CONCLUSIONS

The establishment of a complete building dynamic model connected to heating or cooling system is a challenging problem requiring a lot of parameters related to outdoor environment, outdoor and indoor building walls, wall location, thermal bridges, air apertures, air movement, convection heat exchanges, occupant behavior and equipment components.

This work aimed to build a *building lumped model*, on a set of resistances and capacities, and to validate it. A second purpose was to generate a *building ventilation model*, built on a set of resistances and generators. The connection of the building model to so called equipments *daughter models* [11] can then provide a reliable estimation of the system ability to maintain indoor comfort as well as to assess primary energy consumptions, carbon dioxide emissions and energy costs.

10.1 Building lumped model

Lumped models were applied in several fields, namely building simulation and HVAC equipment control.

A simple zone model, developed by Laret [18], is obtained by connecting the wall models to a global temperature indoor node, gathering radiation and convection heat exchanges. It includes two branches. A first purely resistive branch accounts for ventilation exchanges and no mass walls behaviour. The second branch is provided with a capacity representing outdoor massive wall behaviour. A second capacity is added to the zone indoor node gathering the weighted indoor air mass and the indoor walls mass effect.

10.1.1 Methodology

Two modifications can be first brought to Laret building zone lumped model, in order to get a more realistic model:

- A specific branch can be added to account for internal massive walls, the indoor node capacity representing then only the weighted indoor air mass.
- The ventilation heat exchanges can be dealt with separately (see §10.2), so that Laret's model purely resistive branch can only represent no mass wall behaviour.

A methodology can then be proposed to adjust the wall model parameters and to generate a building zone simplified model.

The model can be validated by comparing its results to those provided by a detailed dynamic model, built on wall *response factors* [24], [25], on a set of houses and on an office room. Error indicators can be built for that purpose and provided with a reliability threshold.

The model can then be improved by adding a specific branch related to roof and connected to an *outdoor equivalent temperature* accounting for solar radiation and infrared sky radiation.

Solar factors can be generated for a specific earth location so that windows solar gains are processed through the concept of *equivalent solar area*.

10.1.2 Model Parameters Adjustment

Wall parameters can be tuned through a *frequency characteristic analysis* for a 24h time period sinusoidal solicitation, according to their boundary conditions.

Internal walls can be first shared in two parts by a null heat flow plane by equalizing the dampening factors of two sinusoidal temperature solicitations acting separately on each wall side. They can be modeled through *3R2C networks*. The wall model tuning can equalize magnitude and angle of the wall 24 h adiabatic admittance.

External walls can be modeled through *2R1C networks*, quicker to compute than 3R2C networks, but less reliable at high frequencies. 2R1C networks can be chosen anyway because they are characterized through two parameters instead of four. The wall model tuning can equalize magnitudes of the wall 24 h isothermal admittance and transmittance. The zone model reliability can be improved further (see §10.1.5) by sharing the external walls in several categories according to their specific boundary conditions, before gathering them in separate zone model 2R1C branches (one branch for each category).

Partition walls can be modeled roughly through *2R1C networks*, the capacities being equal to the whole wall capacity and located at the level of the wall null heat flow plane, defined as for internal walls.

10.1.3 Model Analytical Validation

A validation can be carried out on a set of houses and on an office room. It can first be performed for a *one zone* building model including external and internal walls, and neglecting solar radiation and sky radiation associated to opaque walls. It can then be enlarged to *two zones* model including partition walls. It can finally include solar radiation and sky radiation associated to opaque walls.

A reference model can be built on wall *response factors*. Response factors are computed through finite element method with degree 2 elements, for a triangular temperature impulse. The convolution process is performed with a *1200 s* time step, over a whole year for Belgium reference weather data.

The reference model computation can yield a reference heat flow profile and an associated *reference indoor temperature profile*. Reference heat flows can be used as input data for the simplified model that can generate an indoor temperature profile which can be compared to the reference indoor temperature profile.

