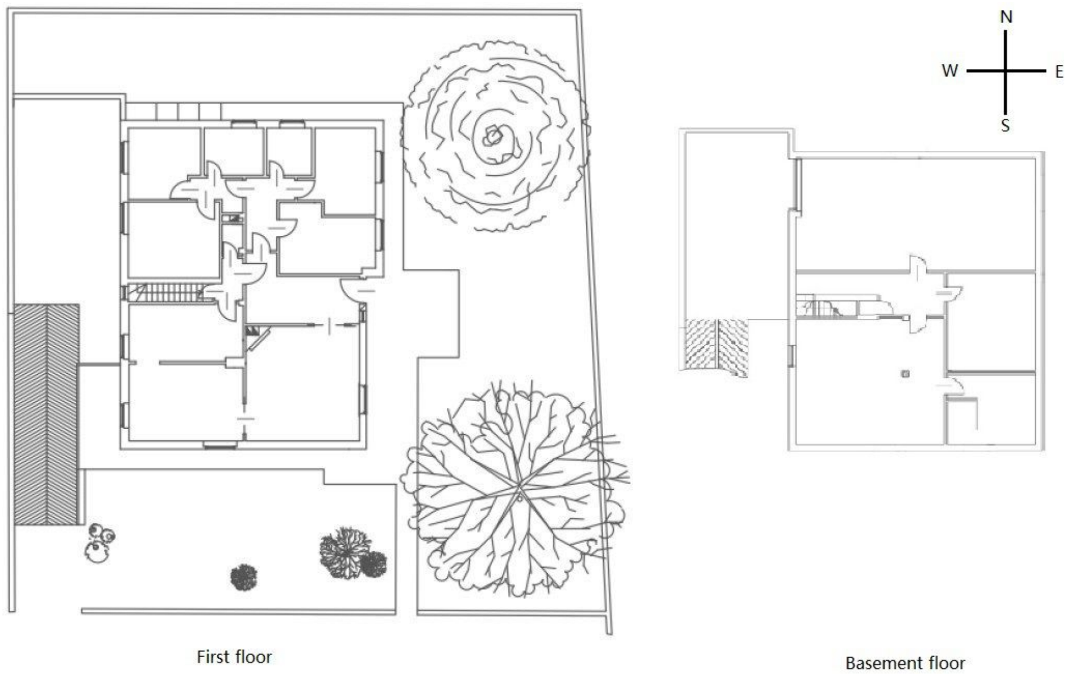

Figura 3.1 Floor plan of the villa.

In order to have a quick reference to each room of the building, they were named with a number, from 1 to 19, as showed in the figure below.

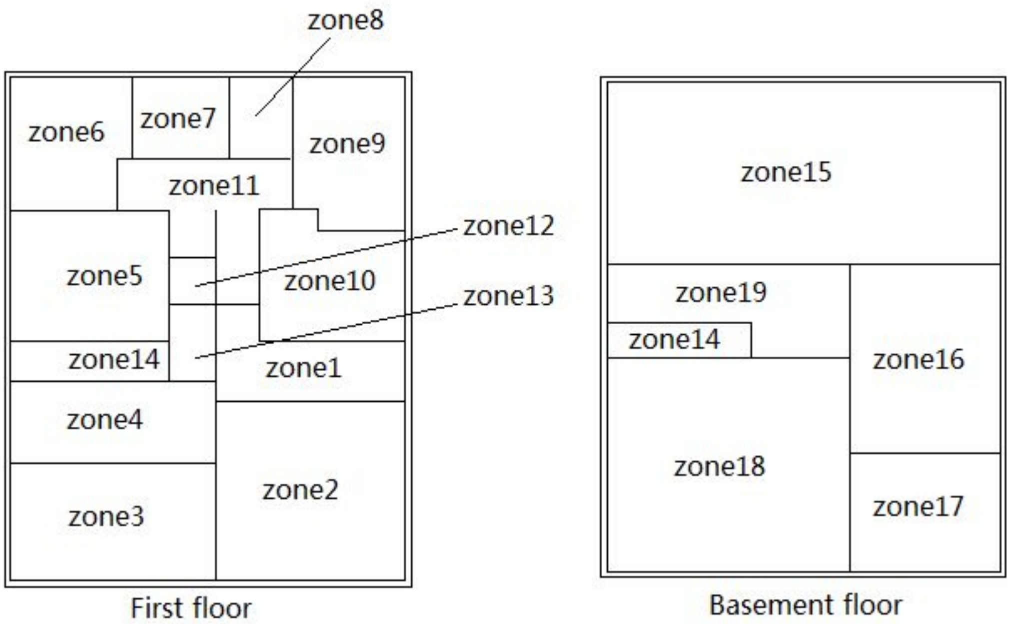

Figure 3.2 Scheme of villa

As there is a strong relationship between underfloor heating and the zone surface area, it is very important to have precise data of each zone surface area. The data are listed in the table below.

Zone No.	Zone type	Surface area[m^2]
First floor		
Zone1	Entrance	12.75
Zone2	Living room	27.09
Zone3	Living room	18.01
Zone4	Kitchen	13.43
Zone5	Bed room	14.51
Zone6	Bed room	10.07
Zone7	Bathroom	5.85
Zone8	Bathroom	4.43
Zone9	Bed room	11.51
Zone10	Bed room	12.45
Zone11	Hallway	8.53
Zone12	Hallway	1.32
Zone13	Hallway	2.09

Zone14	Stairs	3.19
Basement floor		
Zone15	Garage	64.18
Zone16	Storage area	20.45
Zone17	Laundry	14.76
Zone18	Storage area	44.86
Zone19	Hallway	14.74

Table 3.1 The surface area of all zones in the villa

From Table above, the sum of total heating zones equal 18, the total heating surface equals 240.04 [m^2], the total heating zone volume equals 656.721 [m^3].

For the physical parameters that are given by a table with the quantity of the thermal transmittance, thermal capacity and the thermal resistence for all different type of walls, pavements and windows. See Appendix[1]

The single zone simulation model:

$$C_{wc}\dot{T}_W = U_{wceO}(T_{oa} - T_W) + U_{wci}(T_Z - T_W) + \underbrace{\frac{\alpha_w R_{e\_wall}}{R_{e\_wall} + R_{wall}}}_{kwall} \cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i} S_{op,i} + \frac{1}{2} Ksol,tr \cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i} S_{tr,i} + U_{weG}(T_G - T_W)$$

$$C_Z\dot{T}_Z = U_{wci}(T_W - T_Z) + U_{win}(T_{oa} - T_Z) + U_{pavi}(T_P - T_Z) + \underbrace{\dot{m}_{sa} c_{pa} (T_{oa} - T_Z)}_{P_{AHU}} + P_{\text{int}\, gains}$$

$$C_P\dot{T}_P = U_{pavi}(T_Z - T_P) + \frac{1}{2}\underbrace{(1 - FF) \cdot ggl \cdot F_{sm}}_{K_{sol,tr}} \cdot \sum_{i=N,S,W,E,Ceil} W_{sol,i} S_{tr,i} + U_{pavG}(T_G - T_P) + \underbrace{\frac{G}{\beta} \frac{e^{\frac{\alpha \cdot \beta}{G}}}{e^{\frac{\alpha \cdot \beta}{G}} + 1}}_{hcoeff} (te - T_Z')$$

$$\dot{T}_Z' = \frac{1}{\tau} T_Z - \frac{1}{\tau} T_Z'$$

Based on our physical villa's parameter, we could calculate all the parameters of the zone model.

We took zone 3 as a example.

Walls thermal capacity:

$$C_{WC} = S_{wall} * C_{P\_wall} + S_{ceil} * C_{P\_ceil}$$
$$= 18.937 * 318.88 * 1000 + 18.01 * 220.96 * 1000 = 1.0018 * 10^\wedge 7 [J/K]$$

Zone air mass thermal capacity:

$$\mathrm{C_Z} = V\_zone * \rho * C_{air}$$
$$= 48.92 * 1.2215 * 1010 = 6.0353 * 10\wedge 4 [J/K]$$

Pavement thermal capacity:

$$\mathrm{C_P} = S_{pavl} * \mathrm{C_{P\_pav}}$$
$$= 18.01 * 89.98 * 1000 = 1.6205 * 10\wedge 6 [J/K]$$

External convective conductance of walls (ceiling) with open air:

$$\mathrm{U_{wceO}} = 1/(R_{wall} + R_{e\_wall}) * S_{wall\_air} + 1/(R_{ceil} + R_{e\_ceil}) * S_{ceil\_air}$$
$$= 1/(3.6 + 0.04) * 18.937 + 1/(4.34 + 0.1) * 18.01 = 9.2588 [\mathrm{W/K}]$$

Internal convective conductance of walls (ceiling):

$$\mathrm{U_{wci}} = 1/(R_{wall} + R_{i\_wall}) * S_{wall\_air} + 1/(R_{ceil} + R_{i\_ceil}) * S_{ceil\_air}$$
$$= 1/(3.6 + 0.13) * 18.937 + 1/(4.34 + 0.1) * 18.01 = 9.1332 [\mathrm{W/K}]$$

External convective conductance of walls (ceiling) with ground:

$$\mathrm{U_{weG}} = 1/(R_{wall} + R_{e\_wall}) * S_{wall\_ground}$$
$$= 1/(4.34 + 0.01) * 0 = 0 [\mathrm{W/K}]$$

Convective conductance of transparent surface:

$$\mathrm{U_{win}} = \sum_{i=N,S,W,E} 1/(R_{win} + R_{i\_win} + R_{e\_winl}) * S_{tra,i}$$
$$= 0 + 1/(0.412 + 0.13 + 0.04) * 0.0208 + 1/(0.399 + 0.13 + 0.04) * 0.025 + 0 = 0.07967 [\mathrm{W/K}]$$

Air-pavement convective transmittance:

$$\mathrm{U_{pav}} = 1/(R_{pav} + R_{i\_pav}) * S_{pav}$$
$$= 1/(0.804 + 0.06) * 18.01 = 20.84 [\mathrm{W/K}]$$

Pavement- ground convective transmittance:

$$\mathrm{U_{pavG}} = 1/(R_{pav} + R_{i\_pav} + R_{e\_pav}) * S_{pav}$$
$$= 1/(10 + 0.06 + 0.04) * 18.01 = 1.783 [\mathrm{W/K}]$$

Convection conductance of supply air:

We will explain it on chapter “3.4 Components of the system related to the study”.

Coefficient of solar radiation affect on opaque area:

$$\text{Kwall} = (\alpha_w * R_{e\_wall}) / (R_{e\_wall} + R_{wall}) = (0.6 * 0.04) / (3.6 + 0.04) = 0.00659\,[\#]$$

Coefficient of solar radiation affect on transparent area:

$$K_{sol,tr} = (1 - FF) * ggl * Fsm = (1 - 0.74) * 0.85 * 0.67 = 0.1481\,[\#]$$

3.2 Structure of the heating system of the villa

The heating system of the building consists of a heat pump for heating water, a primary system (from the heat pump to the manifolds) and secondary system of pipes (from manifolds to each pipeline circuit) for its distribution, a group of pumps to regulate the flow of the system and finally a circuit for return water. Radiant panels are distributed throughout the building to heat the air of the surrounding environment receiving heat from the hot water in the pipes. The feedback circuit takes water from the radiant panel to re-introduce it in the circuit.

There is a example of 2- zone system to shows the scheme:

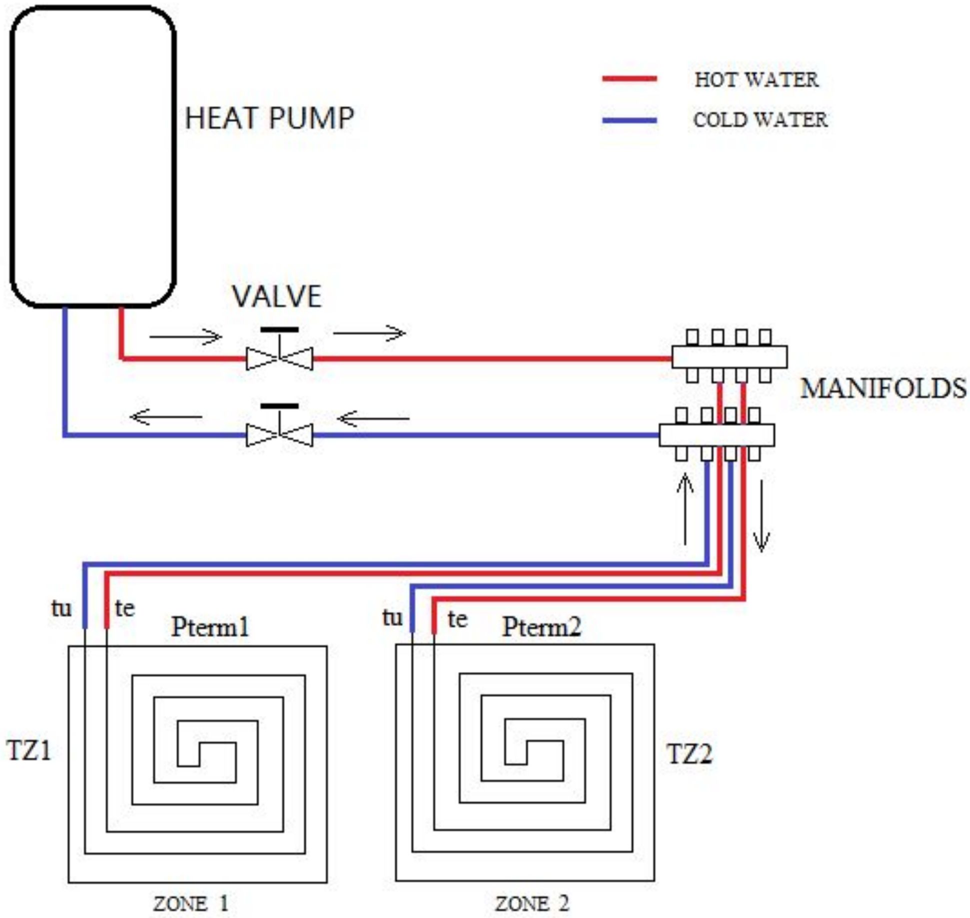

Figure 3.3 Structure of the heating system of the villa.

