Analysis of the Influences of Internal Heat Loads on a Solar Heating System Equipped with a Heat Pump

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Abstract- The work presented in this paper is the study of a solar heating system of student's classroom occupied in the day. This system includes solar thermal collectors, a water storage tank, a heat pump and low temperature hot water radiators. Several heating scenarios have been defined according to the internal heat supply. The objective is to analyze the impacts of each type of internal heat transfer on the performance of system components and thermal comfort. Ambient air temperature regulation is ensured by an on-off regulator that controls the operation of the heat pump and the circulating water pump in the radiators. The system model has been implemented in the Matlab/Simulink environment for simulation.

Keywords: Heating, Building, Regulation, Thermal confort, Matlab/Simulink.

1. Introduction

Men spend more than 90% of their time in an artificial environment (transport vehicles, workplaces or homes) [1]. The habitat whose function is to shelter its occupants from bad weather, in order to cope with climatic adversity in winter and ensure a pleasant and comfortable environment by heating, is a source of significant energy consumption [2]. In France, the building sector consumes annually, according to the Scientific and Technical Center for Building (CSTB) in June 2006, 47% of energy, half of which is due to heating, against 28% for industry and agriculture and 25% for transportation. This important winter consumption of energy by buildings is a quest for a state of satisfaction and well-being towards our thermal environment, called thermal comfort.Thermal comfort is a concept whose appreciation is largely subjective. For this purpose, for the same thermal environment, a first person can feel comfort while another can feel discomfort. This subjectivity is justified paradoxically by objective foundations. The appreciation of comfort is linked to the metabolism of the person and the exchanges made with the thermal environment. These exchanges depend on the person's constitution, state of health and physical activity [3]. Because of subjectivity of the thermal comfort concept, the American Society of Heating and Air Conditioning Engineer (ASHRAE) specifies the body standards of comfort as a whole in terms of operating temperature. This temperature takes into account air temperature, thermal radiation and the air velocity up to 0.15 to 0.2m/s. Thus, for a relative humidity of 50%, ASHRAE standard defines comfort temperatures in the range of 23 to 26°C in summer, and 20 to 23.5°C in winter [7]. These temperature ranges are slightly displaced at a moisture level of 50% or below [3].The search for comfort in winter induces a significant increase in energy consumption of various origins with all its consequences: very high bills, peaks in consumption, greenhouse gas emissions. [2] That is why, today, it is an obligation for everyone to integrate in their daily lives, the use of renewable energies, including solar thermal in the production system of hot sanitary water and especially the residential heating.

In general in domestic or residential heating, the thermal inputs from the solar flows play a key role in the energy consumption of the building. In addition to these external thermal inputs, internal inputs such as lighting and human metabolism are no longer negligible. Unfortunately, they are very little considered in most studies dealing with heating. For this purpose, as part of our study where a solar heating system incorporating a heat pump, several heating scenarios will be studied. The different study scenarios are defined according to lighting and human presence with the hypothesis a sunny sky. These are :

- S_1: Heating with lighting on and presence of people;
- S_2: Heating with lighting on and absence of people;
- S_3: Heating with lighting off and absence of people;
- S_4: Heating with lighting off and presence of people.

The purpose of our work is to analyze the influences of internal heat apply on heating system performance and thermal comfort. The system in its conventional configuration includes solar thermal collectors that maintain the collection of thermal energy to be transmitted by a circulating pump heat transfer fluid to the water tank. The latter serves as a source of cold for the heat pump which takes its calories and then ceded to a distribution system which, in turn will ensure heat transfer to low-temperature radiators.

2. Climate data

For modeling, the Bernard-Menguez model [4] is used to define the temporal function of sunshine from its daily value provided by the weather. This function assumes a sinusoidal distribution of the global solar radiation. But the case, the sunshine is presented by a half-sine wave because the sun radiates only half of the day, from 07:00 to 19:00. So, the expression of the model is :

$$\Phi_s=\Phi_M \sin\left[\frac{2\pi}{24\times 3600}(t-7)\right] \tag{1}$$

Where $Ø_M$ is the maximum observed solar flux amplitude; t is the local time in hours.

