Energy consumptions analysis in a rehabilitated small-scale substation from a district heating system

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Abstract: In the last 10 years, an extensive rehabilitation process and a series of works has been accomplished in Romania, in order to improve the performances of district heating systems. These rehabilitation measures were taken for a better comfort and to reduce energy (thermal and electric) consumptions.

Among modernization solutions we can mention: utilization of heat plate exchangers with high efficiency and smaller dimensions, implementation of control, measurement and automatic regulation equipment, improvement of process regulation principles, introduction of compact small-scale substations. Present article refers to an energetically analysis for a small-scale modern substation which is equipped with 2 heat plate exchangers (one for heating process and another for hot water supply), hot water storage tank, regulation, measurement and pumping equipment. This modern substation was a result of a research theme directed by Technical University of Civil Building Engineering-Faculty of Building Services Engineering Bucharest and it was installed and made functional in February, 2007, in Bucharest. The substation supplies hot water and thermal energy for heating for a riser of a block with 10 floors and 32 apartments. In the current article a comparative analysis of energy consumptions for a constant or variable speed pump is shown. The pump refers to the heating circuit of the substation and the analysis took into consideration 3 scenarios: constant or variable speed of the pump, constant or variable indoor temperatures inside the rooms of the apartments, different meteorological times during the heating period. The simulations were obtained with the help of performant computer software TRNSYS and the results could be validated in the next heating season and also with the measured parameters in the modernized substation.

Key-Words: district heating, small-scale substations, variable speed pump, electrical energy savings

1. Introduction

The justification of the present research subject consist in some exploitation deficiencies that were noticed in district heating system from Bucharest, but also for other cities from Romania [1]. These deficiencies refer to several aspects:

a. There are no possibilities to modify the functioning regimes of interior heating installations according to the real consumers' thermal energy demand. It is well known that the heat demand for a building depends on various factors such as:
   - meteorological factors, with different and hazardous variations in time: outdoor temperature, wind, solar radiation [2],
   - "free" heat supply generated by the presence of occupants inside rooms, due to the electrical equipment, furnaces, lighting installations,
   - intervention of the building occupants in order to modify the thermal regime inside the apartments according to the occupation degree, daily program or weekend,
b. there are no possibilities to establish the correct costs for the thermal energy needed to heat the building corresponding to the real demand of the spaces,
c. at present, the water mass flow coming from the district heating network to the primary heating system of the block of flats is constant, leading to a high electrical energy consumption to pump the fluid.

In order to improve the commissioning of the district heating systems and to correct the deficiencies that we mentioned beforehand, the present paper propose some experimental applications and possible measures inside the building, but also in the substation [1].

Thus, the measures refer to:

1. Implementation of thermostatic valves for each terminal unit, which offers the possibility to automatically obtain the desired thermal comfort for the occupants according to outdoor temperature variations. Each thermostatic valve will modify the fluid mass inside the terminal unit, so its average temperature, which will be reflected in the variation of the emitted heat in the room.
2. Each radiator will be equipped with an individual Heat Cost Allocator (HCA). That offers the

possibility to establish the correct cost for the consumed thermal energy by each flat's occupants, proportionally with their action on the thermostatic valves [3].

3. The implementation on the secondary circuit in the experimental substation of a variable speed pump, in order to adjust the total fluid flow corresponding to the action of thermostatic valves.
4. Tracking the substation functioning during the whole heating season.

Further fundamental premises for the rehabilitation measures and functioning regimes rationing, where considered [4]:

- Existing heat cost allocators on secondary circuits of the substation, for hot water and heating processes, for each block of flats,
- Existing heat meters on primary circuit of the substation,
- Existing water meters for hot and cold water at each sanitary object, which gives the advantage of correct bills for consumers, according to their individual consumptions. In addition, this will lead to a more careful behavior for hot and cold water utilization, in order to control their consumption, to retrieve and improve the technical state of their equipment and water installations.

In order to accentuate the rehabilitation effects and their quantifications a comparison between 2 "witness" buildings (M_1 and M2), in Bucharest, 42-46 Mihai-Bravu Avenue, the second and the third risers of the block was accomplished. One of the risers of the block was kept in the old state, without any rehabilitation and the other one was rehabilitated and it functioned with a modern substation, as we mentioned before.