For each single heated zone, the radiant panel: $P_{TERM} = Q = \underbrace{\frac{G}{\beta}\frac{e^{\frac{\alpha\cdot\beta}{G}}}{1+e^{\frac{\alpha\cdot\beta}{G}}}}_{hcoeff}\cdot(t_e - T_Z{}')$

For each single heated zone, the parameters α and β are depend on its zone's and panel's characteristics (see "2.2 Radiant panel thermal model"). The mass flow G, which we could optimize it with the energy consumption during January (the coldest month in heating season). By setting up parameters α, β and G, we will have a constant value of hcoeff for each heated zone. So our P_{TERM} is only related to the difference between te and T_Z'.

3.3 Thermal external and internal variables

As mentioned in the Introduction of Chapter 1, there exists several external and internal variables that affect the indoor zone temperature, both from outside environment and the inside environment. The input variables of our thermal model of the building are T_{oa}, $W_{sol,N}$, $W_{sol,S}$, $W_{sol,W}$, $W_{sol,E}$, $W_{sol,ceil}$, T_G, $P_{intgains}$ and tei, i= 1, 2, ... 19.

The first variable is the outdoor temperature T_{oa}, which is greatly influenced by seasonal changes and daily weather changes also depend on solar radiation. Below there is a table which gives the average temperature according to each month and also the average temperature excursion.

TEMPERATURES & EXCURSION		
MONTH	TEMPERATURE [°C]	EXCURSION [°C]
January	1.5	6.5
February	4.2	8.2
March	9.3	9.3
April	13	9.8
May	17.7	10.4
June	22	11.1
July	24.4	11.3
August	23.7	11
September	19.9	10
October	13.5	8.5
November	7.8	7.1

December	3.5	6.2

Table 3.2 Average outdoor temperature and average temperature excursion in each month of the year.

We use MATLAB to create a function to represent T_{oa},

$$T_{oa} = Am \cdot \sin(\omega t + \varphi) + D,$$

where:

Am, the amplitude, is half of temperature excursion;

ω, the angular frequence, is equals to $2 \cdot \pi / (24 \cdot 3600)$ [rad/s];

φ, the phase, is equals to $-8 \cdot 3600 \cdot \frac{2\pi}{24 \cdot 3600}$ [rad];

D, the non-zero center amplitude, is vary according to the average temperature in year round.

By using Curve Fitting Tool (cftool), we could get the approximation of polynomial functions Am and D.

The simulation result of outdoor temperature from Oct. 15th to Apr. 15th is shown as follow.

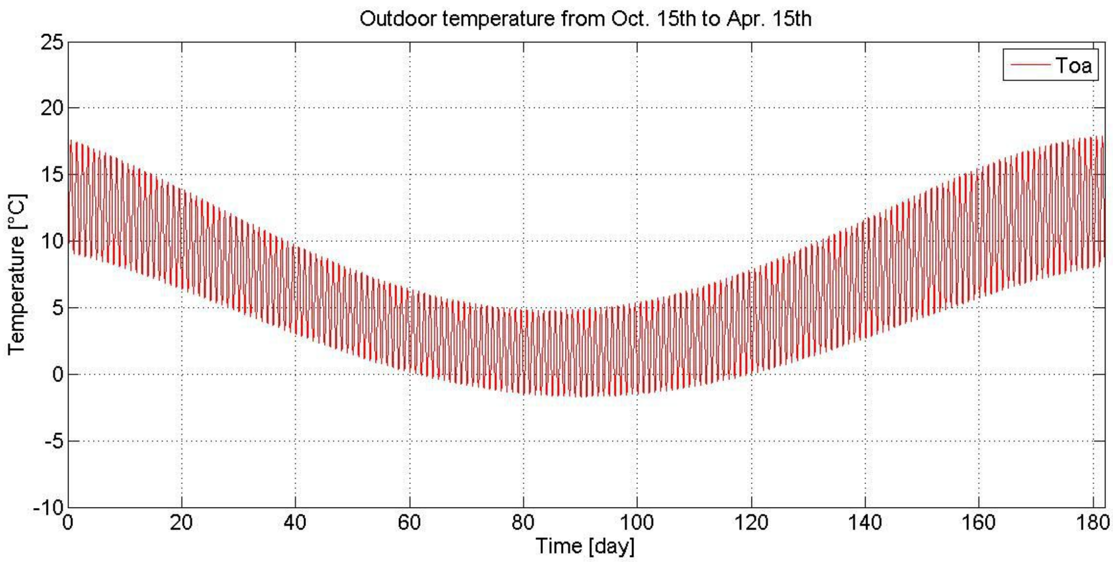

Figure 3.4 Outdoor temperature from Oct. 15th to Apr. 15th

Zoom in, the outdoor temperature from Jan. 1st to Jan. 2nd is shown as follow.

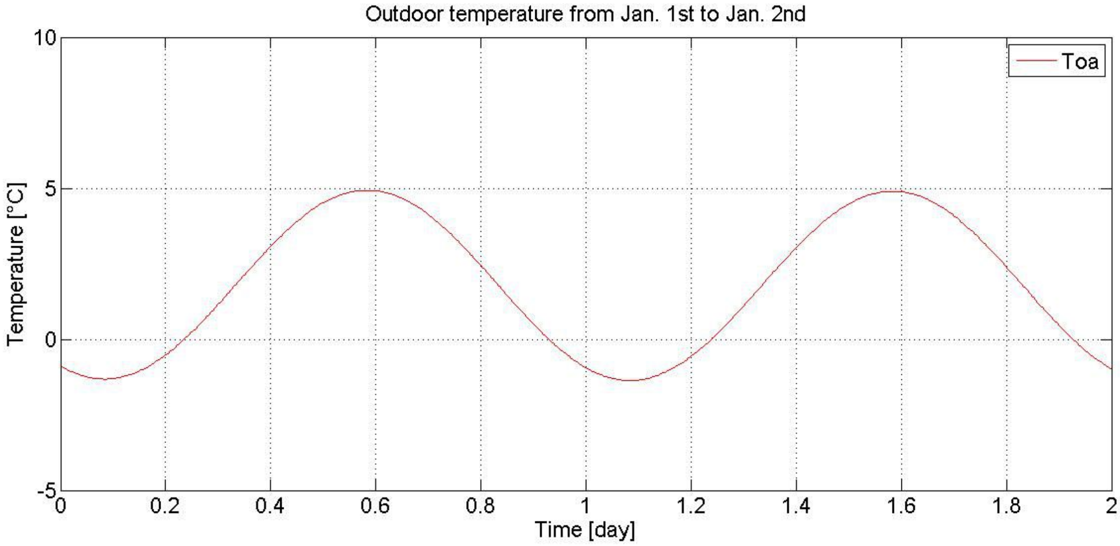

Figure 3.5 Outdoor temperature from Jan. 1st to Jan. 2nd

The Second variable is the solar radiation. Solar radiation is a measure of the irradiance (power per unit area on the Earth's surface) produced by the Sun in the form of electromagnetic radiation, which is perceived by humans as sunlight. Solar irradiance in a specific area may be measured as insolation. The solar radiation energy per unit area during a given time (direct insolation) is the insolation which reaches a location on Earth after absorption and scattering in the atmosphere. In our case, the average energy per day in each month, for each direction, are presented in table below:

Solar radiation [MJ/m^2]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
north	1.7	2.5	3.7	5.4	7.8	9.4	9.3	6.5	4.2	2.9	1.8	1.5
south	8.2	11	12.3	10.6	10.2	9.9	11	11.8	12.6	11.7	9.0	8.4
west	3.7	6.1	9.2	11.1	13.5	14.6	16.1	13.9	10.7	7.1	4.3	3.6
east	3.7	6.1	9.2	11.1	13.5	14.6	16.1	13.9	10.7	7.1	4.3	3.6
horizontal	4.6	7.8	12.4	16.1	20.4	22.5	24.4	20.2	14.7	9.2	5.3	4.3

Table 3.3 Average solar radiation per day for 12 month

Based on the data of solar radiantion for each direction during winter season, we could build the simulation functions of $W_{sol,N}$, $W_{sol,S}$, $W_{sol,W}$, $W_{sol,E}$ and $W_{sol,Ceil}$.

When simulate the solar radiantion, assuming the radiantion exists only during the day, with the amplitude increasing from sunrise till noon, decreasing from noon to sunset. During the night the value of radiantion equals to zero.

$W_{sol} = Am \cdot (\sin(\omega t + \varphi) + D) + E$, during the day;

$W_{sol} = 0$, during the night.

Where,

ω and φ are the same values as function of T_{oa};

A_m is the amplitude;

D is the non-zero center amplitude;

E is a error compensate factor.

We took $W_{sol,N}$ solar radiation from North to make a example, below shown its results from Oct. 15th to Apr. 15th.

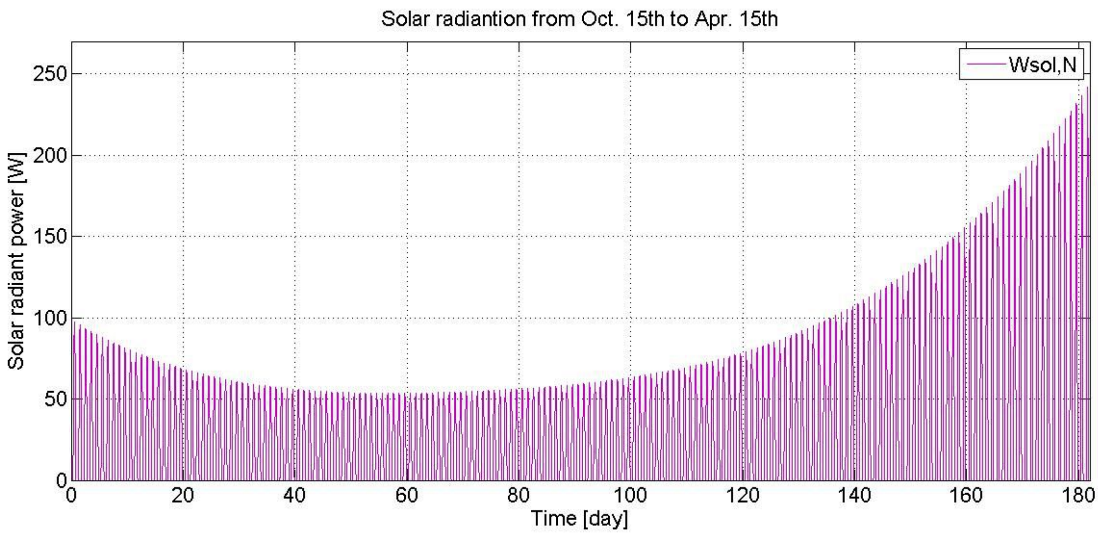

Figure 3.6 Solar radiation $W_{sol,N}$ from Oct. 15th to Apr. 15th

Zoom in, $W_{sol,N}$ from Jan. 1st to Jan. 2nd is shown as follow.

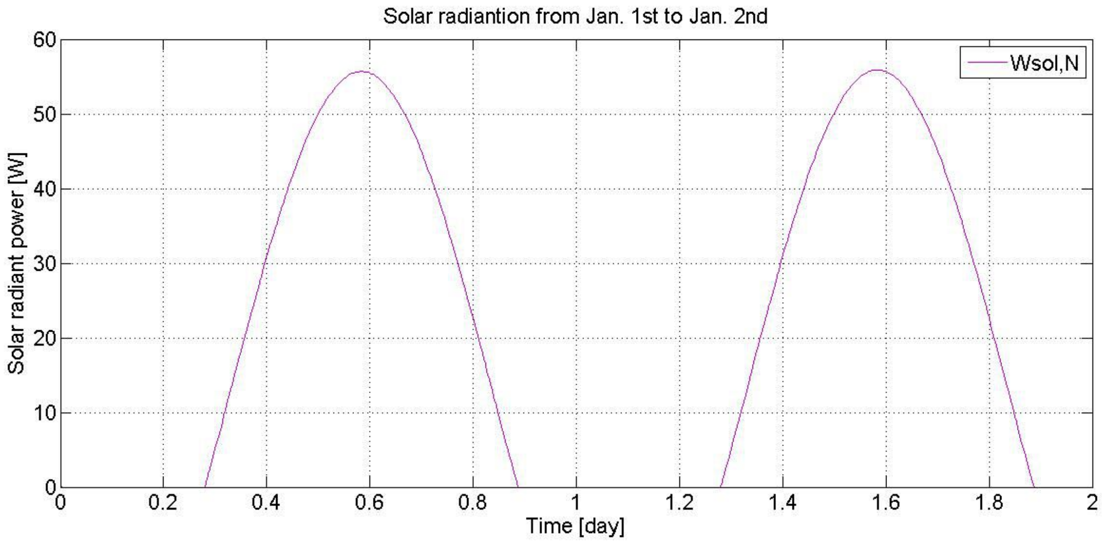

Figure 3.7 Solar radiation $W_{sol,N}$ from Jan. 1st to Jan. 2nd

Third variable is the ground temperature. Compared to the other variables (outdoor temperature, solar radiation), ground temperature will not change rapidly. In our case, it is assumed as a constant and equal to 13.5[°C].

GROUND TEMPERATURE[°C]
13.5

Table 3.4 Ground temperature

Fourth variable is internal gains, anything (such as: household appliances, stove, lamps, people and pets) produce heat as a waste product which affects the heating and cooling loads within the zone. These kinds of heat contributions are called internal gains, which causes a decrease in the heating energy consumption.

In our Simulation model, Internal gains $P_{intgains}$= 5.01 [W], which is a reference value took from Edilclima.

3.4 Components of the system related to the study

There is a component in the building that influences the energy consumption and the zones temperatures, the AHU (Air Handling Unit).

AHU is a device used to regulate and circulate air as part of a heating, ventilating, and air-conditioning (HVAC) system. It brings outside fresh air into the zone, therefore causing convection heat transfer.

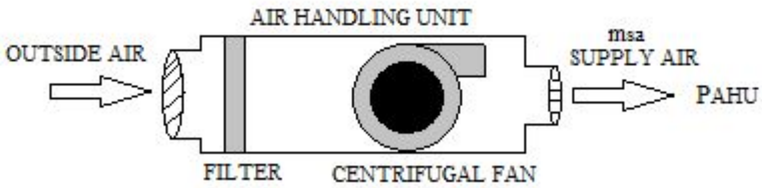

Figure 3.8 Scheme of a Air Handling Unit

The simulation model of AHU is,

$$P_{AHU} = \overbrace{\dot{m}_{sa} c_{pa}}^{U_{sa}} (T_{oa} - T_Z)$$

Where,

$\dot{m}_{sa} = zone\_volume \times \rho \times 0.6 \div 3600$ [kg/s] supply air massflow

$c_{pa} = 1010$ [J/kgK] air specific heat

Model parameter:

- Air density: ρ [kg/m^3];

For our zone 3,

Convection conductance of supply air:

$$\mathrm{U_{sa}} = V\_zone * 0.6 * \rho_{air} / 3600 * C_{air} = 48.92 * 0.6 * 1.2215 / 3600 * 1010 = 10.06[\mathrm{W/K}]$$

4 Thermal model validation

4.1 Introduction of Edilclima

Edilclima is a leading software house which develops computer programs for designing systems and for verifying compliance with the constraints of the law.