According to always Bernard-Menguez [4], the temperature variations of the ambient air are modeled by the formula :

$$T_a=\left(\frac{T_{aM}+T_{am}}{2}\right)+\left(\frac{T_{aM}-T_{am}}{2}\right)\sin\left[\frac{2\pi}{24\times 3600}(t-9)\right] \tag{2}$$

Where T_{aM}, T_{am} are respectively maximum and minimum ambient temperature of the place in winter and t the local time in hours.

3. Modeling of system

The studied system has an architecture illustrated by Fig.1, comprising a source part (electrical and thermal energies), an energy system part and a regulation system. The system includes solar thermal collectors, a water storage tank, a heat pump, radiators and the building, in this case the heated room. In order to conduct this study, simple models found in the scientific literature, of these elements above are selected and presented in the paragraph.

3.1. Model of building

The exploration of the literature dealing with the overall energy modeling of the building reveals the existence of several methods, each with their advantages and disadvantages depending on the work to be done. The thermal modeling of a building is interested in the representation of the temperatures of the latter. Despite its thermal inertia, it suffers the impact of the external environment because of the air circulation and heat exchange with the walls and facades. The thermal model is intended to predetermine the thermal behavior of a building. It results from the literature review that a second

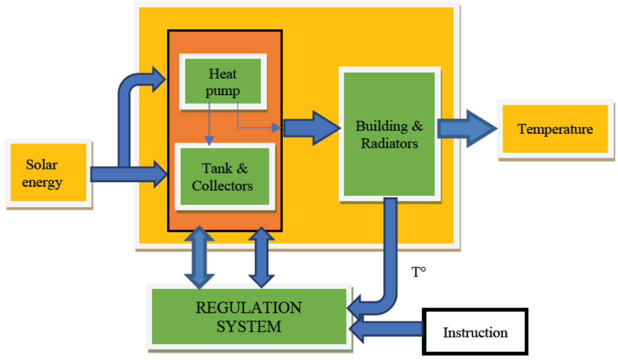

Fig.1: Architecture of the studied system

order RC model is largely sufficient to predict the behavior of a building during heating. Two temperature knots are considered namely, the indoor air temperature of the building and the temperature of the walls. It is thus the application of the Kirchoff law to each knot makes it possible to obtain a system with two equations with two unknown which is written in the form that defines the model used [13, 14, 15, 16, 17, 18]:

$$[C]\frac{d[T]}{dt}=[A].[T]+[B].[U] \tag{3}$$

Where [T], [U] are respectively vector of temperatures and solicitations. [C], [A], [B] are respectively matrix of capacitances, conductances and control.

The building model developed, supposed monozone building, for classroom use can hold 31persons. The dimension of length L = 10m, the width l = 6.5m and the height under ceiling h = 3m, it is occupied only from 08:00 to 13:00 and from 14:00 to 18:00 by the students. It remains unoccupied the rest of the time during the day. The lighting is provided by 12 luminous ceiling boxes with 4 fluorescent lamps of 18W per box.

3.2. Heat pump model

The heat pump acts as heating equipment. It is a thermal machine whose particular thermodynamic system allows the transfer of heat from a medium to a lower temperature where the heat is taken (cold source) to a medium at a higher temperature where it is rejected (hot source). For this study, the model of a heat pump used is the model developed by Jong et al [5].

$$\begin{cases} COP=k_1\dfrac{0,5T_{co,e}+0,5T_{co,s}+273,13}{\left(0,5T_{co,e}+0,5T_{co,s}\right)-\left(0,5T_{ev,e}+0,5T_{ev,s}\right)} \\ C_{co}\dfrac{dT_{co,s}}{dt}=m_{co,e}Cp\left(T_{co,e}-T_{co,s}\right)+COP.Ehp \\ C_{ev}\dfrac{dT_{ev,s}}{dt}=m_{ev,e}Cp\left(T_{ev,e}-T_{ev,s}\right)-\left(COP-1\right).Ehp \end{cases} \tag{4}$$

Where k_1 is heat pump performance determined from measurements at the test site (K_1 = 0.4), Cp (J/K) specific heat capacity of water, C_{co}, C_{ev} (J/K) are respectively thermal capacities of the condenser and the evaporator. $T_{co,e}$, $T_{co,s}$ (°C) are respectively inlet and the outlet temperatures of the condenser; $T_{ev,e}$, $T_{ev,s}$ (°C) are respectively inlet and outlet temperatures of the evaporator. Ehp (W) is electrical power of the heat pump.

