BALANCING OPERATION FOR THE OPTIMISATION OF HYDRONIC NETWORKS

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ABSTRACT

Comfort and energy savings have become more and more a concern in modern buildings. Therefore, design and sizing is the first step towards a performant building. One of the elements in these buildings is the hydronic network for a heating or cooling system.

In a first time, this paper deals with the commissioning of the heating system. It details the important steps to carry out a good heating system by explaining the important steps of the hydronic balancing operation. A good hydronic balancing needs to be taken into account at the beginning of the process of building elaboration and has to be carried out to the end of the cycle life of the building.

In the second part, this paper deals with the study of hydronic networks in terms of design and component sizing. A methodology for an ease simulation of hydronic systems is implemented in the SIMBAD Building and HVAC Toolbox to study its performance and to suggest potential actions for their improvement. Investment costs are estimated for different design of distribution mode and for different components selecting size procedure.

Balancing operation leads to increase efficiency of the heating system by ensuring the thermal comfort in building zones. Several methods exist, energetic performance of the installation starts at the beginning of the process of building elaboration.

INTRODUCTION

Modern buildings are equipped with a rising number of sophisticated products. This potentially allows to operate the building in a performant way, but also requires attention on good design and commissioning of the building and its equipment in order to ensure good operation. This is especially true for buildings equipped with hydronic networks.

A performing hydronic heating system is judged on its global costs, composed of the investment costs, the operation costs and the maintenance costs for the envisaged life cycle of the building considered. The global costs are the only one parameter to take into account to define new methods improving the effectiveness of hydronic heating system.

A hydronic network represents a complex system that requires at the same time to correctly solve design, sizing and control-related questions: a design error in one part of the hydronic network, for example, affects at the same time the rest of the network. To deal with that problem, a large number of components such as balancing valves [8] & [9] and methods exist [7]. Moreover, to correct bad operation of unbalanced networks, (hydronic networks without balancing) building operators mostly increase head of pumps or/and hot water supply temperature to ensure comfort in all zones of the building. The results of these actions are:

- Increased energy consumption of pumps,
- Probably growth of primary energy to produce hot water,
- Overheating of hydraulically favoured zones,
- In some cases instability of control loops.

As a result, occupants will have to pay more to have the same comfort as they would do with a well designed hydronic network.

OBJECTIVE OF THE STUDY

The optimisation of the heating system contains three different steps as the Figure 1 shows:

- The design of the hot water system
- The operation of the heating system
- The heating system deterioration

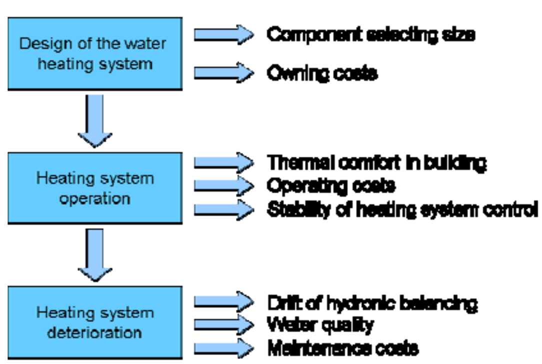

Figure 1 : Main objectives

Design of the water heating system step

The design of the hot water system leads to the selection of all components of the hydronic network. Investments costs can be estimated.

Inputs of this step are:

- The architecture of the hydronic network
- The equipments included in the hydronic network
- The component selecting size procedure
- The implementation or not of a hydronic balancing

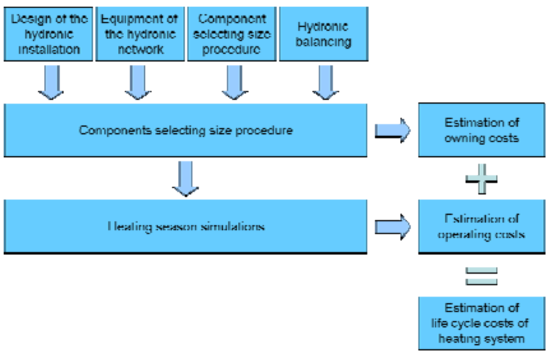

Figure 2 : Objectives of the conception step

Figure 2 shows the process of evaluation of the design step. Inputs are combined one with others to create several case of study. These cases are then simulated to evaluate the owning costs in a first case. Annual simulations allow the estimation of operating costs, composed of the boiler and pump consumptions. Global costs of the life cycle of the heating system could be estimated.