The greater commitment of Edilclima is always to deepen the methodological aspects and normatives, not only actively participating in working groups and subcommittees of the CTI and the CEN, but also anticipating that work with their own proposals previously tested and validated in the field, in tune with the professional organizations of the operators concerned.

The result of this approach has allowed the software developed by Edilclima to become, in the last twenty years, a reference that has often anticipated regulatory events, contributing to a prior cultural training of the operators.

Technical expertise gained in over 30 years of experience in the research and development of solutions for the design-thermal engineering plant, the completeness of the product and the quality of services such as technical support, training for the proper use of the software, professional training events, the opportunity to share ideas through regulatory forum, have made Edilclima the point of reference for thousands of industry professionals.

The goal of Edilclima is to provide flexible computing tools that return to the designer the primary decision-making role that competes, while respecting formal and bureaucratic requirments. This is consistent with an overwhelming need and repeatedly reported by HVAC professionals.

In particular, Edilclima has develpoed a tool to calculate the energy consumption in buildings and classify them according to their energy efficiency.

4.2 Single zone thermal model validation

After the development of the zone model and villa model with the parameters from the physical villa, we need to put them into validation with the reference values (the enery consumption Q_{tot} [kWh]) from Ediclima. In order to validate the single zone model, we choose zone 3-Living room as a example. The scheme of zone 3 is shown below:

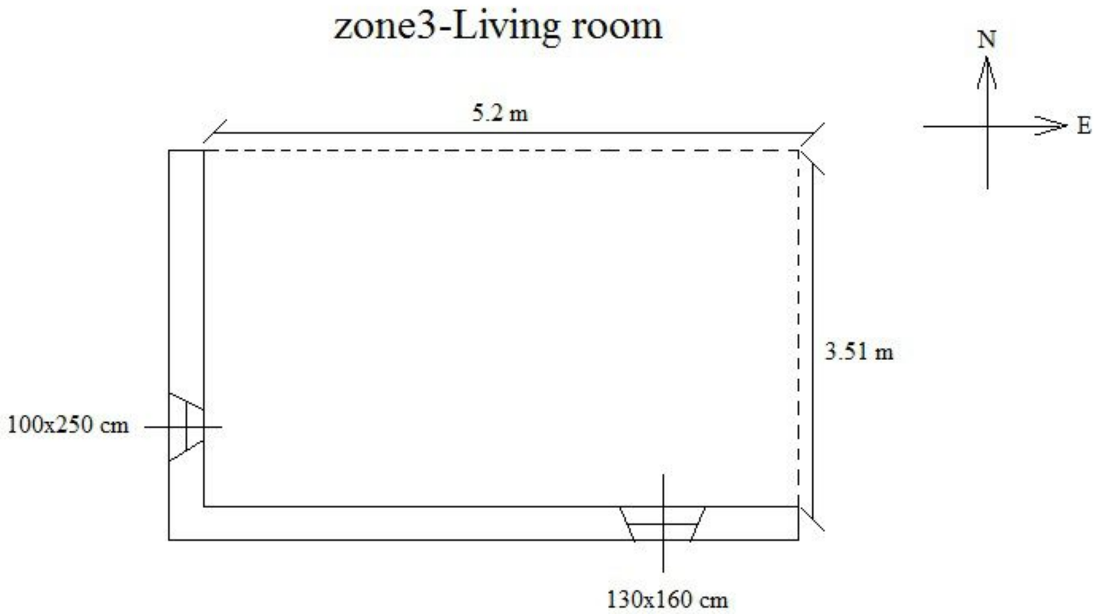

Figure 4.1 Zone 3- Living room scheme

The size of the living room is 5.2 m × 3.51 m, there are 2 windows located on the west side and the south side. The window on the west side is 100 cm × 250 cm, while the one on the south side is 130 cm × 160 cm.

The simulink model of zone 3 shown below:

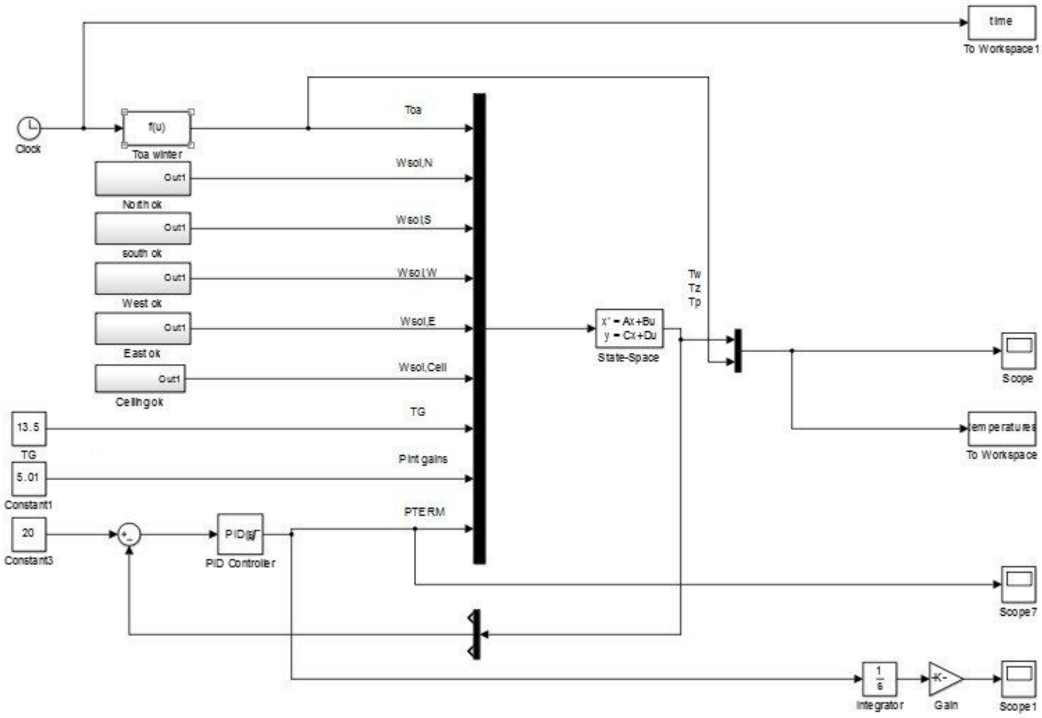

Figure 4.2 Simulink model of zone 3

Simulation conditions:

- The setup zone temperature is 20 [°C];
- The initial conditions of the state variables of the single zone model are: T_Z=20 [°C], T_W=15 [°C], T_P=25 [°C];
- The simulation time, from 15th Oct. to 15th Apr., is 182 days.

In order to validate the dynamic model of the thermal zone, we computed the total energy consumption needed to heat the room and have a temperature of 20°C during the winter season and compared the results with the data from Edilcima.

A PID controller was used to assure that the temperature in the room was set to 20 [°C] by acting on the thermal power from the heating system.

The simulation result of the energy consumption test is shown below.

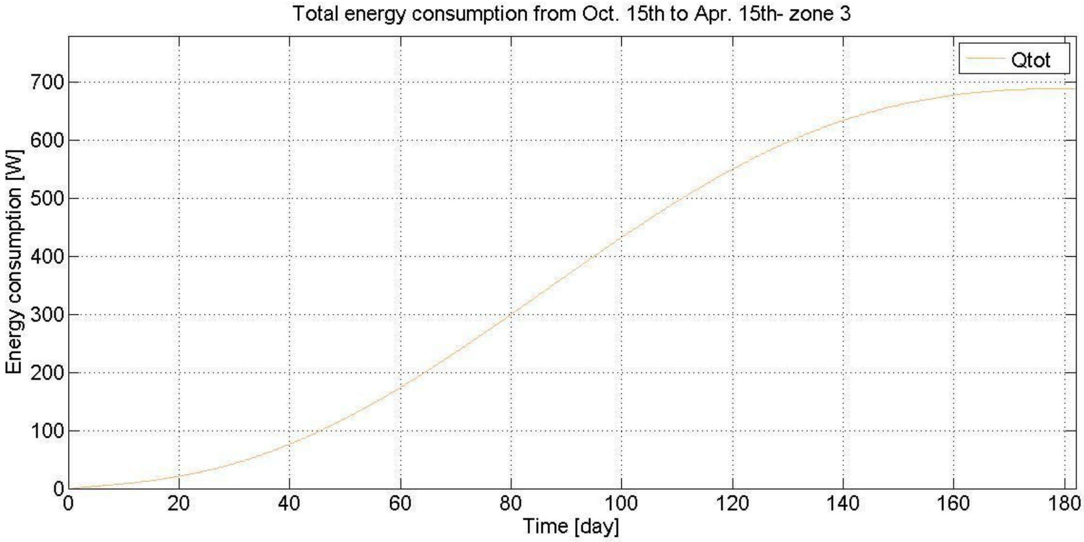

Figure 4.3 Validation of energy consumption- zone 3

From figure above, the energy consumption Q_{tot}= 690 [kWh].

Then we compare it with the reference values Q_{tot}= 720 [kWh] from Edilclima. The difference of 30 [kWh] (4.35 %) is inside our accptable domain of error (5%). So the zone dynamic model leads to the same consumption levels registered in Edilclima.

4.3 Villa thermal model validation

As for the single zone model, we also validated the villa model by calculating the total energy consumption Q_{tot} from 15^{th} Oct. to 15^{th} Apr.

The simulink model of the villa for validation shown below,

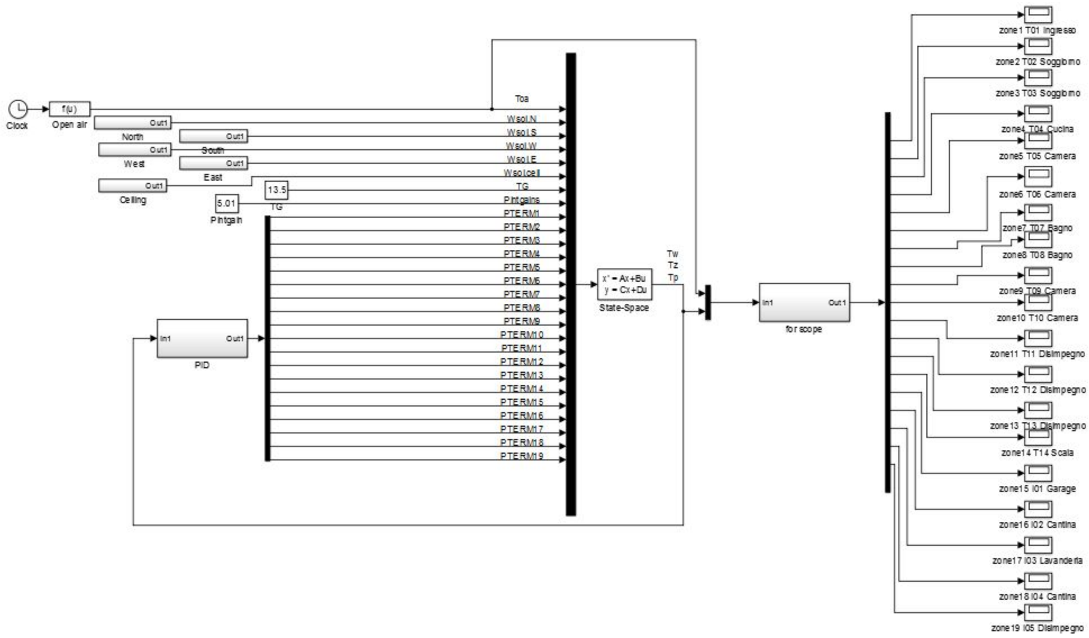

Figure 4.4 Simulink model of the villa with P_{TERM}

The simulation conditions:

- The setup zone temperature is 20 [°C] for all zones;
- The initial conditions of the state variables of the villa model, for each room, are: T_{Zi}=20 [°C], T_{Wi}=15 [°C], T_{Pi}=25 [°C], i=1,2,3... 19;
- The simulation time is winter period from 15th October to 15th April, which is 182 days.

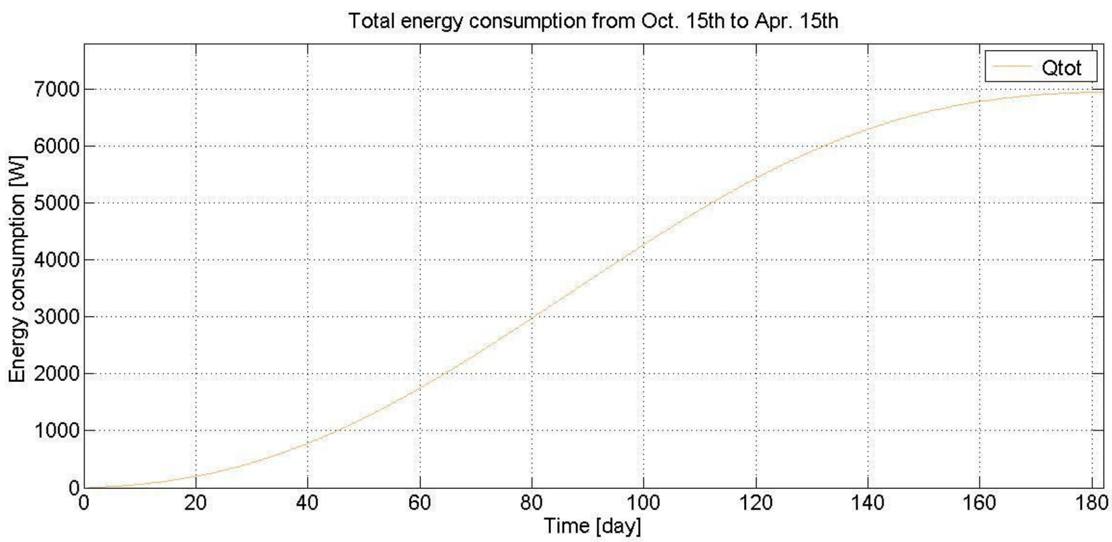

Figure 4.5 Validation of energy consumption- villa

Once again, we used a PID controller (one for each room) to set the temperatures of the zones to 20 °C by acting on the thermal power provided by the heating systems in each room.

The total energy consumption from the simulation is Q_{tot}= 6950 [kWh].