3.3. Model of solar thermal collectors

In this study, we are interested in a simple model of the flat solar thermal collector defined by the following expression [5, 8, 9, 10, 11, 12]:

$$C_c \frac{dT_{cs}}{dt} = \dot{m}_f c_f \left(T_{ce} - T_{cs}\right) + A_c \Phi_s - k_0 \left(\frac{T_{ce}+T_{cs}}{2} - T_{a1}\right) \quad (5)$$

Where C_c is thermal capacity of the solar thermal collector (J/K); c_f is specific thermal capacity of the coolant (J/Kg.K); m_f is mass flow rate of the coolant (Kg/s). Tce, T_{cs} are respectively inlet and outlet temperatures of the coolant in the solar thermal collector. Φ_s is solar flux (W/m^2). A_c is solar collector area (m^2). K_0 is coefficient of heat loss of the sensor (k_0 = 127W/m^2).

3.4. Model of the storage tank

The storage tank combines the energy of the solar thermal collector. The temperature of the storage tank depends on three factors : temperature and input mass flow (Tre and Mre) ; the temperature and output mass flow rate (Trs and mrs) and the storage capacity M. Considering these three parameters, a dynamic model of the reservoir developed by A.M.W et al, is described by the formula [5, 8] :

$$Mc_p \frac{dT_{rs}}{dt} = \dot{m}_{re} c_p T_{re} - \dot{m}_{rs} c_p T_{rs} \quad (6)$$

Where cp is specific thermal capacity of water (J/Kg.K).

3.5. Model of internal loads

The heat gains consist of solar gains and internal contributions. These internal inputs are due to electrical equipment in our case, only lighting lamps and human metabolism. The thermal contribution due to human metabolism is a function of the indoor temperature and the degree of activity. There are two kinds of gains generated by the occupants : significant gains and latent gains. It is calculated by:

$$Q_H = N\left(C_{soc} + C_{loc}\right) \quad (7)$$

Where N is number of occupants. C_{soc}, C_{loc} are respectively sensible heat and latent heat (W) of the occupants.

The heat input by lighting Q_{ecl} is a source of sensible heat and depends on the type of lamp. Depending on the type of lamp, we have the following expressions :

$$Q_{ecl} = \begin{cases} 1{,}25P, & \text{for fluorescent lamps} \\ P, & \text{for incandescent lamps} \end{cases} \quad (8)$$

Where P is lamp power (W).

3.6. Model of the hot water radiator

The choice of a water radiator results from a thermal power balance. This assessment is an inventory between heat gains and losses (walls and ventilation). Thus a radiator at low temperature, the water circulates at 45 - 50°C on average, instead of 75-65°C usual for a conventional radiator [7]. The problem for the use of a radiator in soft heat is to know the power it develops at an ΔT different from 50°C. For that, it is necessary to use the formula of the constructor of the latter [6, 8] :

$$P = P_n \left(\frac{\Delta T}{50}\right)^n, \text{ with } \Delta T = \frac{T_e - T_s}{\ln\left(\frac{T_e - T_{ai}}{T_s - T_{ai}}\right)} \quad (9)$$

Where P_n is the nominal heat emission from radiator; n is the constant describing the type of radiator.

The outlet water temperature of radiator T_s is a function of the actual heat and the inlet water temperature in the radiator Te and is calculated by the expression [6, 8] :

$$C_{rad} \frac{dT_s}{dt} = \dot{m}_r C_p \left(T_e - T_s\right) + UA\left(T_{ai} - T_s\right) \quad (10)$$

Where m_r is water mass flow rate of the radiator inlet (Kg/s).

4. Regulation

In order to optimize the energy consumption in the classroom, the regulation of its temperature becomes a necessity. This is how a thermostat controls the dynamic operation of the heat pump and the radiator hot water supply pump. It keeps the temperature of the room within the limits of the instructions between 18 and 20°C. When the room temperature is less than or equal to 18°C, the thermostat controls the start of the pumps. When it reaches the value of 20°C, the thermostat controls their stops.

5. Simulations

The results of the simulations obtained with parameters corresponding to the aforementioned dimensions of the system, are analyzed and compared with each other. Fig 2 to 5 show the evolution of the parameters during the heating period. These parameters are consecutive to the elements of the heating system, thermal sensor, storage tank, heat pump, radiators and building. The heat transfer fluid output temperatures of thermal sensors Tc2, the storage tank Trs, the electrical power consumed, the thermal power produced and the ambient temperature in the building Tai are all influenced by the sun exposure Es and the ambient ambient temperature Ta1 in the different situations.