Three error indicators can be used to perform the comparison: a maximum related to the daily mean temperature discrepancy, a maximum related to the difference of daily temperature amplitudes around the mean, and a Root Mean Square of the indoor temperature differences. The three indicators showed values lower than *1 K* during most of the year suggesting that the simplified model can be considered as reliable.

Moreover, wall models can be built on non dimensional *default parameters* without significantly increasing the discrepancies. This implies a much easier way to introduce wall data for the user, who can by-pass the tedious detailed description of building wall layers.

10.1.4 Model Experimental Validation

A short test was realized on the experimental results provided by EMPA cell in the framework of IEA-ECBCS annex 43 research project. The use of a test cell whose thermal characteristics were well known and for which disturbances caused by the occupants as well as solar and sky radiations were not present, allowed favourable conditions for the model validation.

The good quality of the results provided by the model can be underlined, as the EMPA test cell is submitted to rather unrealistic step sollicitations, while the simplified model is built on wall responses to sinusoidal sollicitations for a 24h time period.

10.1.5 Model Improvements

The model behavior can be improved by introducing a specific branch modeling the roof, and by connecting it to an outdoor equivalent temperature node, modeling the solar radiation and the sky radiation effects. Solar radiation and sky radiation effects can be neglected on vertical walls in the lumped model, while the reference model accounts for those radiation effects on all the external walls.

The comparison can be performed for a traditional concrete wall house and for a wooden wall house. The daily mean temperature difference can be slightly higher then *1K* for a massive wooden walls house, protected by an insulation layer and a brick. Those vertical walls are lighter than traditional concrete ones and can be more sensible to absorbed solar gains, which are neglected in the simplified model. Other error indicators are lower than *1K*. So the building lumped model is shown to be sufficiently accurate.

10.2 Building ventilation model

Building ventilation models are of rising interest as an increasing insulation level is observed in new buildings, consequently reducing the building transmission heat exchanges and raising the proportion of ventilation heat exchanges in the building whole heat balance.

10.2.1 Model description

The building ventilation model can be built on a set of resistances and generators, respectively handling *pressure drops* through orifices and ducts, and *wind driving forces* due to natural wind and stack effects, or due to static and dynamic pressures provided by mechanical fans.

Pressure drop is related to *mass air flow* through a *K* coefficient and an *n* exponent, in a way that allow both quantities to be positive or negative, leaving the model one degree of freedom as far as the direction of air movement is concerned. A mass air flow balance is performed on each model node and the pressure balance is performed by summing up pressure drops in each model loop.

Such a model can handle *natural air movement* through infiltration cracks as well as through controlled natural ventilation devices. It can account for air flows through opened windows, including window stack effect. The model can also be associated with *mechanical air supply and return devices models*: fans, air ducts and exhaust chimneys.

The ventilation model can be adapted to the building under study. A house ventilation model can be provided with two indoor nodes to handle indoor stack effect, and with four outdoor nodes to deal with wind pressurized and depressurized facades. As wind orientation changes, the ventilation model pressurized and depressurized resistances can vary with time during the simulation process.

An office building ventilation model can be provided with a specific corridor node, which can be connected to an air exhaust chimney or to a ventilation shaft. Each office room is provided with an indoor node which is connected to the outdoor, to the corridor and to the HVAC air supply and air return ducts.

10.2.2 Model applications

The building ventilation model can provide an estimation of the *indoor air quality level*, of summer thermal comfort when *free-cooling* is performed, and of the building *energy balance*.

The indoor air quality level can be approached through the indoor CO_2 concentration evolution yield by a complete room air CO_2 balance, provided the main CO_2 contaminants are identified with their corresponding CO_2 production. A perfect mixing hypothesis can be assumed. Simulations performed on an office building zone allowed the estimation of energy saving potentials associated to heat recovery exchangers and to CO_2 probes which could be used to drive ventilation fans.

The summer thermal comfort evaluation can be based on Fanger's Predicted Percentage of Dissatisfied people. Simulations can be performed in *mean summer conditions*, on a traditional house and on an office building. They showed that thermal comfort can be easily reached through controlled external blinds and window free cooling, provided the occupants clothing insulation level is adapted to the weather.