Heating system operation step

The operation in running conditions of the heating system allows the estimation of the thermal comfort in building zones, the operating costs and the evaluation of the stability of the control system.

Inputs of this step are:

- Weather data
- Actions of occupants (increase of set point temperature, opening of a window)
- Control strategy
- The implementation or not of a terminal control

Figure 3 shows the process of evaluation of the heating system operation. Inputs parameters are combined one with others to create several case of simulation to compare results themselves in order to highlight the more efficient solution depending on several criteria. These criteria are the thermal comfort in the building, the operating costs, the quality of control strategies and also the velocity of water.

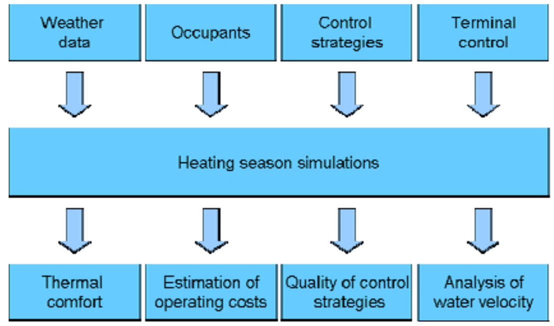

Figure 3 : Objectives of the operation step

Heating system deterioration step

The heating system deterioration step permits to evaluate the performance of the heating system according to the deterioration of the components and for degraded running conditions.

Inputs of this step are:

- Drift of hydronic balancing
- Actions of occupants (actions on the structure of the hydronic network)
- Control strategy (bad settings of controller)
- The implementation or not of a terminal control

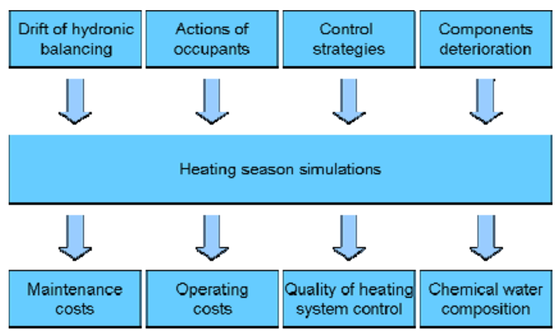

Figure 4 : Objectives of the fault detection step

Figure 4 shows the process of evaluation of the heating system deterioration step. Input parameters are combined one with others to evaluate their consequences on the efficiency of the heating system. Output criteria are the maintenance costs, the operating costs, the quality of control strategies and the chemical water composition (it has consequences on mud deposing and components deterioration).

The aim of this study is to show more particularly:

- the integration of the operation of hydronic balancing in the process of construction & exploitation of the building,
- the influence of the hydronic balancing of the heating system in accordance with the study of the thermal comfort and the auxiliary consumptions (pump, and boiler).

COMMISSIONING OF THE HYDRONIC BALANCING

Figure 5 shows the different steps of the process of the elaboration of a building, from its conception to its exploitation [3]. In every stage, several actors have a mission to accomplish perfectly the elaboration of the building.

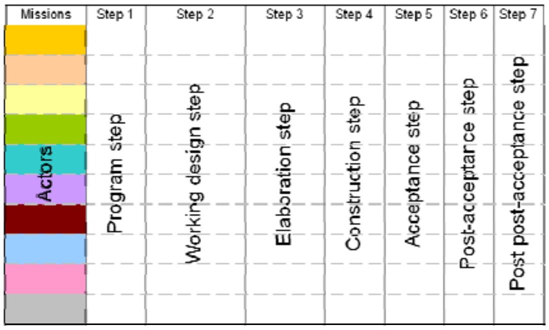

Figure 5 : Schedule of the tasks and the actors

This schedule shows in details the seven different steps of the process of elaboration:

- **Program step :** Definition of needs and constraints
- **Working design step :** Selection of the concept for the building and its equipments
- **Elaboration step :** Design and size of the building and its equipments
- **Construction step :** Construction of the building and installation of its equipments
- **Acceptance step :** Check and tuning equipments in running conditions
- **Post-acceptance step :** Check the performance of equipments after one year of exploitation
- **Post post-acceptance step :** Check the performance of equipments after ten years of exploitation

Each step includes organisational tasks and technical tasks. Organizational tasks deal with the redaction of report due to the end of each step (report on the justification of the hypotheses of calculation, for example) or with the redaction of the protocol for commissioning tests (check of the heating system performance, for example).