For scenario S_1 (Fig.2), when there are thermal inputs from both illumination and human metabolism, indoor air temperature peaks up to 22.4°C are observed during occupation period of the hall. The inputs are more important than the thermal needs of the room. The set limits are exceeded. This reflects the lack of direct effect of regulation on these contributions. From 0:00 to 08:00, the solar flux is low to zero, the heat pump works in a linear way and without stop. In the middle of the day between 08:00 to 18:00, its operation changes. It is characterized by two major stops totaling 09:40 with a 40min walk from 13:20 to 14:00. The energy demand is low because the solar flux provides the need for heating. As a result, radiator heat

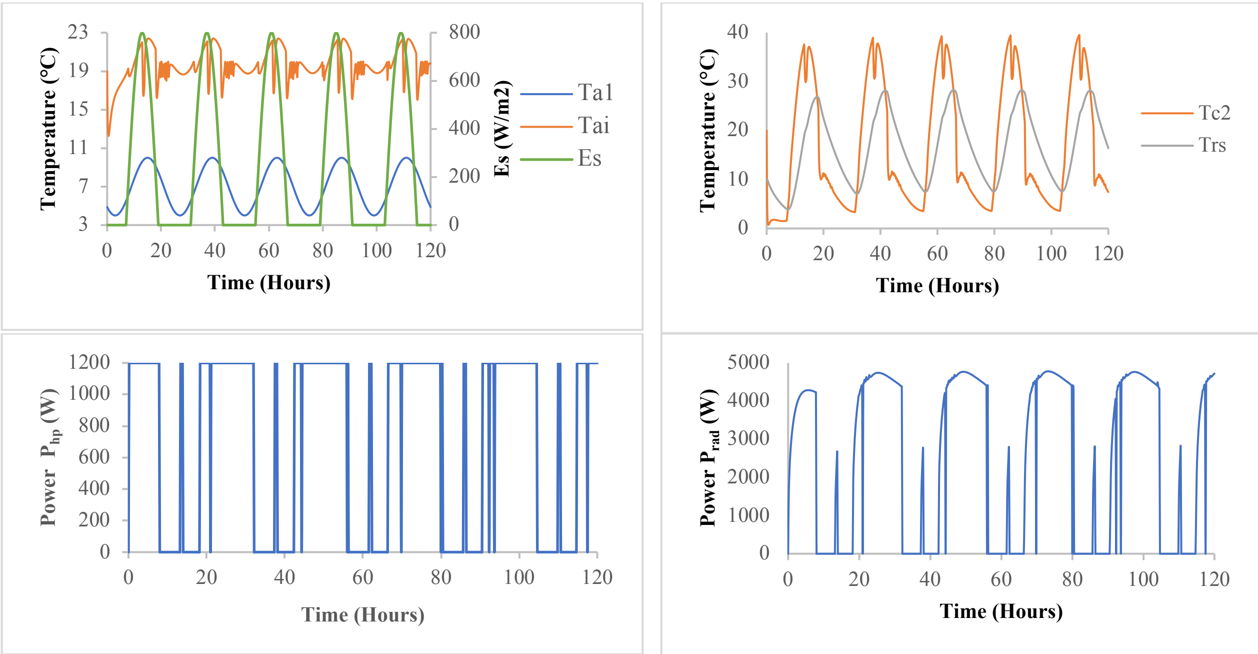

Fig.2: Variation of the studied system parameters during scenario S_1

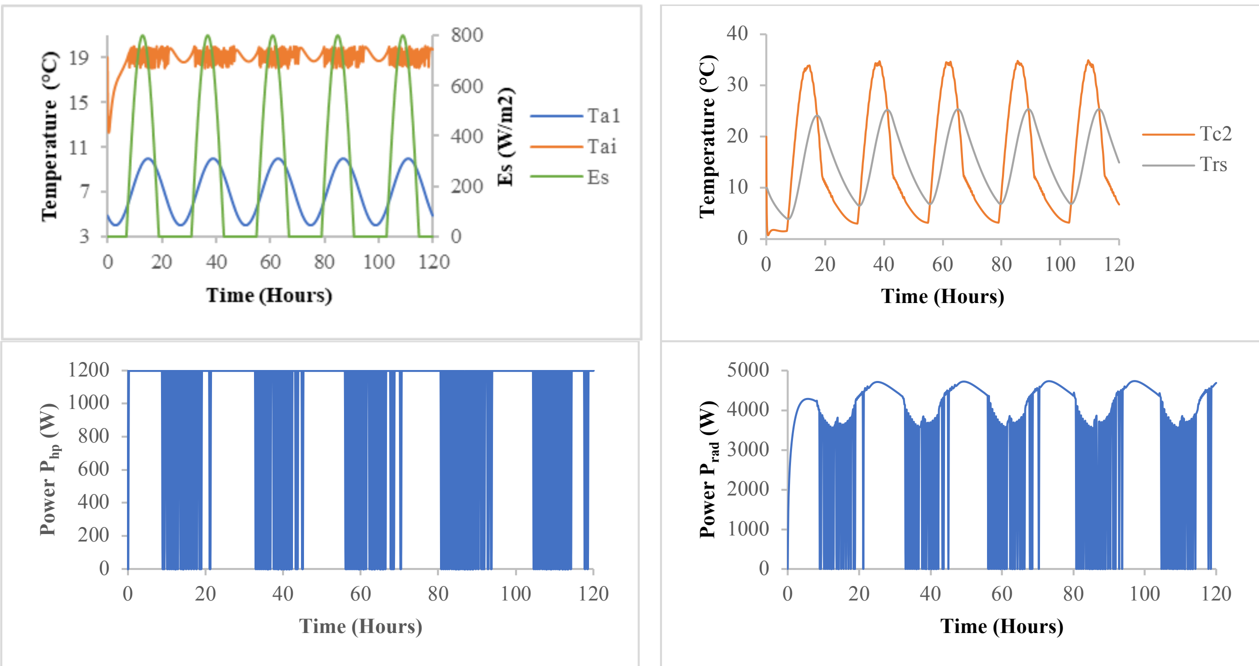

Fig.3: Variation of the studied system parameters during the S_2 scenario

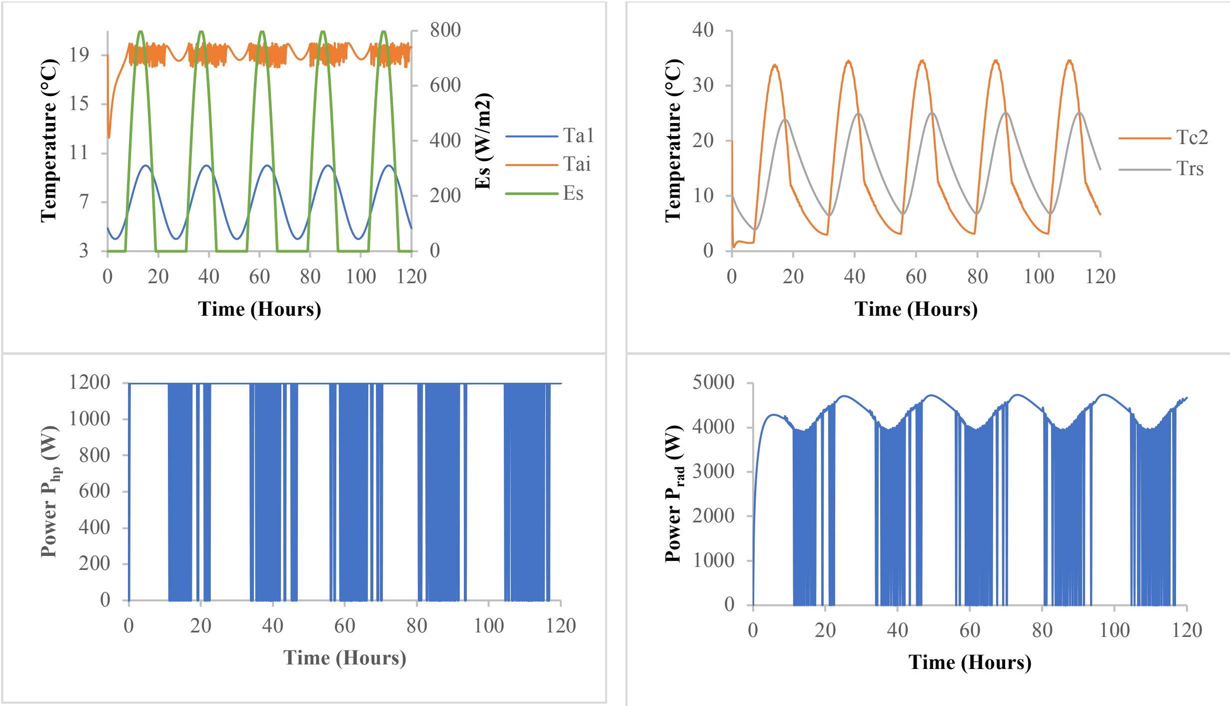

Fig.4: Variation of the studied system parameters during scenario S_3

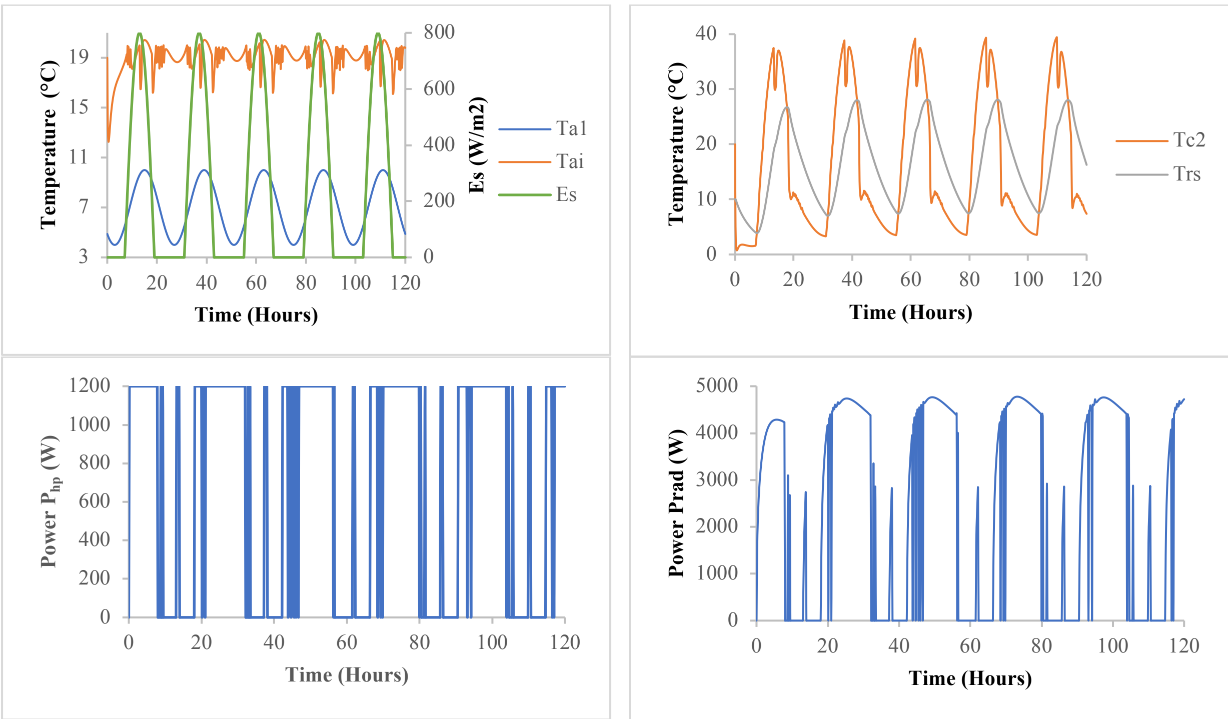

Fig.5: Variation of the studied system parameters during scenario S_4

output is low to zero during this time slot of the day. The heat transfer fluid outlet temperatures of the thermal sensors and the storage tank reach the respective maximum values of Tc2max = 39.51°C and Trsmax = 28.28°C. At 18:20, the continuous regime of the heat pump resumes with a stop of 10min between 20:50 and 21:00.

For the case S_2, there is a better change in internal temperature of the air without exceeding the set point 18 at 20°C. From 0:00 to 8:00, it is a period of linear operation of the heat pump with a constant electric power of 1200W. On the other hand, between 09:00 and 19:00, one observes 17 times the stops of the heat pump of which 2stops of 20min and the remains last each time 10min. From 19:00, the regime becomes normal with a single stop of 10min. In this case, the heat pump is much more solicited during the day than in S_1 with periods of short stopping. Same situation for radiators. The maximum heat transfer fluid outlet temperatures reach only Tc2max = 34.94°C and Trsmax = 25.37°C.