To achieve this task, a simulation with the TRNSYS programming environment was performed. The model was applied on the new substation project which can be adapted in various configurations, according to the consumers' demands and type (one stage for hot water preparation in a serial or parallel position face to heat compartment etc.).

2. Problem formulation

Starting from the analysis of all equipment inside the experimental substation, a detailed operation scheme was traced (fig. 1).

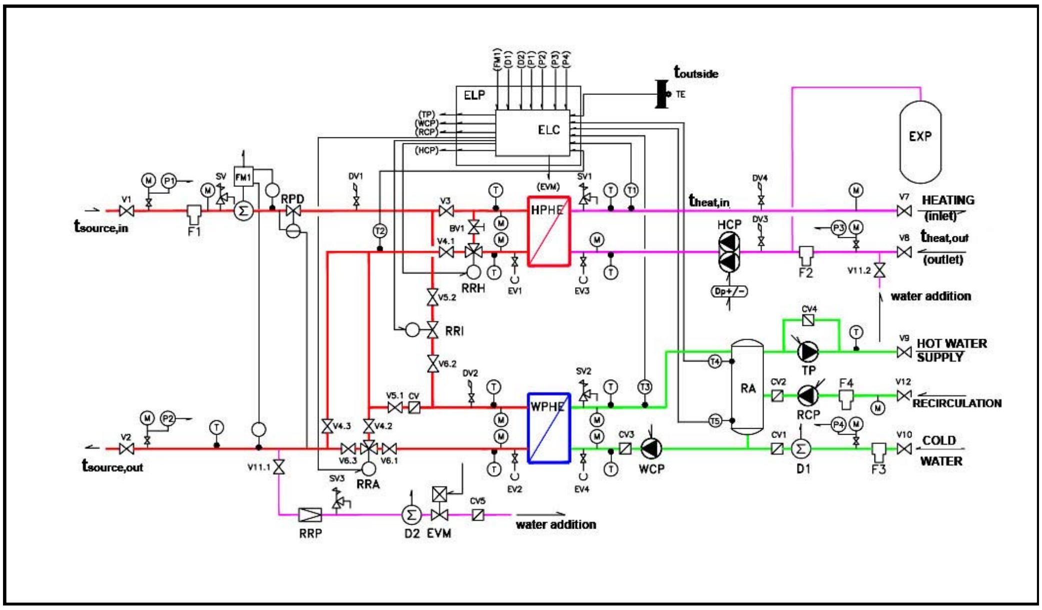

Fig.1: Detailed operation scheme of the small-scale substation

Primary and secondary circuits can be observed (one for heating process and the other for hot water supply). In the connection diagram can be observed also regulation and control equipment which allow maintaining or varying some interest parameters according to heat delivery diagram from fig. 2.

This diagram make a correlation between outdoor temperature variations ($t_{outside}$) and the supply fluid temperatures inlet temperature on primary circuit (t_{source,in_set}), outlet fluid temperature on primary circuit (t_{source,out_set}), inlet temperature on secondary circuit for heating process (t_{heat,in_set}) and outlet fluid temperature (t_{heat,out_set}). This diagram was established by the Transportation and Distribution of Thermal Energy Company and, in principle, it is tracked all over heating season.

The last 2 temperatures have set points values ensured by the intervention of three-way valve RRH modifying the mass flow in primary circuit in heat exchanger HPHE for the heating process (fig. 1).