By following the same reflection as for the process of elaboration of a building, a list of tasks to be executed for the operation of hydronic balancing can be defined.

Program step
At the program step, the owner has to be conscious of the advantages of the hydronic balancing. The list of relevant to be taken into account has to be defined concerning the performance of the heating system and also the hydronic balancing. This list shall be composed of the thermal comfort, the acoustic comfort and the maintenance costs.

Working design step
During the working step, several parameters have to be defined for the heating system:

- The set point temperature for buildings zones,
- The heat losses for building zones,
- The internal gains,
- The heating curve.

During this step, a balancing method has to be hold and the installation of balancing valves in the hydronic network has to be expected.

Elaboration step
Concerning the heating system, the list and the description of the main components has to be written (emitters, balancing valve, distribution components, circulation pulp, and hot water production) during the elaboration step.
On a technical side, the elaboration step consists, for hydronic balancing, in sizing of the balancing valves. Moreover, the calculation of the pre-settings position of balancing valves has to be made. On an organizational side, the location of each balancing valve has to be defined and to appear clearly on the drawings. Moreover, the balancing valves which are chosen must be equipped with pressure sensor in order to allow the measure of the pressure losses.

Construction step
The construction step concerns the installation of the heating system and also the balancing valves in the building. The hydronic network has to be completed from the state of the art and the construction rules. Balancing valves have to be placed on the right place and the calculated pre-settings applied.

Acceptance step
To carry out the acceptance step, the checking of the settings to the operational nominal point of the heating system has to be made. Drawings have to correspond to the real installation otherwise they must be update.
The fitter of the heating system has to measure the supplied water mass flow at each balancing valve and adjust its setting by following the rules defined by the selected balancing method, to have the nominal mass flow rate. This operation is necessary to take into account the real pressure losses in the network and a possible change between the drawings and the reality.

Post-acceptance step
Performances of the heating system have to be check during the post-acceptance step, i.e. during the first year in running conditions. Thermal comfort, acoustic comfort and energetic performance have to be checked and compared to the design step estimation.

Post post-acceptance step
During the post post-acceptance step, after about ten years of operation, the fitter has to check the drift of hydronic balancing. Water mass flow rates in each balancing valve have to be measured and compared to initial values measured during the acceptance step.

All these steps and tasks must be supervised by a commissioner. His mission is to be sure that the work is made and well made.

THE SIMULATOR

Simulation model

The development of the simulator for the study of hydronic networks as well as the pre-processing for its sizing has been shown in a previous study [4]. It is developed under Matlab/Simulink environment with the SIMBAD Toolbox [10] developed by the CSTB, a French research centre, till ten years.

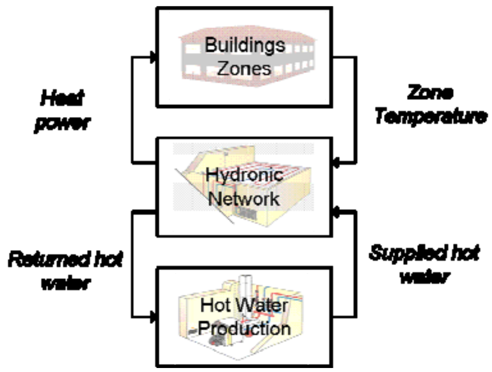

Figure 6 : Structure of the simulator

The simulator developed for this study is divided into three main parts:

- Block "Buildings Zones": it represents the model of the building simulated with the scenario for occupation, internal gains, and ventilation. The building description is made with the "SimBDI Interface" [2] and the used building model is a newly developed multizone model for Simbad [6].