For *hot wave conditions*, external blinds and window opening should be associated with a strong stack effect free-cooling strategy: either a natural stack effect free-cooling i.e. requiring internal doors opening as well as a large staircase surmounted by a turret with opened louvers, or a natural and mechanical stack effect free-cooling i.e. requiring internal doors opening combined with high airflow roof exhaust fans. Anyway, air conditioning seems to be necessary to fulfill comfort requirements in summer hot wave conditions.

10.3 Connection with heating and cooling equipments

The building model can be connected to equipments including heating and cooling terminal units as well as water pipes, air ducts, heating and cooling plants. The connection between the building model and its system, through control laws, can provide an estimation of the system ability to maintain indoor comfort all over the year, as well as to assess its primary energy consumptions, carbon dioxide emissions and energy costs.

For example, the effect of different control strategies related to a *heating floor* system, connected to a brine-water heat pump with a ground heat exchanger, can be evaluated, allowing us to answer the following question: is it worth performing a night set back with such a massive heating system? Simulations can show that the more interesting control strategy in terms of cost management is to maintain a constant indoor temperature set-point the whole day long.

10.4 The use of a solver

All the models used in this thesis, including response factor reference models, were developed through EES Engineering Equation Solver (Klein, ref [42]).

EES solver is very powerful to solve differential equations, thus well adapted to develop building lumped models.

The use of a solver is convenient to develop building ventilation models because it allows equations not to be written in an explicit form.

Models written with a solver are flexible, allowing variables to move easily from input to output status and vice versa. That property enables the same model to be used either for simulation purposes or for parameters tuning on measured data. At the beginning of this thesis work, that flexibility allowed us to tune the parameters of a lumped building model on EMPA test cell experimental data (§ 10.1.4) in order to verify the relevance of lumped models.

Last but not least, models written with a solver are transparent and easily readable by people not accustomed to programming languages. They are far from so called black-box models.

10.5 Limitations and perspectives

The validation study did not consider the category of passive solar buildings with highly insulated walls (20 cm insulation thickness) though wall parameters default values have been obtained for that kind of walls.

Double skin facades were not considered in our study, but could be assessed through ventilation models similar to those developed in our work, i.e. built on resistances and generators.

Very tight buildings may cause numerical problems when analyzed through the ventilation model, due to the very small infiltration air flows encountered when pressure differences are becoming too small.

As far as latent heat balance is concerned, humidity transfers from indoor to outdoor through building walls should be approached with more accuracy.

The use of a global temperature indoor node, gathering radiation and convection heat exchanges, may not be relevant to analyse thermal comfort when large windows areas are present or when radiation heating or cooling systems are used (heating or cooling floors, heating or cooling ceilings). Anyway, the building lumped model can be easily adapted by introducing two separate indoor temperature nodes: an air temperature node dealing with convection heat exchanges and a radiation temperature node connected to wall surfaces and dealing with heat radiation exchanges.

Solar heat gains through windows are directly input on the indoor global temperature node. The model doesn't allow them to directly reach the indoor wall surfaces. For that reason, the application of our model to greenhouses may not be relevant. Detailed response factor models can be more adapted for the study of such specific spaces.

The purpose of our work was not to replace existing detailed building models, often based on walls response factors, but to simplify the building dynamic model as much as possible in order to open it to other fields of interests such as ventilation modeling, indoor air quality estimation, simulation of control strategies, connection with heating and cooling plants as well as with humidity control equipments.

In that sense, other fields of interest could be assessed by the modeling process, such as indoor air contamination through dust or bio-contaminants. The range of equipments could be enlarged to the infinite including Variable Refrigerant Systems, active solar system, photovoltaic panels, cooling floors and ceilings, cooling towers, free-chilling strategies, PI control systems, cogeneration systems, hot or cold water storage tanks, ice storage systems, vertical and horizontal ground exchangers …