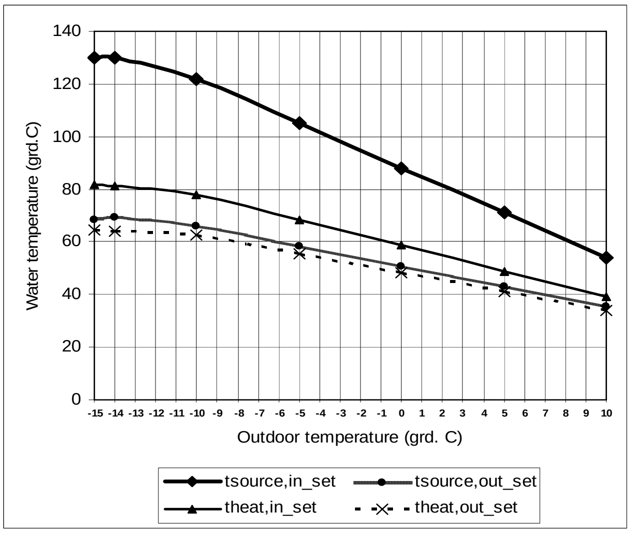

Fig. 2: Heat delivery diagram of the small scale substation

2.1 Description of the studied building and its interior heating and hot water supply installations

The apartment block (the block riser) studied for the energetically analysis has 10 floors, a bowel and a technical floor. In order to give a general image on heat demand of the building we'll make a short description of the envelope. Thus, the exterior walls are made of full brick (λ=0,8 W/mK), with a thickness of 30 cm, rendered on both sides with cement mortar without any thermal insulation.

The windows are double and made of wood with a global coefficient of transfer U_F = 2,83 W/m^{2}K and reduced permeability for air infiltrations. The floor under the unheated bowel is made of 25 cm reinforced concrete, plated with cement mortar with a thickness of 3 cm. The last floor from the 10th level of the building has 34 cm (under the circulated terrace) and it is composed from superposed beds of reinforced concrete, concrete flat-dipping bed, polystyrene, sand and cast mosaic, with a global coefficient of 0,606 W/m^{2}K (well insulated). At each floor there are 4 apartments with 3 rooms arranged in a symmetrical manner. There are 44 apartments. At the technical floor there are 2 dry-laundry rooms, 2 administrative rooms, cable hoist elevator room, all of them heated with radiators. From the information and data obtained from the lodgers and Administration Office at the beginning of the experimental project no important or major modifications were effectuated inside heated spaces or interior installations and similar for hot water supply system. Most of the radiators are cast iron madden having elliptic columns, 600/150/2 type, with high thermal inertia and variable number of elements according to each room demand. The total installed load ($P_{heat,inst}$) of all the radiators is at 265153 W, a value much bigger than the theoretical load required by the Romanian design standard STAS 1907/1,2-1997 assuming the stationary heating regime ($P_{heat,req}$ = 178 784 W).

According to initial proposal, all the radiators were equipped with thermostatic valves and individual heat cost allocators, thus permitting to consumers to control indoor temperatures as function of their metabolic comfort and financial availabilities. A typical diagram for the thermostatic valves regulation is very difficult to establish taking into consideration each of the 44 apartments, thus the simulations were effectuated considering average indoor temperatures for the entire building, as a result of the thermostatic valve intervention. These temperatures can vary during a diurnal cycle (for example a lower value during the day because the lodgers are not home at higher in the nights). The temperatures evolutions scenarios are detailed at point 3 together with energetic analysis scenarios in TRNSYS. Following outdoor reference temperatures were taken into consideration corresponding to Romanian standard: bedrooms and living rooms 20 ºC, 18 ºC for kitchens, 22 ºC for bathrooms and 15 ºC for auxiliary rooms heated from the last floor (technical floor and administrative rooms). The difference between theoretical heat demand value and installed load, as the result of addition of all radiators charges, is very important. Those values were taken from initial design project of the building. The reason for such an over dimensioning of the radiators consist in some insurance coefficients applied by engineers. This aspect was confirmed in time, no complains about the indoor temperatures were not registered.

Hot water supply installations for the considered building are designed in order to insure the mass flows and pressures necessary for hot water consumers (taps, gauges, mixing hot-cold taps etc. installed in kitchens or bathrooms). The conception of the installations is with vertical risers, inferior radial distribution, placed in the bowel of the building [5]. The daily mass flow, calculated taking into consideration all utilization taps, is 11,88 m^3/day with a maximum of 15,44 m^3/day. Since the following energetically analysis refers only on electrical energy consumption of the circulation pump, in the heating secondary circuit, we don't see many reasons to insist in description of hot water supply equipment. Although we'll mention that this circuit is supplied with thermal energy through heat-plate exchanger WPHE (fig. 2).