- Block "Hydronic Network": this block includes the hydronic network of the described building, from the circulation pump to the emitters. The structure of this network is explained in [5].

- Block "Hot Water Production": it represents the hot water production (boiler or other system) and the primary distribution of the hydronic installation.

This structure allows, for other study, to modify easily the details and internal structure of each block, e.g. to modify the hydronic system without a need to change of the rest of the model.

Automatic sizing procedure

A sizing procedure including expert rules has also been implemented in a pre-processor of the simulator. The sizing steps are described hereunder.

The sizing operation of the hydronic network starts with the calculation of heat demand for each zone (no occupation, no internal gains, no solar gains, constant external reference temperature of -7°C, and constant set point temperature of 20°C).

The procedure for component selecting size and characteristics in specific data bases follows the steps shown on Figure 7:

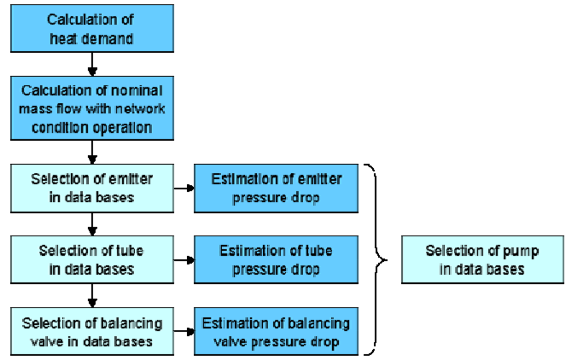

Figure 7 : Sizing procedure of hydronic network

These steps are:

A. Calculation of nominal mass flow rates for emitter with the network conditions for the planned operation of the building (water supply temperature, temperature drop in the emitters),
B. Selection of emitter in data bases depending on heat power (the nominal emitter power is therefore corrected to the temperature operating conditions in the building),
C. Selection of tube sizes and characteristics in data bases depending on section (the ideal section of the tubes are calculated considering flow rates and maximum/minimum water velocity),
D. Selection of balancing valves depending on kvs values (Equation 1).

$$Kv = 36 \frac{q}{\sqrt{\Delta p}} \qquad \text{Eq. 1}$$

E. Calculation of pressure drops at nominal operating point for the whole hydronic network composed of emitters, tubes and all balancing valves.
F. Selection of pump in data base depending on nominal mass flow and nominal head using data from pressure calculation.

To date, the data bases include not only physical characteristics of the components but also costs. This allows to estimate the owning costs. In a next step, average values for installation costs will be implemented in the procedure allowing an estimation of the overall owning costs of the complete hydronic network.

Estimation of consumptions

The first step to calculate the pump consumptions cost is the calculation of the immediate power of the pump for each step time of the simulation as shown by the Equation 2 [7].

$$P_c = \frac{9.81\ H\ q}{3600\ \eta_p\ \eta_m} \qquad \text{Eq. 2}$$

Then, the cost of electrical energy for the pump is obtained thanks to the Equation 3.

$$C_{cp} = \frac{P_c\ C_w}{1000}\ t \qquad \text{Eq. 3}$$

Boiler consumptions costs are estimated depending on the mass flow rate of gas consumed by the boiler as shown by the Equation 4.

$$Costs_{gaz} = \int \frac{q_{gaz}\ PCI_{gaz}\ C_{gaz}}{\rho_{gaz}}\ dt \qquad \text{Eq. 4}$$

Global cost calculation method

The present worth (PW) of an annual cost over a selected time period, using an interest of money and a cost escalation is called present worth escalation factor (PWEF) and is determined by the Equation 5 [1].

$$PWEF = \frac{\left(\frac{escalation}{interest\ rate}\right)^{amortization\ period} - 1}{1 - \left(\frac{interest\ rate}{escalation}\right)} \qquad \text{Eq. 5}$$

The present worth is then obtained by multiplying the annual cost by the PWEF as the Equation 6 shows.

$$PW = Cost_{Annual}\ x\ PWEF \qquad \text{Eq. 6}$$

BUILDING IMPLEMENTED

For this study, a small office building, two storey building has been simulated. The first floor has four zones (Figure 8), and the second one nine zones (Figure 9). The internal halls are included in the zones 10 and 11 for the first floor, and 12 and 13 for the second floor.