The reference value from Edilclima is Q_{tot}= 6658 [kWh]. The difference between these two values is 292 [kWh]. The error 4.38% is inside our accptable domain (5%). So the villa model is acceptable.

5 Temperature control strategies

The purpose of applying different control strategies to the villa model are:

- To obtain a sensible energy saving for the villa;
- To increase the thermal comfort for occupants who live in the villa.

For a better understanding of the effects and performances of different control strategies, they will be applied to both the single zone model and the villa model.

We consider two reference indicators:

- Total energy consumption: Q_{tot} [kWh];
- The amplitude of the variation in the zone temperature: dz [°C].

5.1 Thermal zone model

5.1.1 Single PID controller

For a single PID controller applied to our zone model, the control scheme is presented below. We took zone 3 - Living room to preform simulation tests.

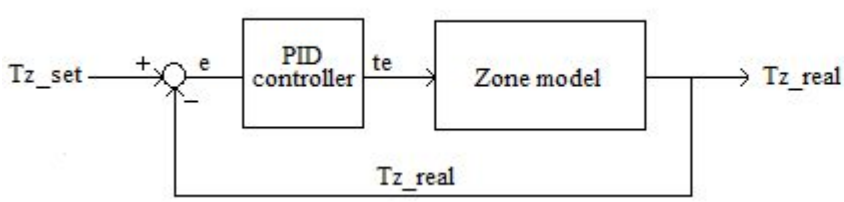

Figure 5.1 Single zone PID control

In Figure 5.1, where:

- The set point of zone temperature: T_Z_set [°C];
- The measured zone temperature: T_Z_real [°C];
- The error between the set point and the measured zone temperature: e [°C];

- The inlet temperature of the panel: te [°C].

Simulation conditions:

- The set point of zone temperature T_Z_set= 20 [°C];
- The initial conditions of the model state variables are: T_Z=20 [°C], T_W=22 [°C], T_P=25 [°C], T_Z'=18 [°C];
- The simulation time, from 15th Oct. to 15th Apr., is 182 days.

Simulation results are presented in the figure below.

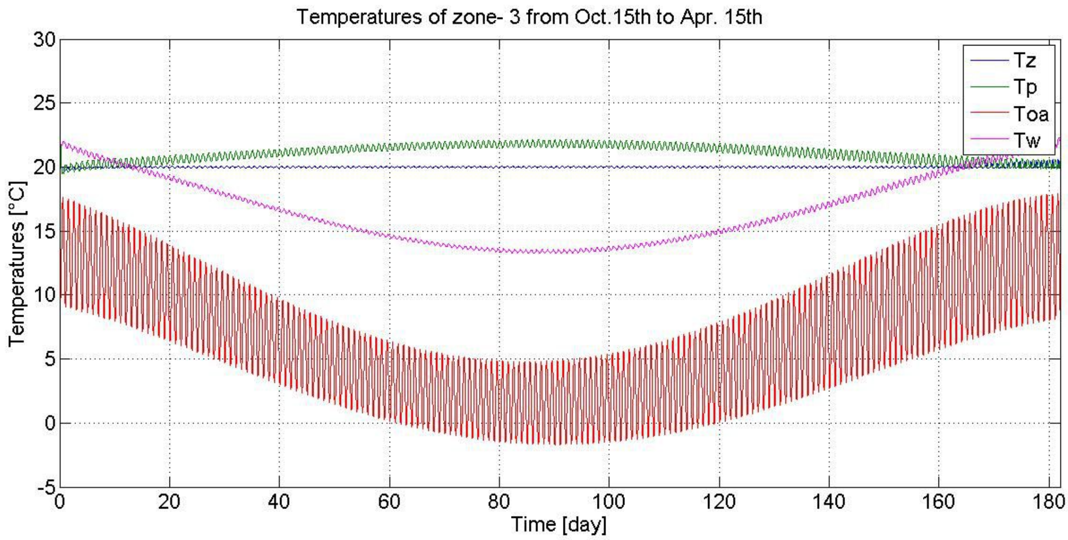

Figure 5.2 Simulation results of T_W,T_P, T_Z and T_{oa}

We can consider two days, Jan. 1st and Jan. 2nd, to have a better view of the behaviours when T_{oa} is low.

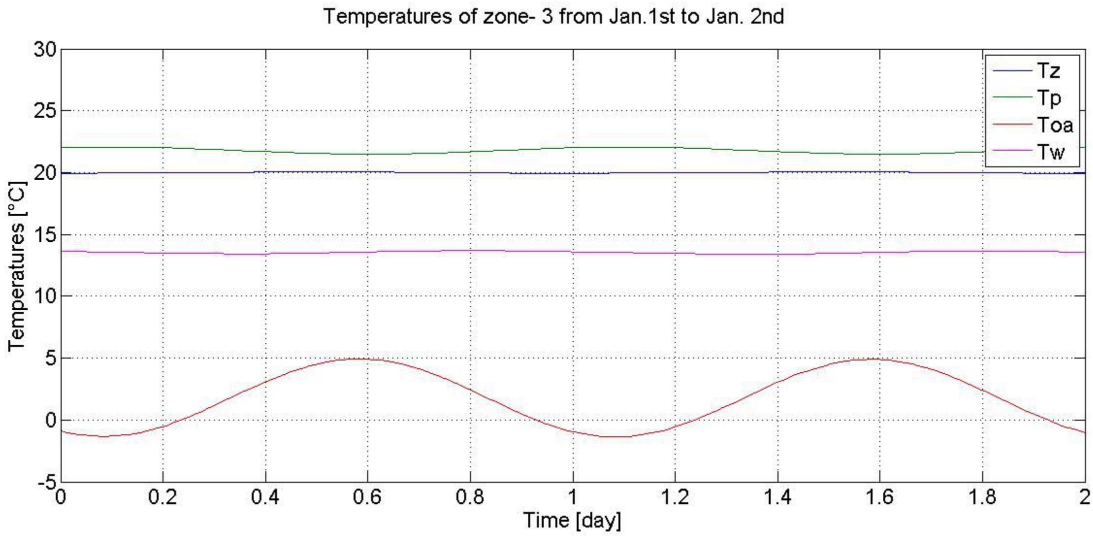

Figure 5.3 Simulation results of T_W,T_P, T_Z and T_{oa} in Jan 1st and 2nd

The amplitude of the variation of the temperature T_Z during Jan. 1st to Jan. 2nd is shown in Figure 5.4.

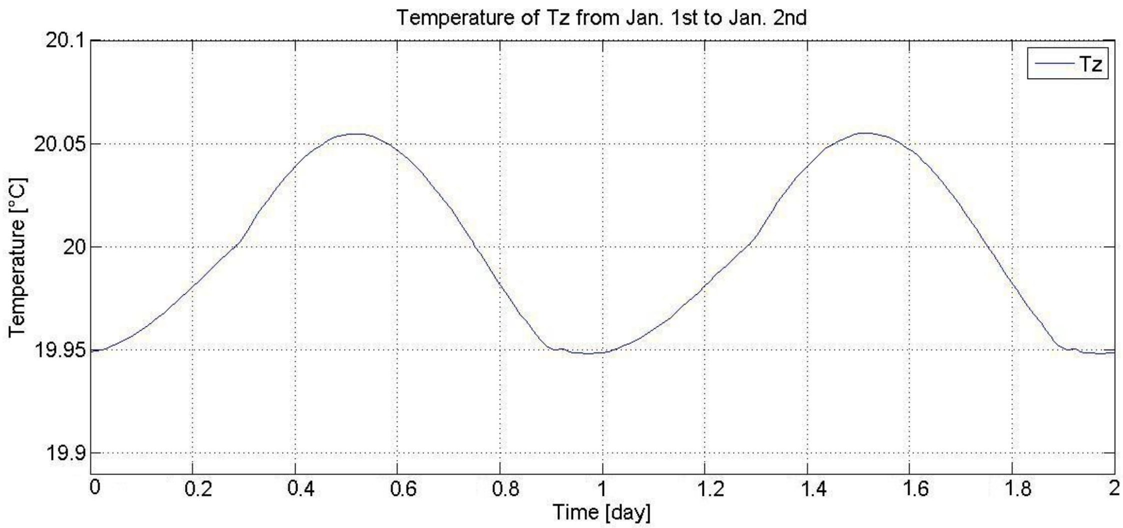

Figure 5.4 Simulation results of T_Z in Jan 1st and 2nd

The total energy consumption from Oct. 15th to Apr. 15th could be see from below,

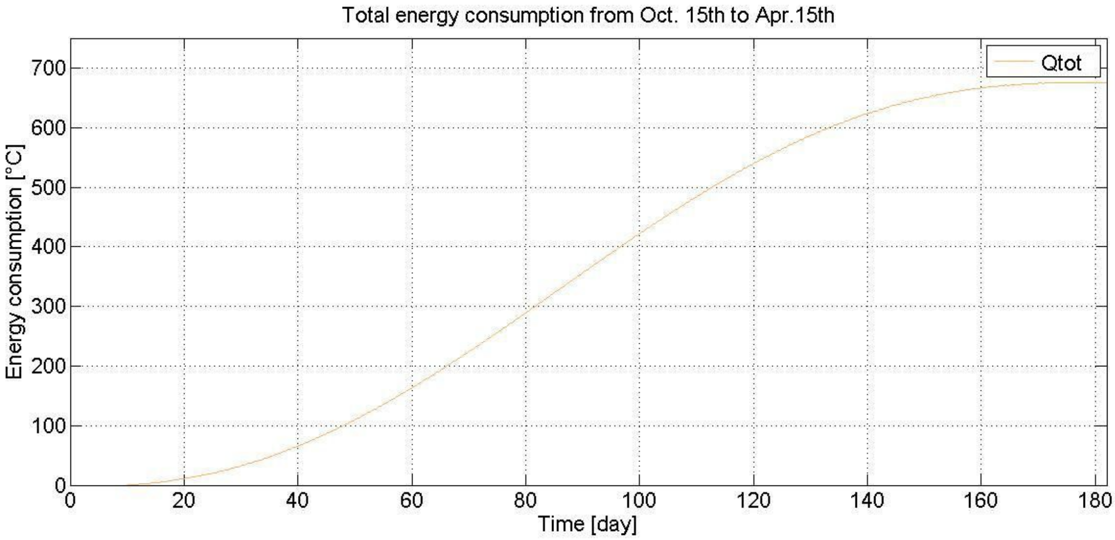

Figure 5.5 Simulation results of total energy consumption- zone 3

From the results above, the variation of T_Z during Jan. 1st and Jan. 2nd, dz= 0.05 [°C].

The total energy consumption Q_{tot}= 675 [kWh].

5.1.2 Single PID controller with compensator

The basic concept of feedforward compensator is to use the measure of the disturbance signal in order to generate the appropriate control signal that cancels (or reduces) the effect of the disturbance on the controlled variable.

In our model, our measurable disturbance is the external temperaure T_{oa} so we could develop a compensator to cancel the effects caused by T_{oa} on the temperature of the zone.

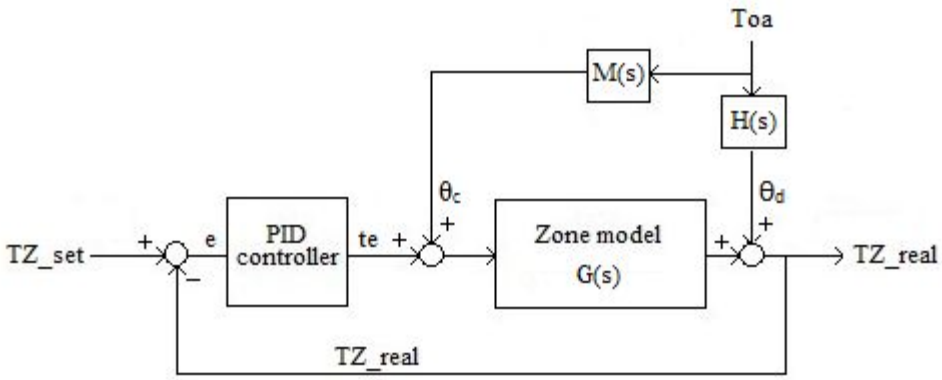

Figure 5.6 Single PID controller+ compensator

In Figure 5.6,where

- The disturbance signal from T_{oa} to T_Z: θ_d;
- The compensation control signal from T_{oa} to T_Z: θ_c.

The compensator M(s) could be derived as follow.

Based on our state space matrices A, B, C, D, the transfer functions matrice of zone 3,

$$G(s) = C(sI - A)^{-1}B + D$$

Where,

$$G(s) = \begin{bmatrix} G11(s) & G12(s) & G13(s) & G14(s) & G15(s) & G16(s) & G17(s) & G18(s) & G19(s) \\ G21(s) & G22(s) & G23(s) & G24(s) & G25(s) & G26(s) & G27(s) & G28(s) & G29(s) \\ G31(s) & G32(s) & G33(s) & G34(s) & G35(s) & G36(s) & G37(s) & G38(s) & G39(s) \\ G41(s) & G42(s) & G43(s) & G44(s) & G45(s) & G46(s) & G47(s) & G48(s) & G49(s) \end{bmatrix}_{4\times 9}$$

$$\begin{bmatrix} T_W \\ T_Z \\ T_P \\ T_Z' \end{bmatrix} = G(s) \bullet \begin{bmatrix} T_{oa} \\ W_{sol,N} \\ W_{sol,N} \\ W_{sol,N} \\ W_{sol,N} \\ W_{sol,N} \\ T_G \\ P_{\text{int}\,gains} \\ te \end{bmatrix}_{9\times 1}$$

The transfer function from input 1 (T_{oa}) to output 2 (T_Z) is G21(s) (that is H(s)=G21(s)). The transfer function from input 9 (te) to output 2 (T_Z) is G29(s).

The transfer function of compensator is $M(s) = -\frac{G21(s)}{G29(s)}$.