2.2 Description of the heat supplying source and of the modern small-scale substation

Heat supplying source for the substation which delivers heat and hot water for considered building is a cogeneration source from South-Bucharest. Theoretical regime from the conception project design is 150^{0}C / 80^{0}C on primary circuit and 95^{0}C/75^{0}C on secondary circuit. Nominal primary fluid mass flow equals to 3,25 m^3/h 11 m^3/h, delivered from South Bucharest cogeneration source. On the secondary circuit nominal mass flow is 11 m^3/h and it is assured by a variable speed pump (HCP). The necessity of implementation of such a pump type derives from the interventions of thermostatic valves which will increase or decrease the mass flows of hot water for each radiator (fig. 2). Following the implementation of this system, the hydraulic functioning mode of the internal heating system (the secondary circuit) is characterized by variable mass flow. The control of heat supply for buildings becomes mixed (qualitative – quantitative), based on temperature regulation in the supply pipe relative to outdoor temperature variation and to the local adjustments of mass flow correlated with the rooms heat losses [6]. In mixed control of heat supply it is accepted to use circulation pumps with variable speed; a reduction of the energy consumption is obtained in this way, comparing to using constant speed pumps, as a result of lower flows and pump heads. In addition, the pumps function with a superior efficiency (0.75 – 0.8). The speed adjustment is achieved through frequency converters. The electronic regularization mode consists in linear adjusting of the available pressure (pump head) between its nominal value H_n (corresponding to the maximum mass flow) and ½ H_n (corresponding to zero mass flow).

The circulation pumps as well as all the other pumps inside the rehabilitated substation are WILO type, and on the secondary circuit, the WILO variable speed pump has the following nominal operating characteristics: D_n= 7 m^3/h (nominal flow), H_n=3 mCA (nominal pump head).

These values will be constantly adjusting to the secondary heating circuit variable flow, resulted from the intervention of thermostatic valves of the rooms. Temperature control on supply and return in the primary and secondary circuit, according to the diagram from fig.1, is achieved through two three-way valves: RRH and RRA and a RRI two- way valve (insert valve), mounted on the primary circuit, and controlled with an ELC type electronic regulator (fig.2) according to the following effective measured temperatures:

- $t_{heat,in}$ for the RRH valve (by-passing a fraction of the primary flow that passes through HPHE) if $t_{source,out}$>55 °C ; in this case, RRI is completely closed and RRA completely open (on the way to WPHE);

- $t_{in,WPHE}$ – the thermal agent supply inlet temperature in the WPHE heat exchanger for hot water supply, when 45 °C < $t_{source,out}$ < 55° C (lower than in the first case); in this case the RRI insert valve opens, mixing the primary thermal agent flow coming from the heat exchanger HPHE with the $t_{source,out}$ temperature, with a fraction (by-pass) of the flow that comes from the heat source at the $t_{source,in}$ temperature, thus achieving a higher thermal potential for preparing hot water supply in the WPHE heat exchanger [7];

- $t_{in,WPHE}$, when $t_{source,out}$ < 45 ° C **;** in this case the RRA valve closes completely (on the way to the WPHE heat exchanger), and the RRI insert valve opens (up to 100 % if it's the case), in order to prepare hot water in the secondary circuit of WPHE at the required consumer parameters (55-60 °C). In conclusion, it can be stated that in the case of the studied substation two types of controls have been applied (quantitative and qualitative) in order to obtain thermal and electric energy savings:

- Temperature control from the substation according to heat deliver diagram and the outdoor temperature, and
- A control of the nominal point (by reducing the pump head) at the HCP variable speed pump on the secondary heating circuit, related to the modification of the total mass flow in the heating system resulting from adjusting the thermostatic valves. Both aspects will be illustrated through the energy analysis to be presented in the following paragraph.

2.3 The algorithm model of the modernized small-scale substation

Based on the operating characteristics of the equipments that compose the modernized substation the general simulation model of this system has been built in the programming environment TRNSYS (TRaNsient System Simulation), connecting the substation with the consumers that it effectively supplies [8].

These consumers are placed in a 10 floors block of flats which also was built in TRNSYS, with the help of the building preprocessor TRNBuild. The simulation scheme made in TRNSYS for the thermal substation described in fig.2 is presented in fig.3.