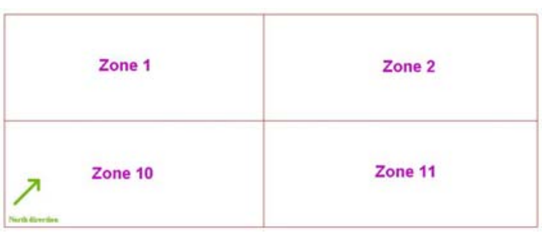

Figure 8 : Plan of the first floor of the simulated building from the SimBDI Interface

Figure 9 : Plan of the second floor of the simulated building from the SimBDI Interface

This building is located in Nancy, France. The outside reference temperature is -7°C and the set point temperature is 20°C for heating. The building has no cooling system. The permeability between two juxtaposed zones corresponds to an air mass flow rate of 0.05 kg/s.

Table 1 details the general settings concerning building operation and occupation of the building.

	Building zones												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Surface [m²]	123	122	35	25	35	42	21	56	28	123	122	154	91
Number of occupants [-]	15	15	3	2	3	4	2	5	2	15	15	19	11
Occupation period [h]	8h - 18h												
Setpoint temperature (occupation period) [°C]	20												
Setpoint temperature (inoccupation period) [°C]	16												
Heat demand [W]	2166	2276	571	331	539	706	331	803	417	2336	2452	3316	1723
Nominal water flow through each emitter [l/h]	149	202	28	10	23	44	10	109	18	245	185	310	189
Ventilation air flow [m^3/h]	270	270	54	36	54	72	36	90	36	270	270	342	198
Internal gains [W]	861	854	245	175	245	294	147	392	196	861	854	1078	637

Table 1 : General parameters of building

Figure 10 shows the structure of the hydronic network. Supply and return flow paths are not represented in this figure for simplicity. The network is in fact a real bi-tube network. There is one column for each façade of the building. The hot water production is ensured by a gas boiler. The supply temperature is controlled by a heating curve depending on outside temperature.

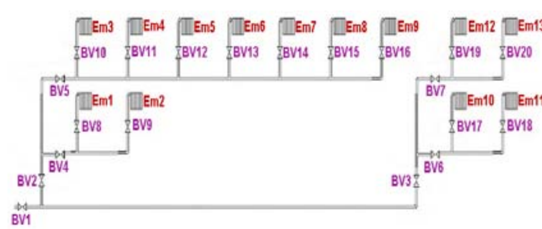

Figure 10 : Structure of the simulated hydronic network including balancing valves

SIMULATIONS

The objective of these simulations is to highlight the influence of the balancing operation. Figure 11 shows the process of evaluation of the different balancing methods selected [7].

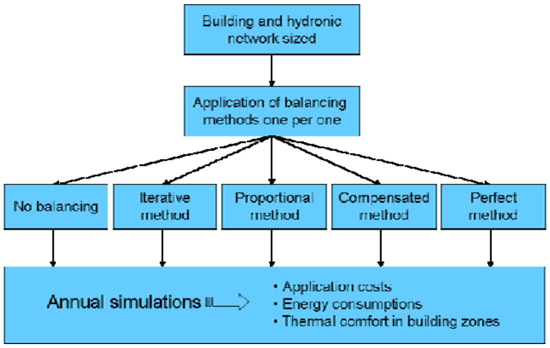

Figure 11 : Principe of studies of balancing method

The procedure of simulation begins by the size of the building for nominal conditions. It calculates the heat demand per zone. According to theses results, the simulator sizes the whole hydronic network and also the hot water production. Two balancing methods are available in the simulator [7]:

- Iterative method: Balancing valves are set without predefined order. The fitter sets each balancing valve independently some of the others. He could set balancing valves several times.
- Proportional method: The first step of this method is to measure all pressure losses of each balancing valve. This permits to define an order to set balancing valve. Each balancing valves are set only one time.