We calculate the compensator for zone 3 M(s) and approximated it with the dominant pole and zero method. The simulation results are shown below,

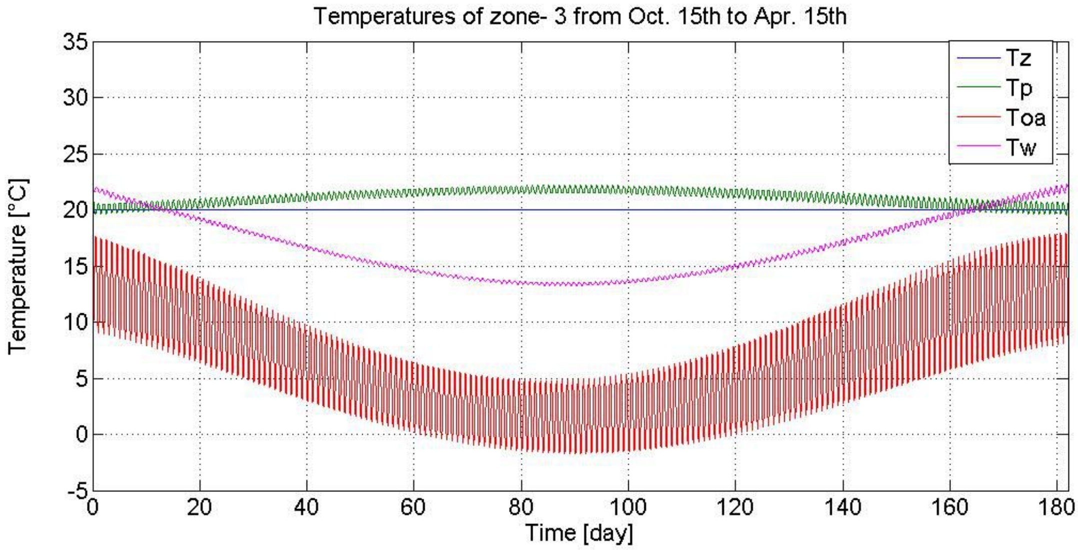

Figure 5.7 Zone with compensator simulation results

Zoom in, to see the results in Jan. 1st and Jan. 2nd

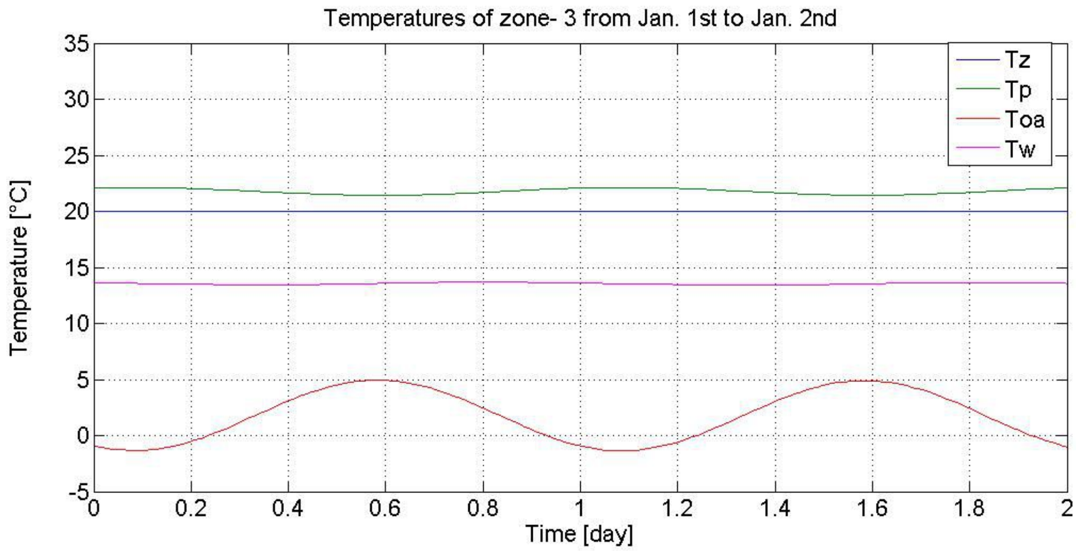

Figure 5.8 Zone with compensator simulation results for Jan 1st and 2nd

The amplitude variation of temperature T_Z from Jan. 1st to Jan. 2nd.

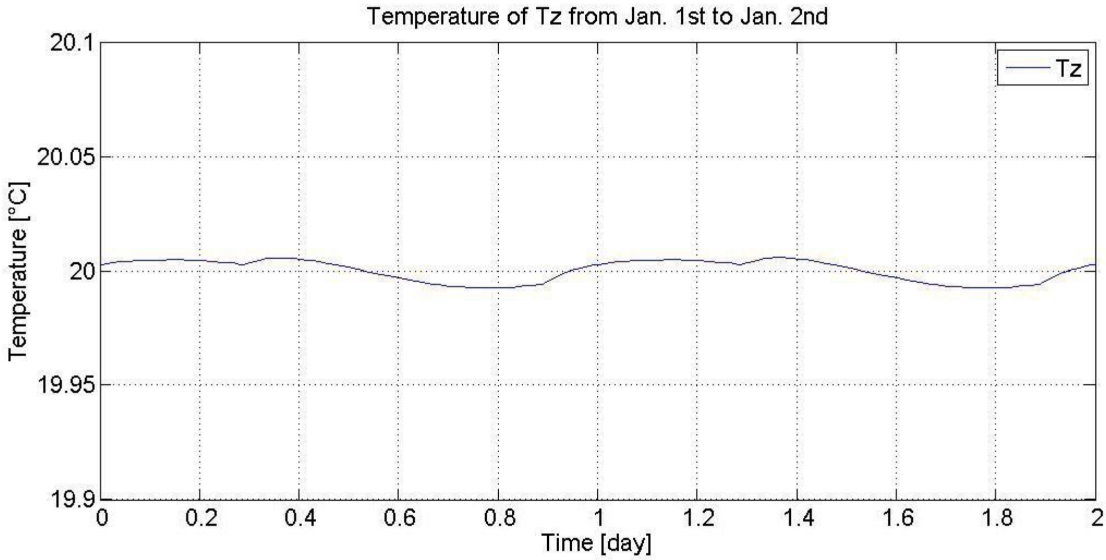

Figure 5.9 Single PID controller+ compensator T_Z in Jan 1st and 2nd

The total energy consumption from Oct. 15th to Apr. 15th could be seen from below,

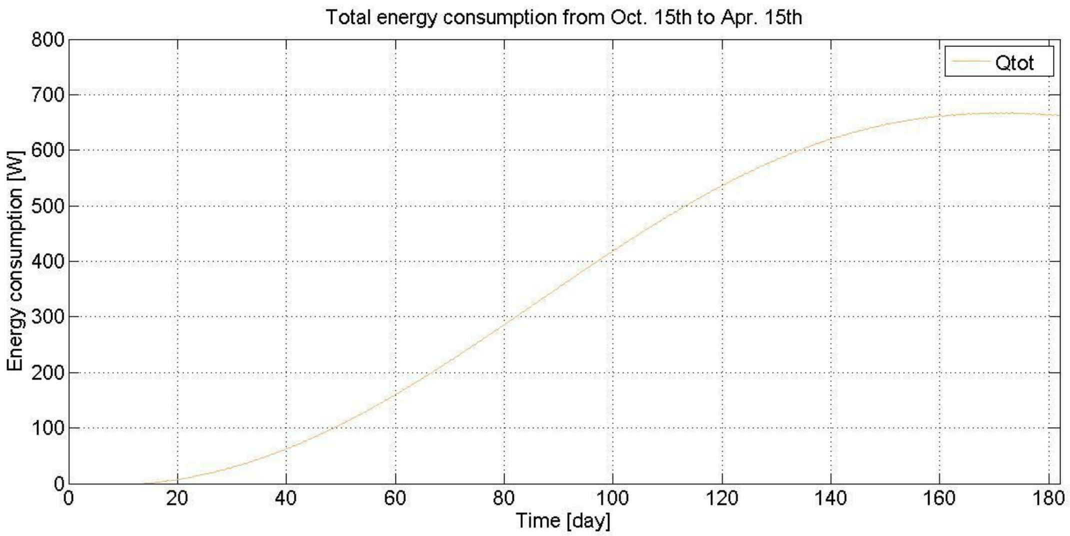

Figure 5.10 Single PID controller+ compensator total energy consumption

From the results above, the zone temperature variation dz=0.01 [°C], the total energy consumption Q_{tot}= 662 [kWh].

In conclusion, by comparison the results between the two different single zone control strategies:

- The Q_{tot} of Sigle PID controller with T_{oa} compensator reduced 13 [kWh] (1.9

%);

- The dz (the amplitude of temperature variation of T_Z) of Sigle PID controller with T_{oa} compensator reduced 0.04 [°C], which is 80%.

By adding the compensator for T_{oa} to the model of zone 3, we could notice a big improvement for the stability of zone temperature T_Z, where the value of dz is decreased 80%. At the same time, the energy consumption also slightly reduced, by 13 [kWh]. So zone model with compensator could slightly save energy and increase the thermal comfort for occupants.

5.2 Thermal villa model

The parameters of the underfloor radiant panel model, introduced in Chapter 3, need to be optimized in order to have a heating system which satisfies the energy comsumption levels of the room where it's installed. The parameters α and β depend on the floor characteristics and panel characteristics. By referring to the energy consumption Q_{tot} during January, when the outdoor temperature is lower and the energy demand for heating is higher, it is possible to size properly the underfloor heating system in order to make it capable to provide the thermal power needed by the room. So, for each room, the values of the parameter of the heating system where chosen according to this criterion.

5.2.1 One PID controller for each heated zone

When we adopt the control strategy 'one PID controller for each heated zone', each zone, except for the garage, has a classical PID controller to control its temperature.

This scheme makes it possible to choose different setup value for each zone but this scheme will increase the initial expenditure as more PID controllers are needed.

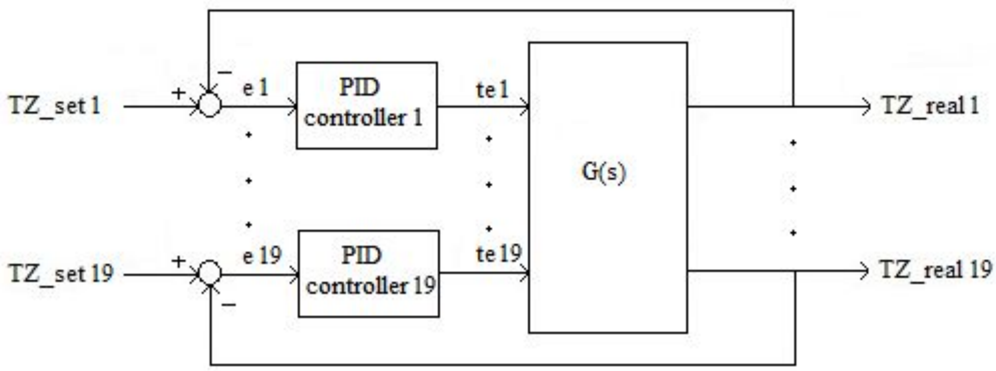

Figure 5.11 One PID controller for each heated zone

From scheme above, G(s) is the transfer functions matrice of the villa model.

Simulation conditions:

- The zone temperatures set point T_Z_set i=20 [°C], i= 1, 2, 3...19;
- The initial conditions of the state variables of all zones are: T_Z= T_W= T_P= 20 [°C];
- The simulation time is winter period from 15th October to 15th April, which is 182 days.

To show the results obtained in the simulations, we select one heated zone from each floor as a example to see the behaviours, zone 6- Bedroom and zone 16- Storage area.

The simulation results of zone 6- bedroom:

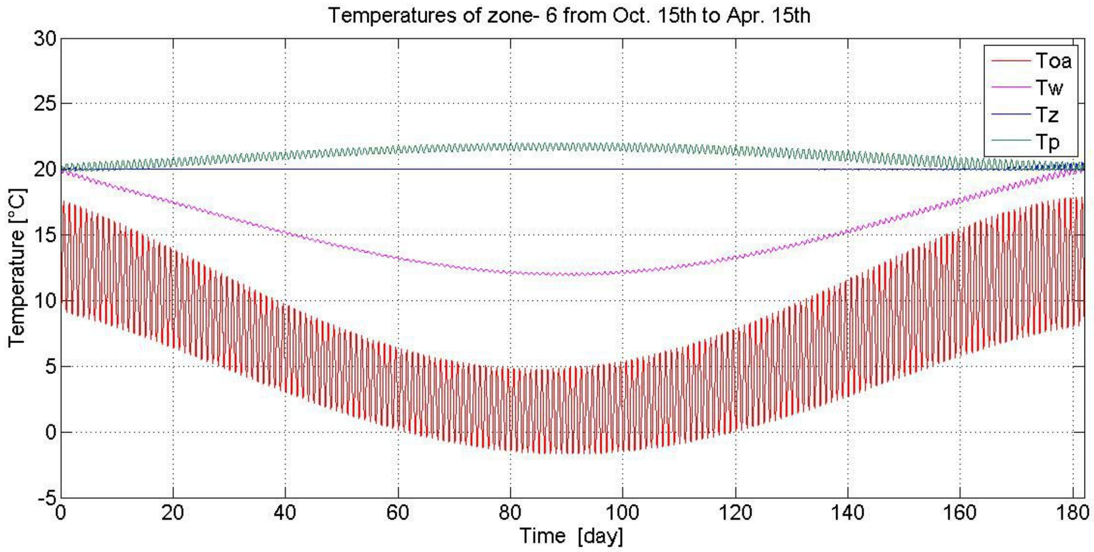

Figure 5.12 One PID for each heated zone- zone 6

Zoom in, shown the results from Jan. 1st to Jan. 2nd.

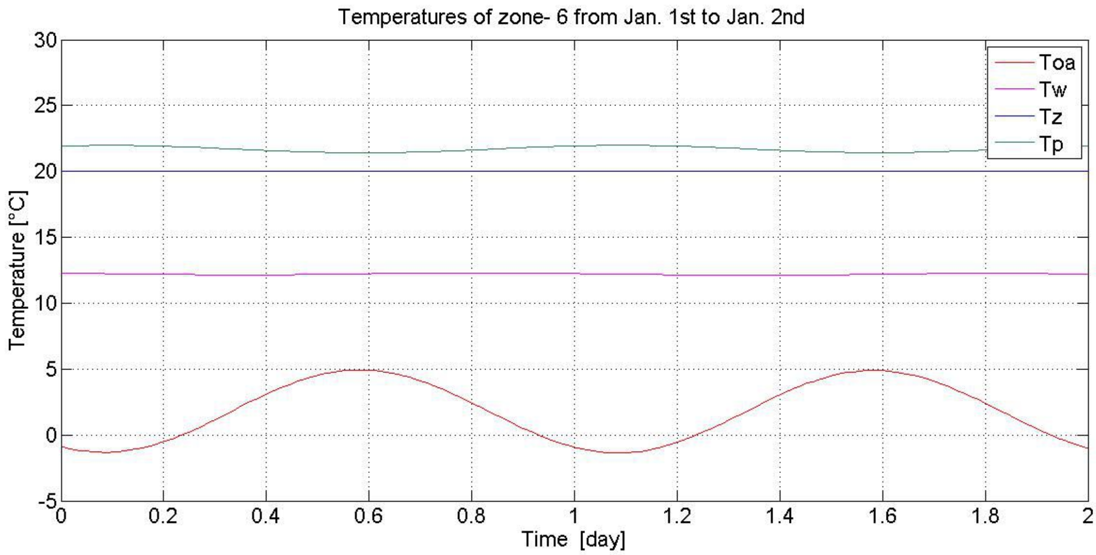

Figure 5.13 Simulation results of zone-6 in Jan 1st and Jan 2nd

The amplitude variation of temperature T_Z from Jan. 1st to Jan. 2nd.