Regarding the S_3 scenario, the heat pump runs almost the whole day with stops of 10min each time. it stops 16 times in 24 hours. It is too much solicited. As a result, its power consumption is high at 16.53kWh per day for an daily average COP of 2.41. The analyzes of S_1 are valid in case S_3. The maximum heat transfer fluid outlet temperatures, for case S_3, reach the maximum values of Tc2max = 34.66°C and Trsmax = 25.13°C.

Finally for the scenario S_4, between 0:00 to 07:50, the heat pump runs continuously. Then, from 08:00 to 18:00, the regime changes. It is characterized by 4stops of respective durations 50min, 20min, 220min and 250min. the only time of walk lasts 10min between 08:50 and 09:00, 10min between 09:30 to 09:40 and finally 50min, between 13:00 to 13:50. Its daily average COP is 5.5 higher than the other scenarios and its consumption is the lowest, 11.40 kWh per day. S_2 analyzes are also valid for S_4. The maximum outlet temperatures of the coolant, they are 39.43°C and 28.12°C respectively Tc2max and Trsmax.

Table.1: Characteristic parameters of the heat pump according to different heating scenarios

Parameters	S_1	S_2	S_3	S_4
Daily energy consumed (kWh)	11.40	15.67	16.53	11.40
Average daily COP	5.17	2.48	2.41	5.50

Table.2: Thermal power produced by radiators according to different heating scenarios

Parameters	S_1	S_2	S_3	S_4
Daily heat dissipated (kWh)	40.96	56.23	60.49	40.93

Table.3: Mean and standard deviation of ambient air temperatures heated according to different scenarios

Parameters	S_1	S_2	S_3	S_4
Average indoor air temperature (°C)	19.63	18.94	18.96	19.00
Standard deviation of ambient indoor air temperature	1.69	0.95	0.95	1.15

Table.4: Maximum temperatures of the coolant in different heating scenarios

Maximum temperatures	S_1	S_2	S_3	S_4
Temperature at the output of solar thermal collectors T_{c2} (°C)	39.51	34.94	34.66	39.43
Temperature at the output of the storage tank T_{rs} (°C)	28.28	25.37	25.13	28.12

6. Conclusion

The simulation results of the solar heating system equipped with a heat pump helped to analyze the influence of the internal thermal loads on the system performance and the thermal comfort. For that purpose, four study scenarios have been defined. As a result, the internal thermal contributions that had been studied, in particular lighting and human metabolisms, should be considered in home solar heating when these contributions are significant. Taking scenario S1 into consideration, the greater the input, the less the heat pump uses electrical energy up to 11.40kWh with a better COP equal to 5.17. On the other hand, radiators are less needed with a production of 40.96kWh. The internal temperature reaches 22.4°C, because of the strong sunshine. The electrical power consumption of the heat pump falls by 3.07kWh when there are all internal thermal inputs than in the absence of inputs. In the absence of inputs, comfort is supplied but the heat pump consumes more with a poorer COP of 2.41. The analysis of the results of these scenarios shows that internal thermal inputs play an essential role in the heating system. They contribute to the reduction of the electricity consumption of the heat pump by reducing its time and its daily operating regime. They induce a reduction in the thermal production of radiators. The daily operating time of the pump is reduced by 40% when all internal loads contribute to heating. This same time falls to 10% when there is no internal load. In addition, internal inputs play a major role in improving the performance of the thermal sensors and the tank. The temperature of their heat transfer fluid is better and maximum when there is supply.

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Nomenclature

C_{rad} Thermal capacity of the radiator, J/K

COP Heat pump coefficient of performance

Es Solar radiation, W/m^2

Tai Indoor ambient air temperature, °C

Ta1 Outside ambient air temperature, °C

T_e Hot water inlet temperature radiator, °C

T_s Hot water outlet temperature radiotor, °C

Tc2 Outlet temperature of the heat transfer fluid of solar collector thermal, °C

Trs Storage tank temperature, °C

P_{hp} Electric power consumed by the heat pump, W

P_{rad} Thermal power dissipated by the radiators, W

UA Loss coefficient-area product, W/°C

ΔT Logarithm temperature difference, °C