The reference balancing method is the perfect one. It optimises the balancing operation by minimising the pressure losses due to balancing valves. The real mass flow rate through hot water radiator correspond the nominal ones.

The owner can choice not to balance the hydronic network of his building. So, the simulator can simulate this case.

Outputs of these simulations are the evaluation of:

- the application costs of balancing method,
- energy consumptions of the heating system (pump & boiler),
- thermal comfort in building zones,
- The global costs of the heating system.

ANALYSIS OF RESULTS – DISCUSSION

Results of balancing operation

The Table 2 deals with the results of balancing operation of the three balancing methods chosen. It describes the ratio of real mass flow rate by the nominal mass flow rate.

On the one hand, if the ratio is superior to 100%, it corresponds to a hydraulically privileged branch. On the other hand, if it is inferior to 100%, the branch is considered as hydraulically disfavoured.

Ratio of real mass flow rate by nominal mass flow rate				
Balancing valve	No balancing	Iterative method	Proportional method	Perfect method
1	100%	100%	100%	100%
2	127%	103%	112%	100%
3	83%	98%	92%	100%
4	112%	99%	104%	100%
5	149%	107%	123%	100%
6	85%	87%	94%	100%
7	80%	108%	90%	100%
8	133%	108%	89%	100%
9	97%	94%	116%	100%
10	164%	115%	135%	100%
11	476%	336%	394%	100%
12	196%	138%	162%	100%
13	158%	91%	126%	100%
14	448%	320%	369%	100%
15	63%	58%	53%	100%
16	234%	169%	194%	100%
17	77%	74%	86%	100%
18	96%	104%	106%	100%
19	79%	101%	89%	100%
20	83%	119%	91%	100%

Table 2 : Results of balancing operation

The previous table shows that, for the perfect balancing method, the distribution of mass flow rate is perfect. All balancing valve are set to have the nominal mass flow rate.

For the iterative method, the fitter had set two times each balancing valve. Water mass flow rate are more better ensure than before the balancing. Lot of balancing valve have a mass flow rate different of more than 10% regarding the nominal one. Results with proportional method are less efficient than the iterative method.

Application costs

According to each balancing method process, the time of its application and its costs must be taken into account for a good evaluation of its performance.

To apply a balancing method, a fitter is needed. He costs about 550 € per day (about 8 hours of work). One setting of balancing valve takes about 15 minutes. According to the number of balancing valves to set for each balancing method, the time and the cost of to apply a balancing method can be estimated.

	Number of balancing valve set	Time spend for balancing operation	Application costs
Iterative method	40	10 hours	705 €
Proportional method	20	5 hours	353 €

Table 3: Application costs of balancing operation

The Table 3 shows the time and the cost of application for each balancing method. The cheapest application id obtained for the proportional method as the fitter has to set each balancing valve only one time.

Global costs estimation

Global costs of this building for heating system are estimated for a typical french heating season of 20 days representative of the total heating season. Results for this month are extrapolated to the global heating season of the location of simulated building.

According to the annual day degrees shown by Figure 12, the Day-Degrees of January represents 18% of a complete year if months from May to September are not taken into account (during these months, building zones are not heated).

City : Nancy
Setpoint heating temperature : 20°C
No heating outside temperature : 16°C

Month	Day Degrees
January	582
February	492
March	459
April	376
May	248
June	87
July	34
August	77
September	143
October	306
November	432
December	587
Total	**3823**

Figure 12 : Annual Day Degrees for Nancy, France

The *Figure 13* shows the operation costs of the three hydronic installations for a simulated period of one month during french heating period.

Pump consumptions depends directly on pressure losses of hydronic network. More the pressure drop in the hydronic network is, more pump consumptions are expensive. Perfect method minimize pressure losses due to balancing operation, so pump consumption are less than the others methods, about 64% low cost than the iterative method and 71% than the proportional one.