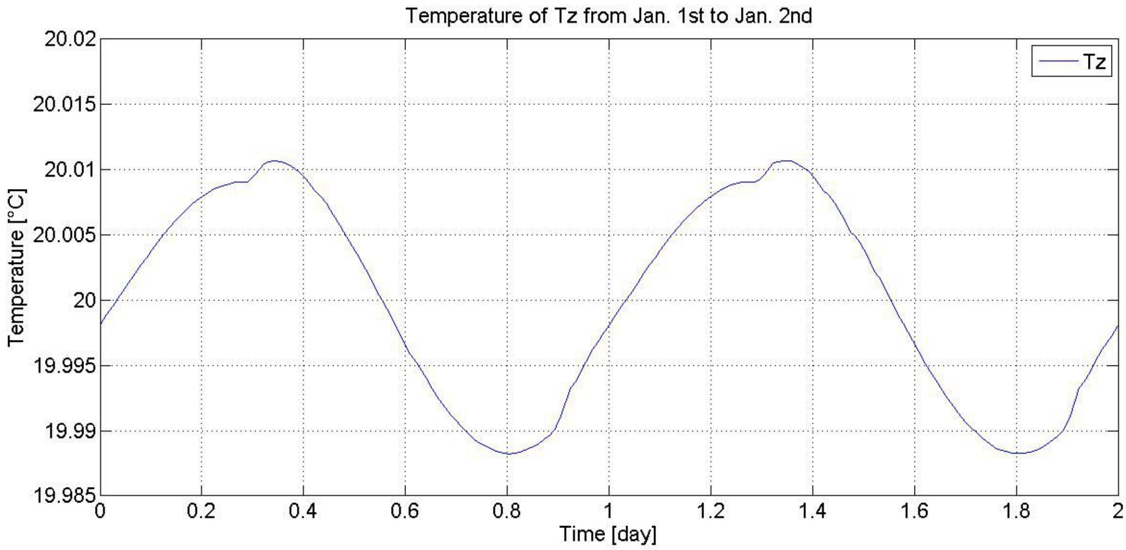

Figure 5.14 T_Z of zone-6 in Jan 1st and Jan 2nd

The simulation results of zone 16- store room:

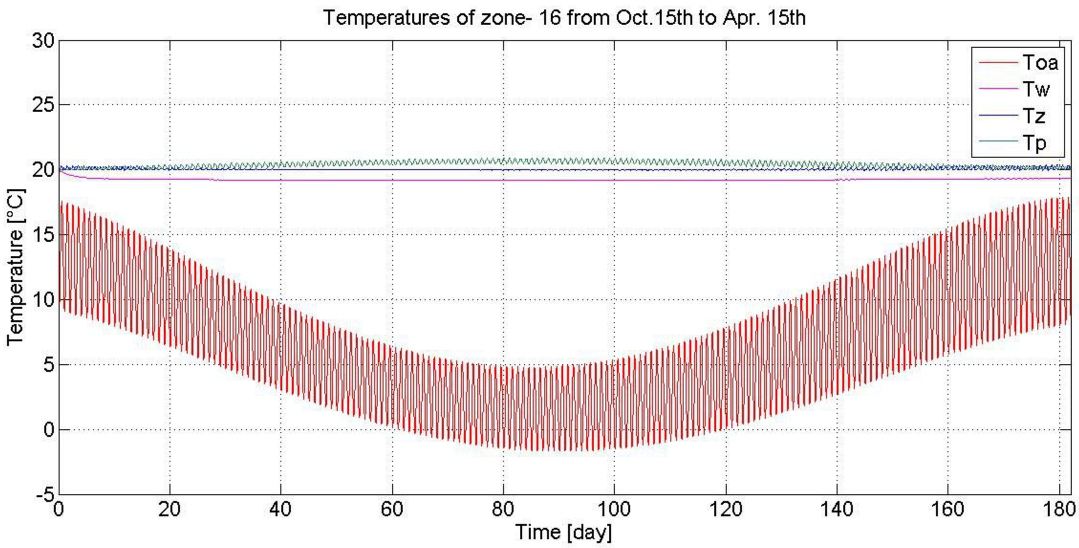

Figure 5.15 One PID for each heated zone- zone 16

Zoom in, shown the results from Jan. 1st to Jan. 2nd.

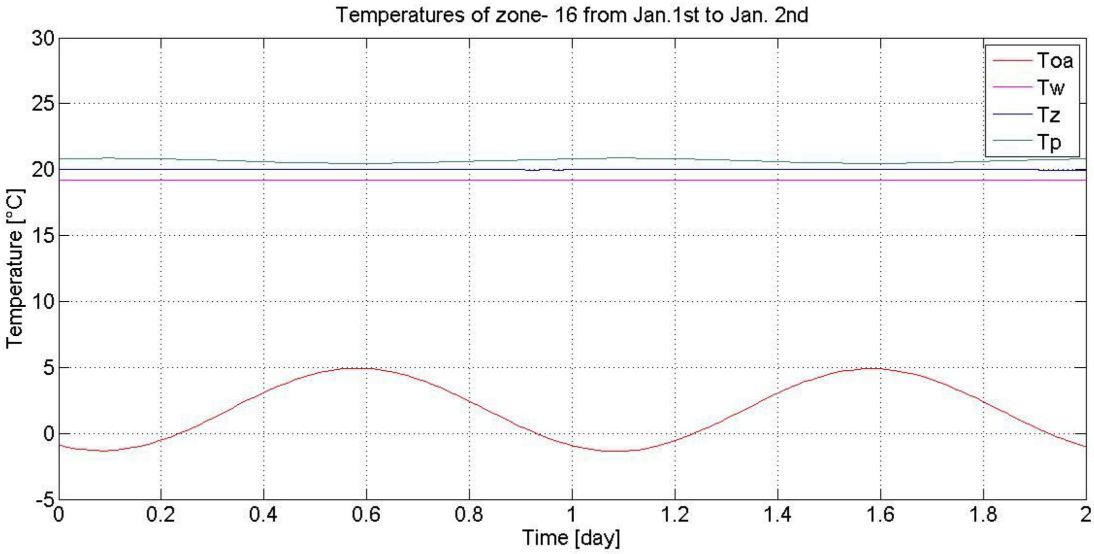

Figure 5.16 Simulation results of zone- 16 in Jan 1st and 2nd

The amplitude variation of temperature T_Z from Jan. 1st to Jan. 2nd.

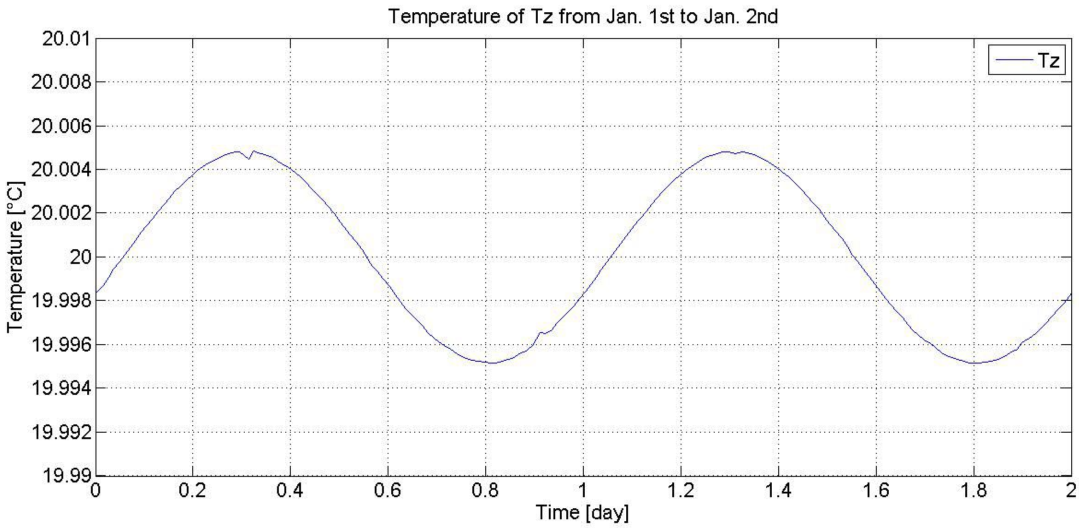

Figure 5.17 T_Z of zone- 16 in Jan 1st and 2nd

The total energy consumption of villa from Oct. 15th to Apr. 15th could be see from below,

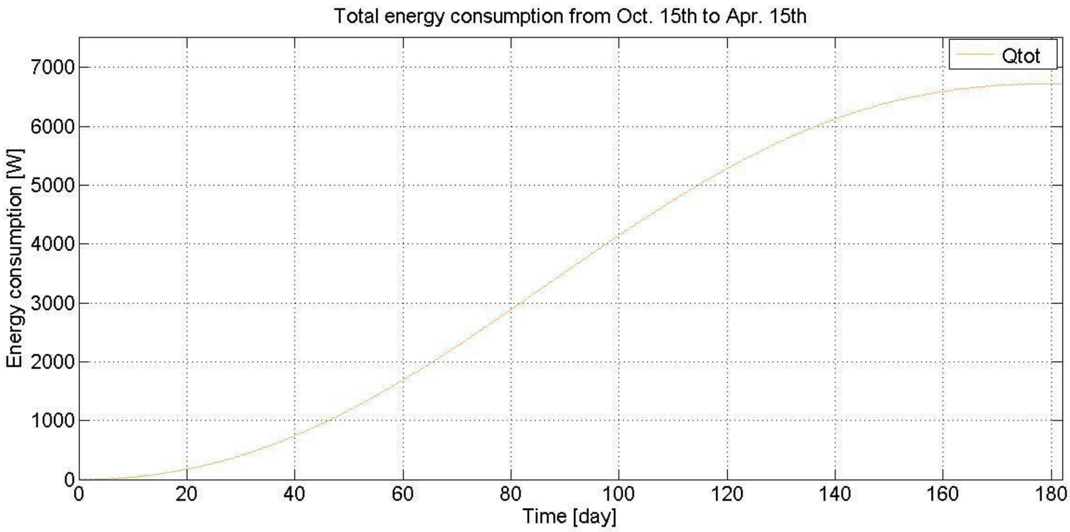

Figure 5.18 Total energy consumption of villa

In conclusion:

- The total energy consumption for the villa Q_{tot}= 6720 [kWh];
- The amplitude variation of T_Z of zone- 6 dz= 0.012 [°C];
- The amplitude variation of T_Z of zone- 16 dz= 0.005 [°C];

We could find that with one PID controller for each heated zone, the T_Z stay at the value of set point 20 [°C] with tiny variation dz. So the villa model was well controlled, which benefit much for human comforts. In another hand, the total energy consumption Q_{tot} is a big value, as the effect by feedback control for each heated zone will use more energy.

5.2.2 A single PID controller for the villa by using weighted average zone temperature

This control strategy will lead to significant savings on devices in respect to the previous scheme. Only one PID controller is used to control each zone's temperature.

The PID controller will use the weighted average zone temperature as the feedback signal for control each T_Z.

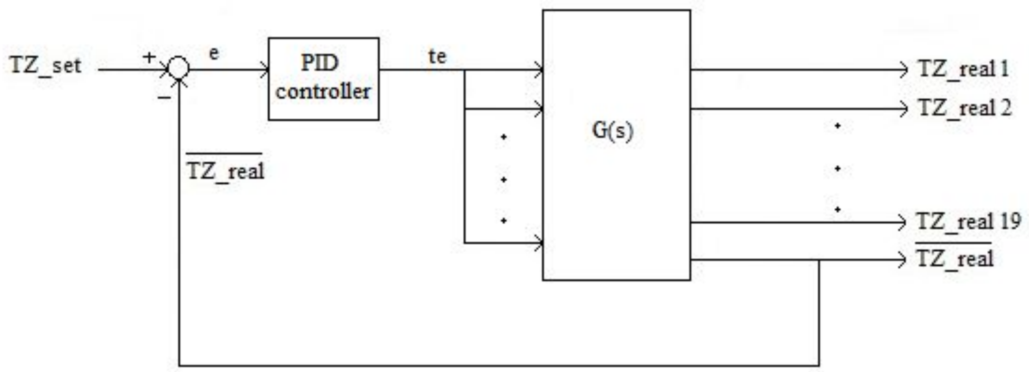

Figure 5.19 Single PID + weighted average T_Z scheme

The simulation conditions were setted up the same as chapter 5.2.1 and for the reason to make a comparison between different control strategies, we took zone- 6 and zone- 16 as two examples, as well as the average value of T_Z.

The simulation results of zone- 6 from 15th Oct to 15th Apr:

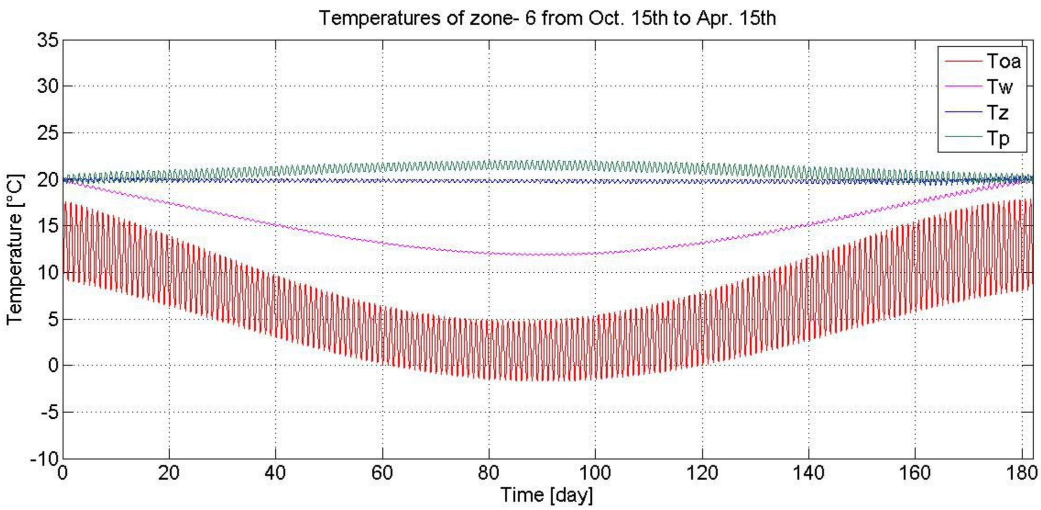

Figure 5.20 Single PID + weighted average T_Z- zone 6

Zoom in, shown the results from Jan. 1st to Jan. 2nd.