Following composing elements have been built in TRNSYS, corresponding to the general operating scheme depicted in fig.2 and to the operating characteristics used to design and build the substation:

- Plate heat exchangers units for the heating circuit (HPHE) and for the hot water preparation circuit (WPHE);
- the variable speed circulation pump in the secondary circuit (HCP);
- the hot water supply variable speed circulation pump on the secondary circuit of the heat exchanger for hot water supply (WCP), with ON/OFF functioning type according to the hot water demand of consumers ;
- the storage tank for hot water on the secondary circuit of the heat exchanger WPHE, called "Water tank";

- calculation modules for the fluid flow that passes through a two-way concession valve;
- a module that regroups all the heat transfer phenomena in the building which includes the heat consumers connected to the modernized substation (a module that is generically named ”BUILDING”), built by introducing the geometrical, thermo-physical data of the studied building with the help of the TRNBuild preprocessor;
- ”PI-RRH”, **”**PI-RRI” and ”PI-RRA” – calculation modules which simulate the proportional-integral operation of regulators (part of the ELC general regulator), that calculate the action signal depending on the closure degree of the RRH, RRI, and RRA valves according to the correspondent temperature signal;
- ”Reg_WCP”– differential controller of ON/OFF type, with hysterezis, which controls the WCP (constant speed circulation pump) according to the consumer’s domestic hot water (DHW) demand, introduced in the calculation module of the substation through the subroutine Consumer Profile DHW**.** This profile is introduced by the user based on the future use of the building and on the hot water daily utilization diagram for domestic users in collective living buildings.
- ”Flow_RRH_I1”, ”Flow_RRA_I1” and **”**Flow_RRI” – calculation modules for the flow of liquid in the primary circuit based on the command signal received from the regulators PI-RRH, PI-RRI and PI-RRA; these flows are calculated with the help of a specialized subroutine of TRNSYS, which takes into account the respective valve authority, of its characteristic (logarithmic or linear), of the maximum flow of the valve, kv_s and of the kv_o constant representing the flow percentage from the maximum flow that passes through the valve at the maximum closing.

All these calculation modules, as well as the links between them, are illustrated in the fig.3. It can be noticed on this figure the connections between the modules created in order to describe the composing elements of the modernized substation**,** as well as the control elements for the liquid flow regulation in the three-way valve on the primary circuit.