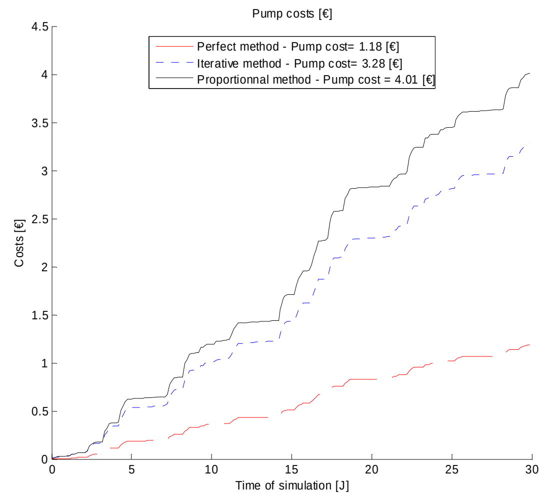

Figure 13 : Costs of pump consumptions

The Figure 14 shows the costs of the boiler to ensure the hot water production. Gas consumptions are equal whatever is the chosen balancing method. In fact, heat demand per zones and heat losses due to hydronic distribution are the same because the regime of temperature is the same.

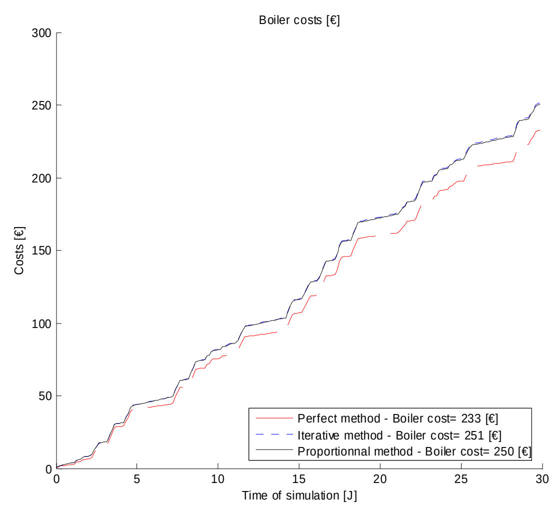

Figure 14 : Costs of boiler consumptions

Concerning investment costs, the choice of the balancing method has an impact of them. Indeed, pump depends on the pressure losses due to balancing operation. The Table 4 shows the costs for the investment according to each balancing method.

	Perfect method	Iterative method	Proportional method
Emitters	2 678 €	2 678 €	2 678 €
Balancing valves	703 €	703 €	703 €
Tubes	717 €	717 €	717 €
Pump	337 €	3 500 €	3 500 €
Total owning costs	4 435 €	7 598 €	7 598 €

Table 4 : Investment costs for each balancing method

As the previous table shows, the pump is more expensive for the iterative and proportional method.

Indeed, these two methods create more pressure losses than the perfect method, which is considered as a reference. The aim is to find a solution to have investment costs close to the reference.

With the equations 5 and 6, global costs of the three cases studied can be estimated. An inflation of 10 % per year of the energy cost is taken. To simplify the calculation, no interest rate on investment cost is taken into account. For an amortization period of 15 years, the global cost of the heating system with the perfect method is about 49 582 €. It is evaluated to 57 775 € for the iterative method and to 57 352 € for the proportional method. According to these results, the better choice is the proportional balancing method. It costs less expensive in running conditions as his application on site (in the case, a re-balancing operation is necessary to correct the drift of the hydronic balancing).

Thermal comfort

To visual thermal comfort in building, one zone representative of the building has been selected, the zone 4. This zone is a hydraulically privileged zone. The water mass flow is equal to 336% of the nominal one for the iterative method and 394% for the proportional one.

The temperature of zones and walls, composing it, is initialised at 18°C. The three first days of simulation are representative of realistic operation condition. They correspond to the initialisation of the building.

The building is occupied from 8 am to 6 pm from Monday to Friday. Building is unoccupied on Saturday and Sunday.