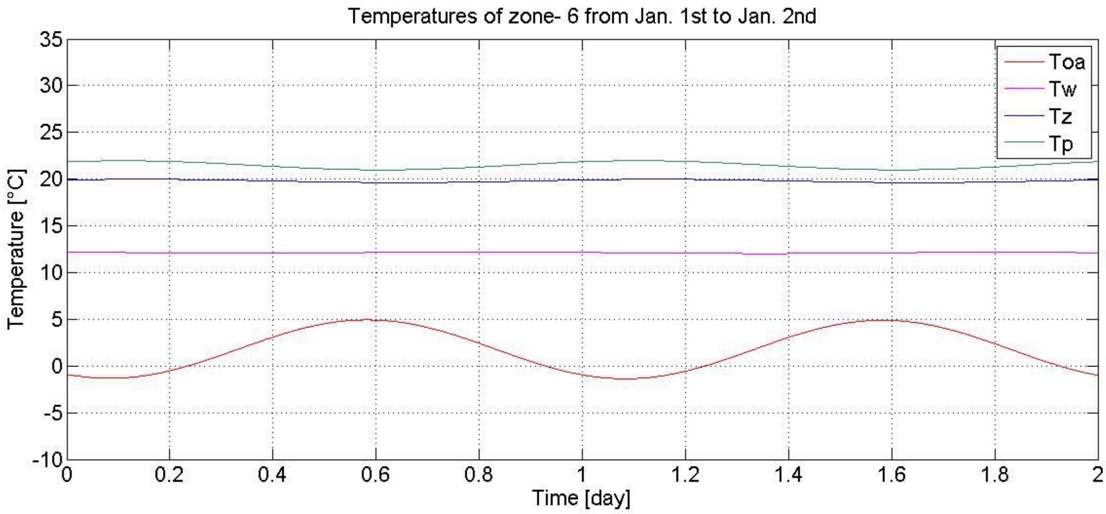

Figure 5.21 Single PID + weighted average T_Z- zone 6 in Jan. 1^{st} and 2^{nd}

The amplitude variation of temperature T_Z from Jan. 1^{st} to Jan. 2^{nd}.

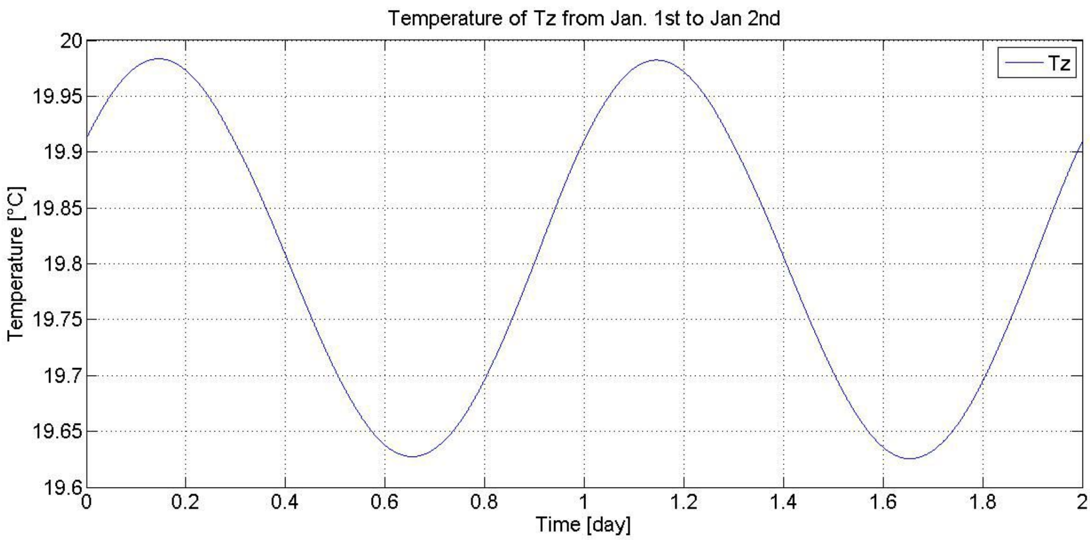

Figure 5.22 T_Z of zone- 6 in Jan 1^{st} and 2^{nd}

The simulation results of zone- 16 from 15^{th} Oct to 15^{th} Apr:

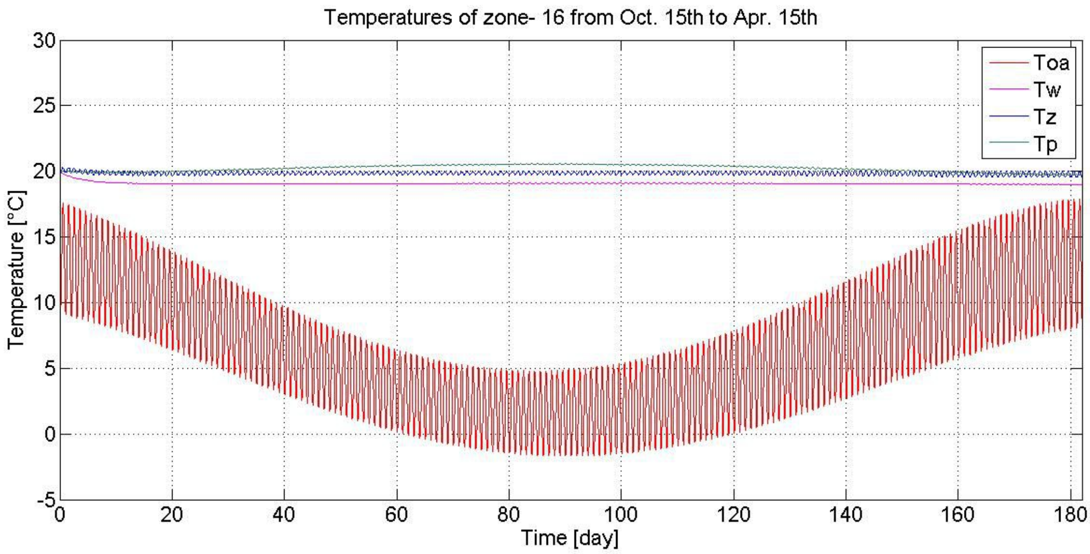

Figure 5.23 Single PID + weighted average T_Z- zone 16

Zoom in, shown the results from Jan. 1st to Jan. 2nd .

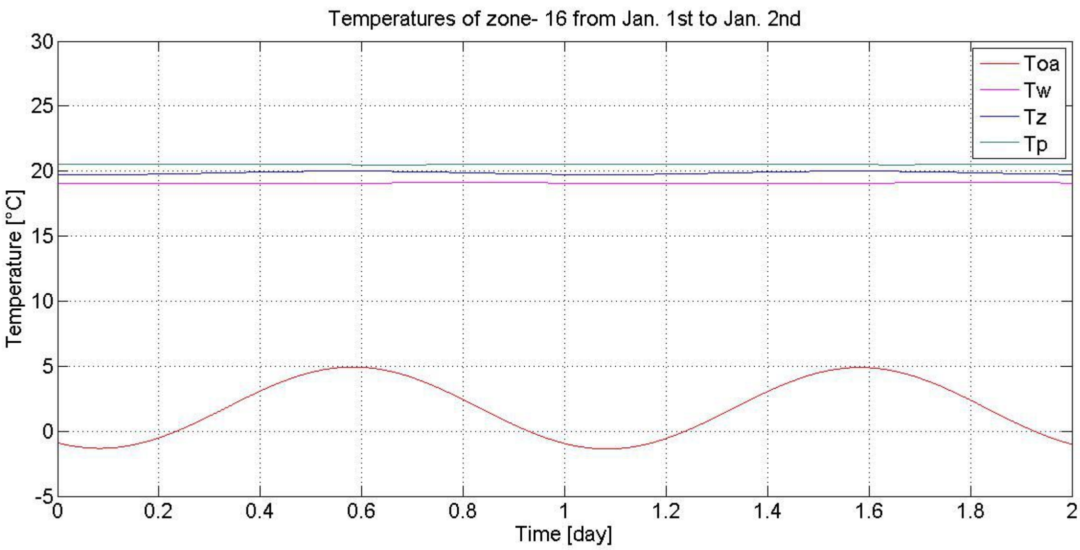

Figure 5.24 Single PID + weighted average T_Z- zone 16 in Jan. 1st and 2nd

The amplitude variation of temperature T_Z from Jan. 1st to Jan. 2nd.

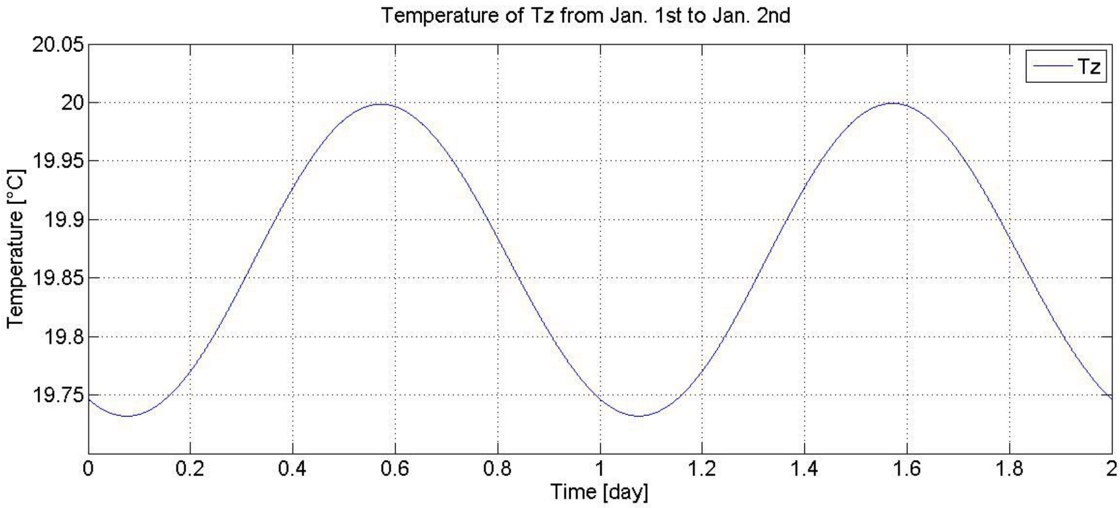

Figure 5.25 T_Z of zone- 16 in Jan 1st and 2nd

The weighted average temperature shown below,

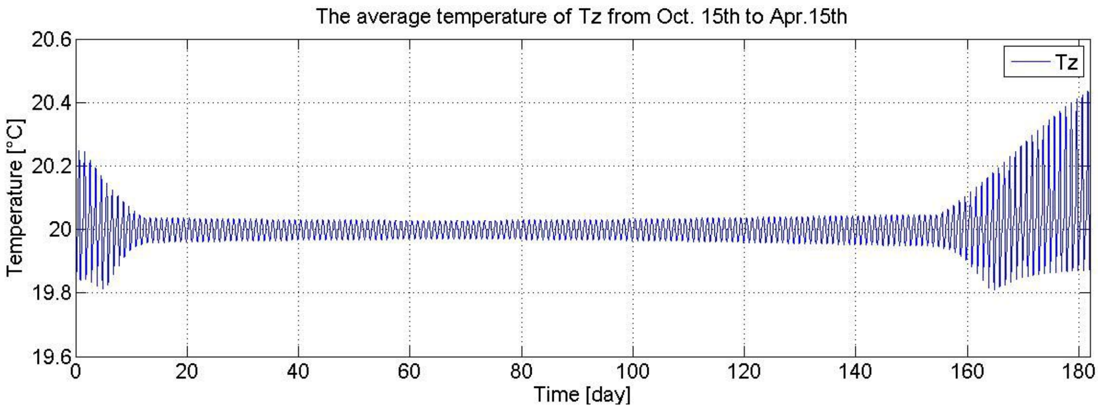

Figure 5.26 The average T_Z of villa

The amplitude variation of the weighted average temperature T_Z from Jan. 1st to Jan. 2nd.