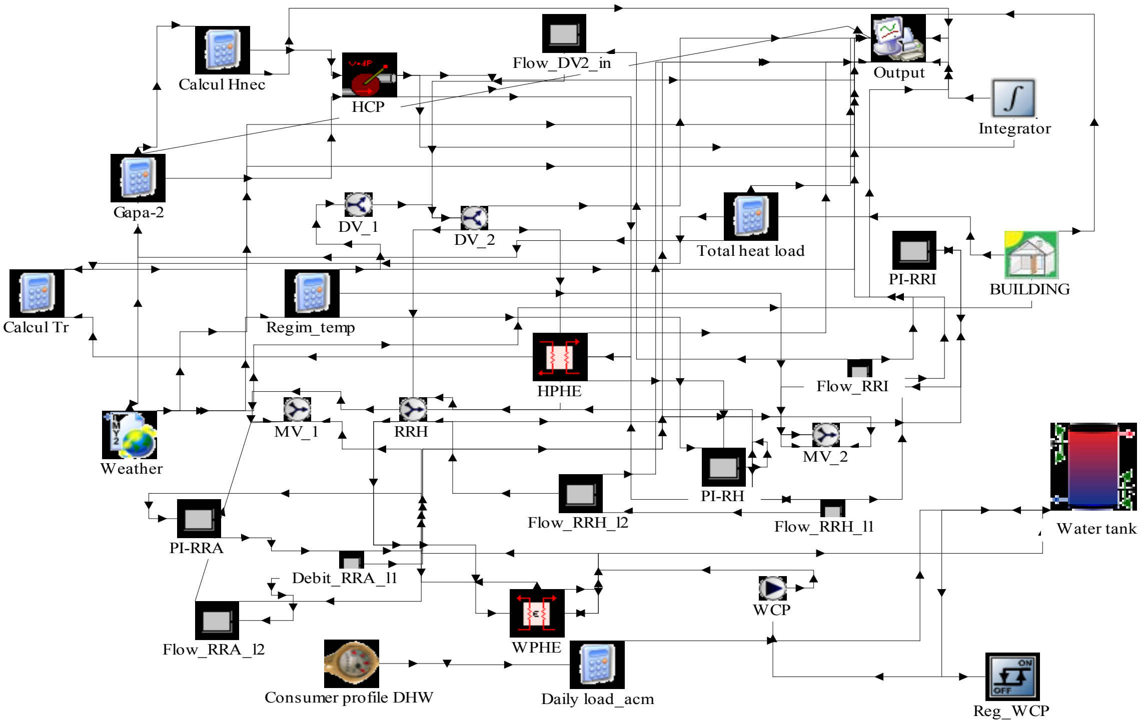

Fig.3: Schematic representation of the TRNSYS simulation diagram for the small scale substation

Also, in this scheme it can be observed the relation between the system and its respective model for the building thermal behavior (the BUILDING module). It has also to be noticed the presence of Integrator which allows determining the energy consumption for each equipment, based on the calculus made regarding its demand of power. The elementary object named ”Weather” that appears in the left of the operating scheme contains all the weather data needed for the “BUILDING” module (for calculating the heat load and energy consumption for heating). This weather file of text type was taken from TRNSYS data base METEONORM, for the city of Bucharest, where the substation is situated.

3. Problem solution

In order to outline the energy savings due to the modernization of the small scale substation, we carried out a comparative analysis of energy consumptions for two main cases:

A) using a Constant Speed (CS) pump HCP on the secondary heating circuit of the HPHE heat exchanger (see fig.1), and

B) using a Variable Speed (VS) pump for the same heating circuit

In addition, both cases were associated with two sub-cases regarding the daily schedule of the mean indoor temperature assumed to be established in the building supplied with heat from the substation. Thus, the schedule 1 considered a mean constant temperature of 20 ºC in the building over the daytime (continuous heat supply and best indoor comfort conditions assured by occupant's action on thermostatic valves), while the schedule 2 considered a mean constant temperature of 20 ºC over the night time (20h – 8h) and a lower temperature (18 ºC) over the daytime (8h – 18h), when the occupants are supposed to be absent and close their thermostatic valves to save thermal energy.

In order to compare the energy savings between two different parts of the heating period (which in Romania lasts generally from October to April), we have chosen two entire months: January (colder) and March (warmer), for what we performed TRNSYS simulations, taking into account the cases A and B, combined with the schedules 1 and 2. It resulted eight simulations to be performed, from what we choose to compare two main category of results:

- the fluid (hot water) temperatures on the secondary circuit obtained by simulation ($t_{heat,in}$ and $t_{heat,out}$) and the corresponding setpoint temperatures (t_{heat,in_set} and t_{heat,out_set}) desired to be reached by the qualitative regulation (see fig.2); this type of comparison is depicted in figures 4 and 5, where case A1 is represented;
- the electrical power (hourly values of $P_{cons,HCP}$, in kJ/h) consumed by the pump installed on the secondary heat circuit (HCP) in the cases A and B (constant speed-CS or variable speed-VS) and schedules 1 and 2 described previously, resulting by integration the total electrical energy consumed by the same pump ($E_{cons,HCP}$ in kJ) over one simulation month (January or March) considering the same cases; in the table 1 are presented the results of $E_{cons,HCP}$ for January and in table 2 for March;
- the total sensible heat demand ($Q_{sens,tot}$ in kJ) obtained by simulations, in the subcases A1 and A2 when considering the two different simulation periods, January and March; these heat demands should accord to the building thermal energy bill received by the administrator for the one-month period analysed – see table 3.

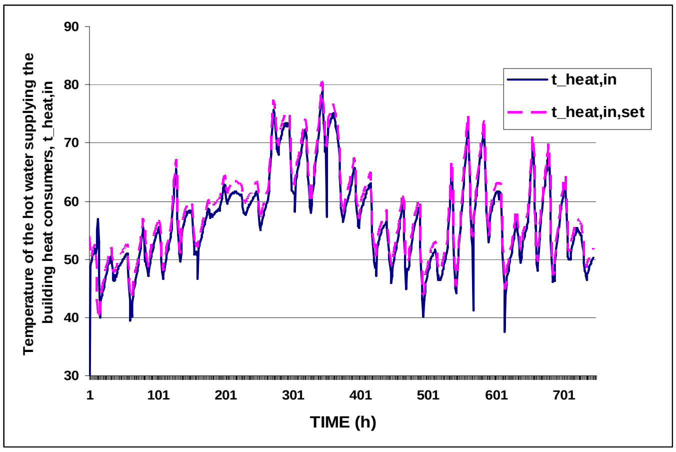

Fig. 4: Comparison between the heat supply temperatures calculated by TRNSYS and their setpoint values on the secondary heating circuit, for January and case A1