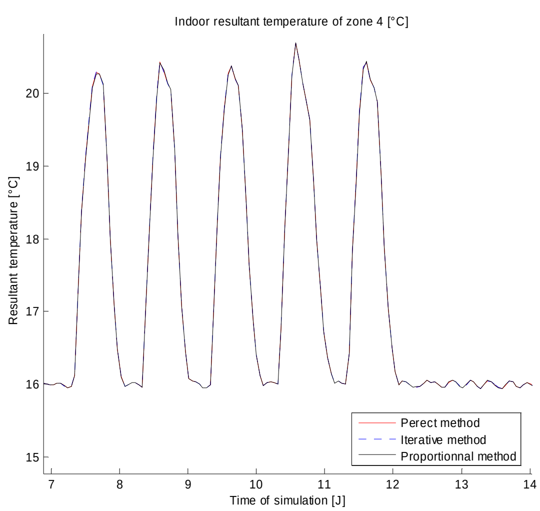

Figure 15 : Radiant temperature in zone 4: evolution for one week

The Figure 15 shows that the set point temperature is reached whatever the balancing method is. After an unoccupied period, the set point temperature is reached depending on inertia of building zones:

- On the one hand, the temperature is reached after a long time for a high inertia zone,
- On the other hand, the temperature in a low inertia zone takes little time to be raised.

Therefore, for extreme outside conditions, set point temperature may not be raised for the hydraulically disfavoured zones.

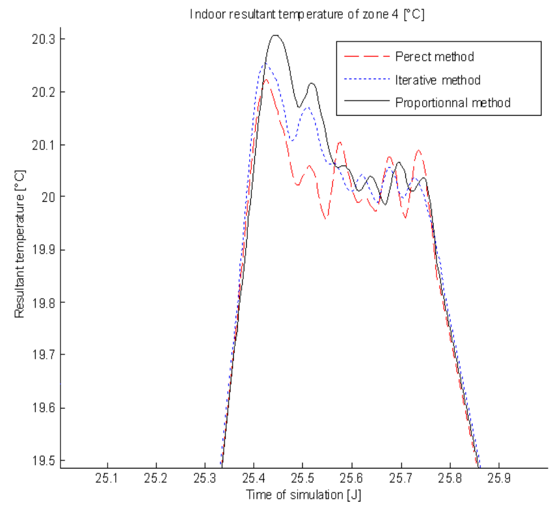

Figure 16 : Radiant temperature in zone 4: focus on one day

Figure 16 shows the evolution of the radiant temperature in zone 4 for a single day. The occupation set point temperature is reached but in different condition depending on the balancing method chosen. The control of the temperature is best with the perfect method; it is reach earlier in the occupation period. The delay to obtain it is longer with the iterative method and still longer with the proportional method. As this zone is favoured, the radiant temperature is upper than the set point one but terminal regulation control it to the set point.

CONCLUSION

This paper deals with commissioning of heating system and focuses on the hydronic balancing operation. It deals also with the optimisation of the design of hydronic network. This process is complex and should be exactly followed to perform the heating system. Therefore, a new simulator based on the models of the SIMBAD Building and HVAC Toolbox has been developed.

The simulator developed in this study allows to study the influence of balancing operation and balancing methods on thermal comfort and costs by presenting global costs for the total cycle life of the heating system of the building. The quality of control strategies is also taken into account. It could also show the consequences on energy efficiency of the heating system if a task in commissioning process is forgotten.

Since the differences of this studied building have been shown to be small, the next step will be to carry out parametric studies for larger buildings where networks and thus pump costs are more important.

Future development of the simulator will treat also about several new analyses as defined in the heating system operation step and the heating system deterioration step:

- the development and the evaluation of new control strategies for the control of a variable speed pumps to minimise pump consumptions,
- the implementation of new balancing method (such as methods using differential pressure controllers) into the simulator,
- the studies of influence of supply temperature level as well as temperature drop in the emitter.

NOMENCLATURE

H	Head of the pump	[mce]
q	Mass flow rate of water	[kg/s]
η_p	Efficiency of the pump	[-]
η_m	Efficiency of the engine	[-]
P_c	Pump consumptions	[W]
C_w	Average costs of electrical kWh	[€/kWh]
t	Time of pump functioning	[h]
C_{cp}	Costs of pump consumptions	[€]
q_{gas}	Mass flow rate of gas	[kg/s]
PCI_{gas}	Lower calorific power of gas	kWh/m^3
C_{gas}	Costs of gas kWh	[€/kWh]
ρ_{gas}	Density of gas	[kg/m^3]
$Costs_{gas}$	Boiler consumptions	[€]

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