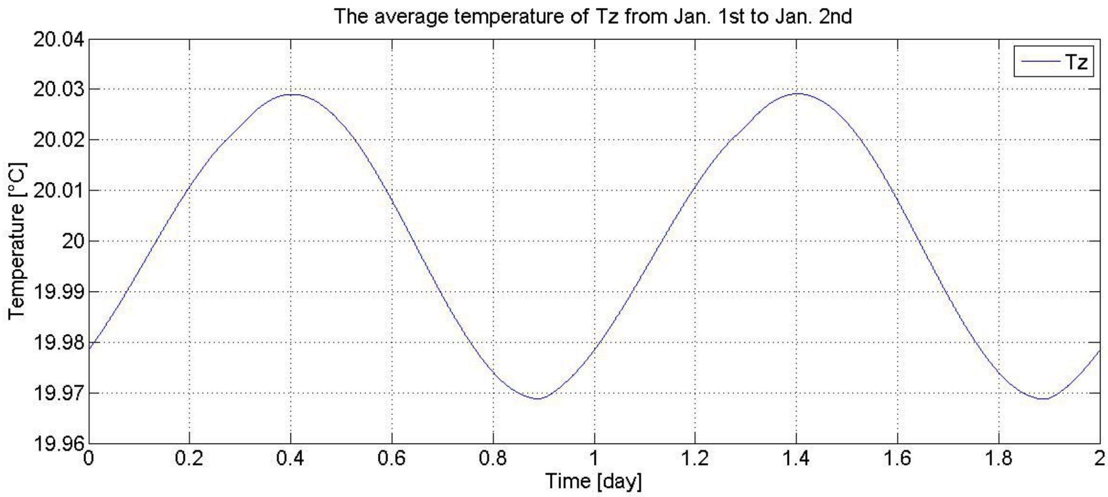

Figure 5.27 The average T_Z of villa in Jan 1st and 2nd

The total energy consumption of villa from Oct. 15th to Apr. 15th could be see from below,

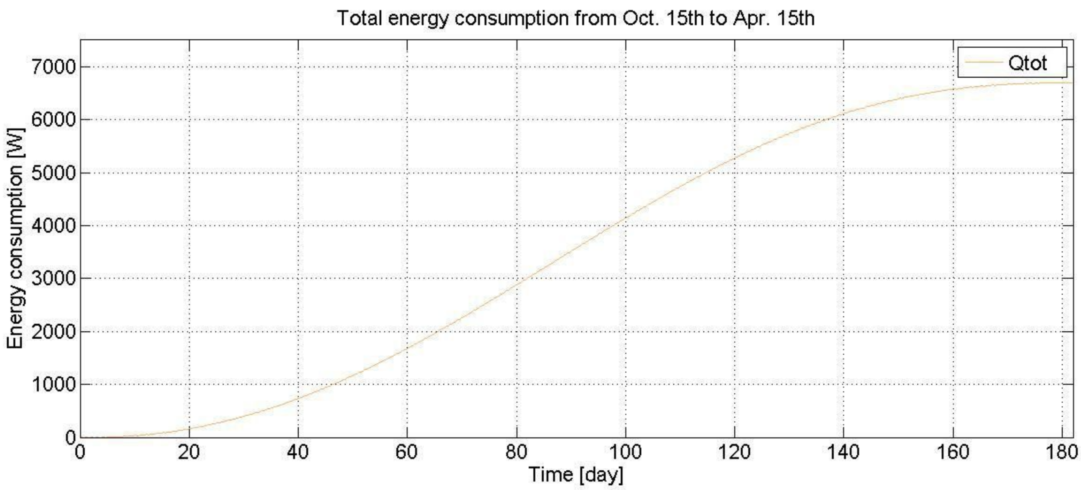

Figure 5.28 Total energy consumption of villa with single PID

In conclusion:

- The total energy consumption for the villa Q_{tot}= 6690 [kWh];
- The amplitude variation of T_Z of zone- 6 dz= 0.37 [°C];
- The amplitude variation of T_Z of zone- 16 dz= 0.27 [°C];
- The amplitude variation of the weighted average T_Z of the villa dz= 0.031 [°C];

In this controll strategy, we have one PID controller and the controlled variable is the weighted average temperature of zone. The result of average T_Z is very good, which stay at 20 [°C] with a small variation. When evaluate from zone to zone, the T_Z stay slightly below or over the set point due to the fact than the inlet temperature of the panels it's the same for every room and therefore it is not possible to obtain the same results as in the case of a single PID for each room .

For the Q_{tot} of the villa which reduced 30 [kWh] by comparing with the result from last chapter.

5.2.3 A single PID controller + compensator controlled with weighted average zone temperature

As for the case of a single zone, we ccanb develop a compensator to minimize the effect from T_{oa} to the weight average T_Z, which was introduced on chapter "5.1.2 Single PID controller with compensator". the scheme presented as:

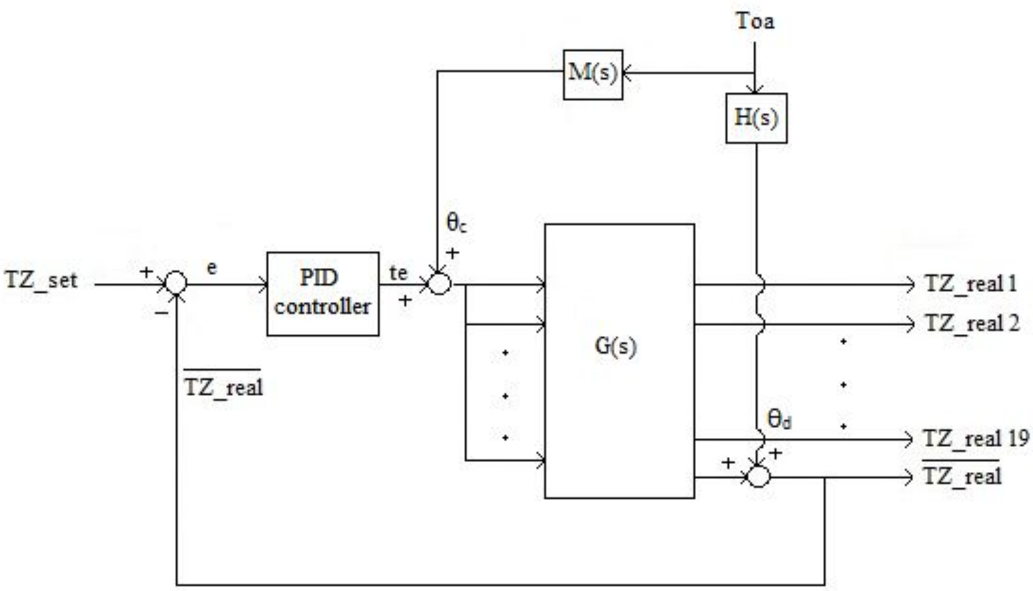

Figure 5.29 Single PID + weighted average T_Z + compensator scheme

The simulation conditions were setted up as chapter 5.2.1 and for the reason to make a comparison between different control strategies, we took the average value of T_Z for evaluation.

The weighted average temperature shown below,

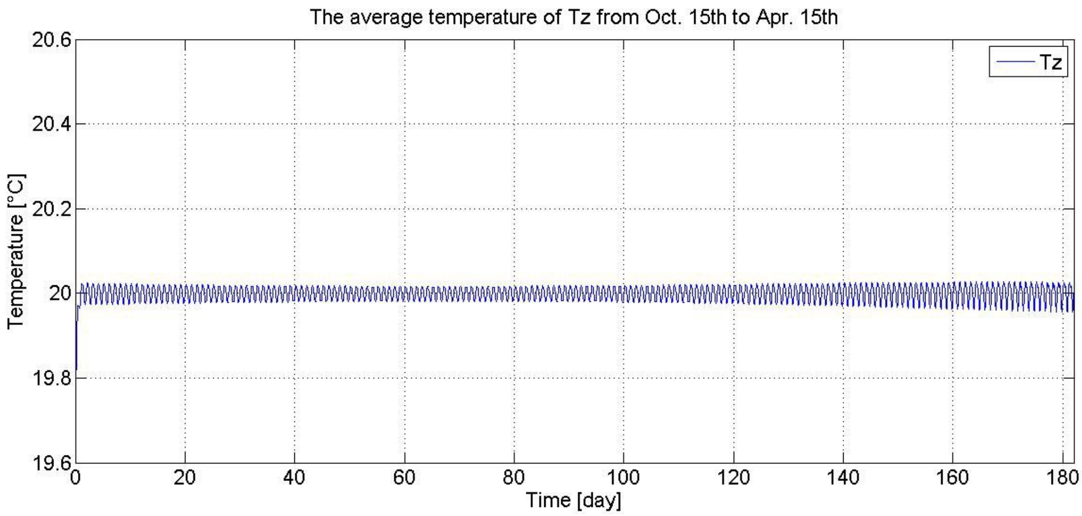

Figure 5.30 The average T_Z of villa with compensator

Zoom in, choose the data from Jan 1st to Jan 2nd

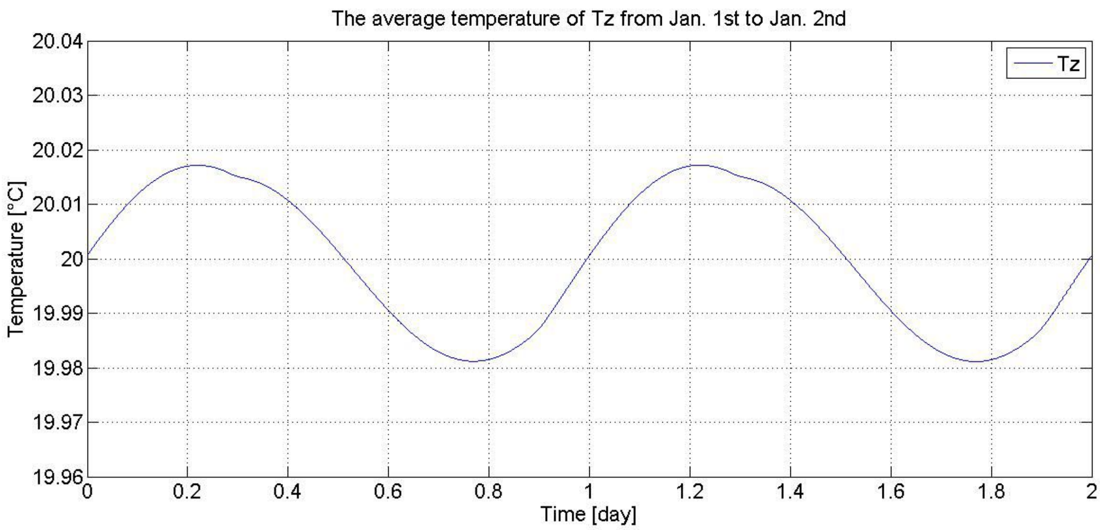

Figure 5.31 The average T_Z of villa with compensator in Jan 1st and 2nd

The total energy consumption of villa from Oct. 15th to Apr. 15th could be see from below,

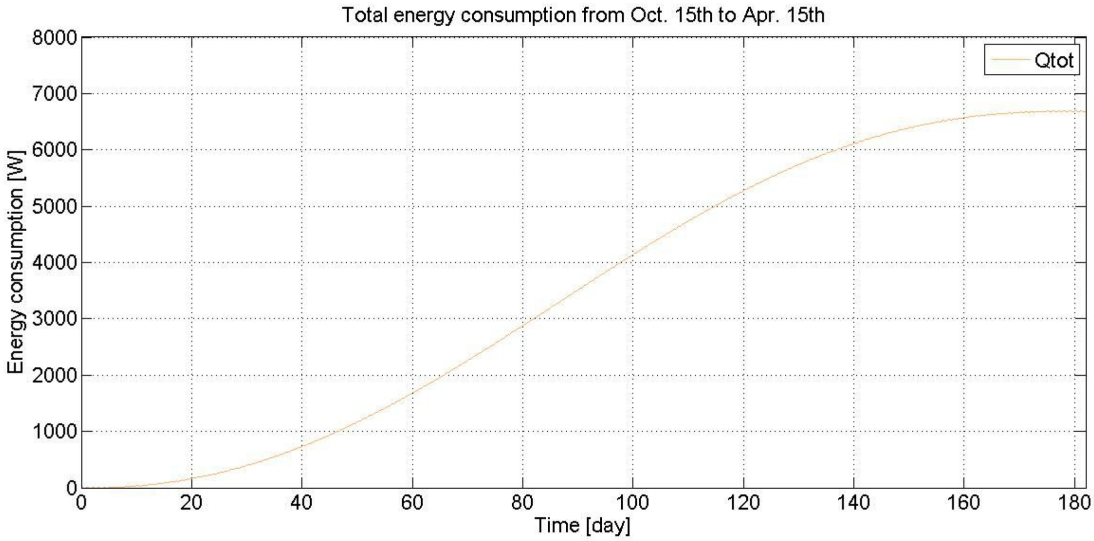

Figure 5.32 Total energy consumption of villa with compensator

In conclusion:

- The total energy consumption for the villa Q_{tot}= 6685 [kWh];
- The amplitude variation of the weighted average T_Z of the villa dz= 0.018 [°C].

Thanks to the compensator of T_{oa}'s exist, make the average temperature variation decreased 0.013 [°C], which is 42% less. The total energy consumption Qtot has a slightly decrease with 5 [kWh].

6 Conclusion

In this thesis, we have studied a single zone thermal model with external and internal variables that influence the energy balance of the thermal zone. Namely, outside temperature, solar radiation, ground temperature and internal gains. Then we studied two components bringing in energy into our zone model.

One is the AHU (Air Handling Unit), which helps in circulating air.

Another one is the underfloor radiant heating panels, which provide heat to our zone during winter period.

We also developed a model for a villa based on the single zone model. To validate the energy consumptions computed by these models and, therefore, the models themselves, the results of the simulations were compared to the data from Edilclima.

Finally, we used different control strategies applied to our single zone model and to the villa model to achieve a increase in human comfort, by creating a steady zone temperature, and to improve energy efficiency.

In the future, we could apply other different control strategies (such as: Model predictive control) on the villa model in order to have a better performance.

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Appendix

[1] Physical parameters of villa model: transmittance, capacity and resistence for all different type of walls, pavements and windows (doors).

WALLS											
DESCRIPTION	WIDTH [mm]	TRANSMITTANCE [W/m2K]	SUPERFICIAL MASS [kg/m2]	CAPACITY[kJ/m2K]	Ri [m2K/W]	Rw [m2K/W]	Re [m2K/W]	alpha			
Perimeter walls	410	0.265	321.5	318.88	0.13	3.6	0.04(0.13 if to other zone)	0.6			
CEILING											
DESCRIPTION	WIDTH [mm]	TRANSMITTANCE [W/m2K]	SUPERFICIAL MASS [kg/m2]	CAPACITY [kJ/m2K]	Ri [m2K/W]	Rw	Re	alpha			
First Floor Cieling	356	0.22	254.9	220.96	0.1	4.34	0.1	0.6			
WINDOWS/DOORS											
DESCRIPTION	LENGTH [mm]	HEIGHT [mm]	TRANSMITTANCE [W/m2K]	Ri [m2K/W]	Rw [m2K/W]	Re [m2K/W]	Fsm	ggl	FF		
Window 100/160	100	160	1.808	0.13	0.38	0.04	0.67	0.85	0.7		
Window 130/160	130	160	1.718	0.13	0.412	0.04	0.67	0.85	0.74		

Window 100/250	100	250	1.755	0.13	0.399	0.04	0.67	0.85	0.74		
Window 60/250	60	250	1.753	0.13	0.4	0.04	0.67	0.85	0.61	CAPACITY[kJ/m2K]	SUPERFICIAL MASS [kg/m2]
First Floor Door	110	250	0.369	0.13	1.11	0.04				11.3	11.6
Garage Door	258	258	2.587	0.13	1.11	0.04				11.3	11.6
FLOORS											
DESCRIPTION	WIDTH [mm]	TRANSMITTANCE [W/m2K]	SUPERFICIAL MASS [kg/m2]	CAPACITY [kJ/m2K]	Ri [m2K/W]	Rw [m2K/W]	Re [m2K/W]				
First floor	245	0.307	224.5	89.98	0.06	0.804	0.04				
Garage	875	0.307	624	617	0.06	3.59	0.04				
Basement	945	0.263	714.5	545	0.06	3.59	0.04				
DESCRIPTION											
Fsm	windows solar protection shading factor [#]										
ggl	windows solar factor [#]										
FF	windows frame factor [#]										
alpha	solar radiation coefficent [#]										