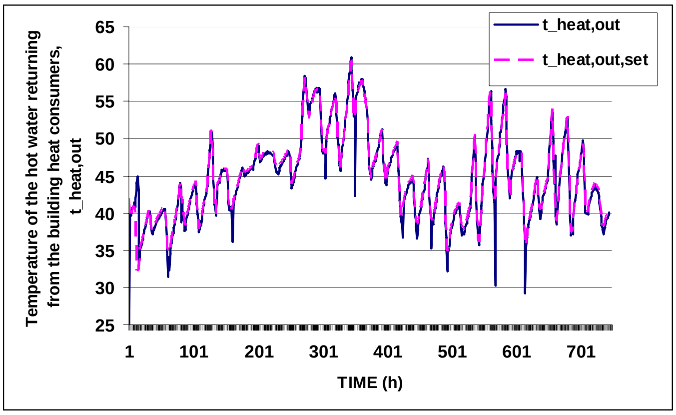

Fig. 5: Comparison between the heat return temperatures calculated and their setpoint values, for January, case A1

	Schedule 1 (t_i = 20 ºC 24h/24)	Schedule 2 (t_i = 20ºC for 20h-8h and t_i = 18ºC for 8h-20h)
Case A (Constant Speed)	10 690	9 856
Case B (Variable Speed)	8 523	6 776

Table 1: Total monthly electrical consumption $E_{cons,HCP}$ (in kJ)) by HCP pump for the January simulation period

	Schedule 1 (t_i = 20 ºC 24h/24)	Schedule 2 (t_i = 20ºC for 20h-8h and t_i = 18ºC for 8h-20h)
Case A (Constant Speed)	9 154	6 367
Case B (Variable Speed)	7 588	4 585

Table 2: Total monthly electrical consumption $E_{cons,HCP}$ (in kJ) by HCP pump for the March simulation period

	Subcase A1 (Case A and schedule 1)	Subcase A2 (Case A and schedule 2)
January	$1{,}62 * 10^8$	$1{,}5 * 10^8$
March	$8{,}74 * 10^7$	$7{,}63 * 10^7$

Table 3: Values of the total sensible heat demand $Q_{sens,tot}$ *(in kJ) of the building simulated, for the two simulation periods*

4. Conclusions

Let outline some interesting conclusions after taking an overview of this simulation results:

- firstly, we could notice than the use of a variable speed pump on the secondary heating circuit means, in each of the two analysis period, to an important relative reduction in the electrical energy consumed by the HCP pump, more precisely: 20,3% (for schedule 1) and 32% (for schedule 2) in January and respectively: 18% (for schedule 1) and 28% (for schedule 2) in March; this shows that the schedule 2 is even more energy efficient scenario for the electrical energy consumption than the schedule 1, depending on the occupant's behaviour related to their interest to save energy ;
- secondly, this occupant's behaviour is more precisely linked to their direct interest to reduce their monthly heating bills, which is shown by the reduction of the total heat demand observed in the table 3 when schedule 2 replaced schedule 1; this relative reduction is: 8% for January and 8,7 % for March.

In addition, the comparisons depicted in the figures 4 and 5 show that the TRNSYS representation of the thermal substation and its regulation are working properly, when the temperatures on the secondary circuit are very close to their setpoint values defined in fig.2.

The final conclusion of this paper is that the use of a variable speed pump on the heating circuit, combined with a judicious occupant's beahviour regarding the use of thermostatic valves, mean to important electrical energy savings, as well as to reduction of heating bills.

Our research perspective is to compare some real field data (energy consumptions measured at the building level) with the simulation results, for the next winter period, in order to confirm the TRNSYS calculations.

Acknowledgements

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