IOP Conf. Series: Materials Science and Engineering **353** (2018) 012004 doi:10.1088/1757-899X/353/1/012004

Solar air heating system: design and dynamic simulation

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Abstract. The building sector is one of the big energy consumers in Morocco, accounting for about 23% of the country's total energy consumption. Regarding the population growth, the modern lifestyle requiring more comfort and the increase of the use rate of electronic devices, the energy consumption will continue to increase in the future. In this context, the introduction of renewable energy systems, along with energy efficiency, is becoming a key factor in reducing the energy bill of buildings. This study focuses on the design and dynamic simulation of an air heating system for the mean categories of the tertiary sector where the area exceeds 750 m3. Heating system has been designed via a dynamic simulation environment (TRNSYS) to estimate the produced temperature and airflow rate by one system consisting of three essential components: vacuum tube solar collector, storage tank and water-to-air finned heat exchanger. The performances estimation of this system allows us to evaluate its capacity to meet the heating requirements in Ifrane city based on the prescriptive approach according to the Moroccan Thermal Regulation. The simulation results show that in order to maintain a comfort temperature of 20°C in a building of 750m3, the places requires a thermal powers of approximately 21 kW, 29 kW and 32 kW, respectively, for hotels, hospitals, administrative and public-school. The heat generation is ensured by a solar collector areas of 5 m², 7 m² and 10 m², respectively, for hotels, hospitals, administrative and public-school spaces, a storage tank of 2 m3 and a finned heat exchanger with 24 tubes. The finned tube bundles have been modelled and integrated into the system design via a Matlab code. The heating temperature is adjusted via two controllers to ensure a constant air temperature of 20°C during the heating periods.
Keywords: Solar energy, heating system, tertiary buildings, heat exchanger, vacuum tube collectors.

1. Introduction

At the global level, the building sector accounts for around 28% of final energy consumption and contributes about a third of CO_2 emissions. In Morocco, this sector is the largest consumer of primary energy, 23% of the total consumed energy, which represents 17% for residential and 7% for the tertiary sector. This energy consumption is expected to increase in the coming years due to:

- The significant evolution of the building stock through the setting up of different programs: Azur plan for hotels, emergency program for national education, program of 150000 housing units per year and hospital rehabilitation program.

- The modern lifestyle requirements and the low price of equipment (heating systems, air conditioning, water heating, refrigeration ...) [1].

Significant research and developments have taken place in the last 20 years, in terms of the energy efficiency in buildings, whether for thermal isolation materials, building architectures, electrical equipment and also on energy conversion systems.

In terms of thermal insulation, significant evolutions have been observed, this is the case of low-emissivity double glazing, led to a two-thirds reduction in thermal losses. Thus, the appearance of selective layer glazing, makes it possible to limit solar gains and avoid overheating [2].

The technologies and systems related to the ventilation of buildings have been the subject of significant advances: advent of DC ventilators and double-flow ventilation, allows a considerable increase in the consumption of ventilation systems.

In terms of lighting, the technological evolution is not left out, new lamps have appeared which have a greater luminous efficiency. These include compact fluorescent lamps, which at equivalent luminous flux, divide the installed power by three, as well as LEDs (Light Emitting Diodes), mainly used for signal lighting, which help to reduce the consumption of lighting installations. Although the use of electronic ballasts instead of magnetic ballasts leads to a reduction in the consumption of the installations, thanks to the fact that the control systems are taken into consideration. [3]

In the heating sector, progress is also sensitive. In fact, the efficiency of the heat production units has increased significantly with the appearance of low and very low temperature boilers, condensing boilers and solar water heaters. Improvements in burner technology have resulted in an improved efficiency and reduced emissions of CO_2. Regulation system has also evolved thanks to the introduction of electronic modules, which have made it possible to remote control or diagnosis. Point-to-point control techniques (eg thermostatic valves) have become widespread and have been combined with centralized controls.

Reducing energy consumption in buildings is therefore a major economic and ecological issue. It is in this context that the considered solar air heating system, comes to improve energy efficiency in the building sector especially in the tertiary sector trough the integration of solar energy.

In this article, we will show the calculation methods used, the design and the simulation of the proposed system. The main objective of this system is to maintain a temperature of 20°C inside the building, by adjusting the injected air flow and using solar collectors.

2. Methodology

Based on the seasonal variations of solar irradiation and consequently ambient temperature the required thermal energy in a building has to be estimated in order to optimize the air heating system capacity and consequently ensure the comfort temperature of 20°C.

According to the Moroccan Thermal Regulation in Building, there are two methods to define the required thermal power:

2.1. Performance approach

The performance approach consists of defining the minimum technical specifications in terms of thermal performance of the building, these are evaluated through the annual energy needs of the building related to thermal comfort. In our case, the heating requirements, according to the Moroccan thermal regulation, are about 50 kWh/m²/year for the good insulation conditions and 120 kWh/m²/year for poor conditions in the climatic zone for Ifrane city.

The required power ensured by the proposed solar heating system can be estimated as follows:

$$\boldsymbol{P = H_L \times \Delta T} \qquad \textbf{(1)}$$

With:

P: Thermal power of the system [W]

$\mathbf{H_L}$: Heat losses [W/°C]

ΔT: Difference of the inside temperature and the outside temperature (**$T_{int} - T_{ext}$**) [°C]

Heat losses are calculated using this formula:

$$H_L = \frac{Q_{ann}}{UDD} \quad (2)$$

With:
Q_{ann}: Annual Heat Requirements [kWh/yr]
UDD: Unified Degree Days [°CJ]

An empirical correlation has been established from the measurements of 146 weather stations to estimate the unified degree days [4]:

$$UDD = -100{,}51 \times T_{ext} + 1704 \quad (3)$$

With: **T_{ext}**: Outside temperature [°C]

2.2. Prescriptive approach

The prescriptive approach consists of setting the acceptable technical specifications limit according to the walls thermal characteristics of the building envelope. These characteristics are represented by the volume thermal transmittance for tertiary sector based on the Moroccan thermal regulation [5]. Therefore, the required thermal power is calculated as follows:

$$P = G \times V \times \Delta T \quad (4)$$

With:

P: Thermal power of the system [W]
G: Volume thermal transmittance [W/(m^3×C°)]
V: Volume of the building [m^3]
ΔT: Difference of the inside temperature and the outside temperature ($T_{int} - T_{ext}$) [°C]

The prescriptive approach is considered in the coming simulations because of its precise estimation of the energy needs for a given space and thermal transmittance based on the Moroccan Thermal Regulation.

3. Control and design parameters

The solar heating system design has been conducted in a dynamic simulation environment (TRNSYS'17) to estimate the generated air temperature and airflow rate by one system consisting of three main components: flat plate solar collector, storage tank and water-to-air finned heat exchanger as it is show in figure 1. The heating system has been designed to ensure a comfort temperature of 20°C and to compensate the thermal heat losses from September 22th to March 19th from a volume of 750m^3 in different categories of tertiary sector based on the minimal thermal transmittance recommended by the Moroccan regulation namely: administrative and public school buildings (G=1.78 W/$m^{3\circ}$C), hospitals (G=1.17 W/$m^{3\circ}$C) and hotels (G=1.47 W/$m^{3\circ}$C). Different control functions have been considered according to the daily required heating hours for each category. Hotels and hospitals need to be heated all the time, however, the heating period is from 8 am to 6 pm in administrative and public school buildings.

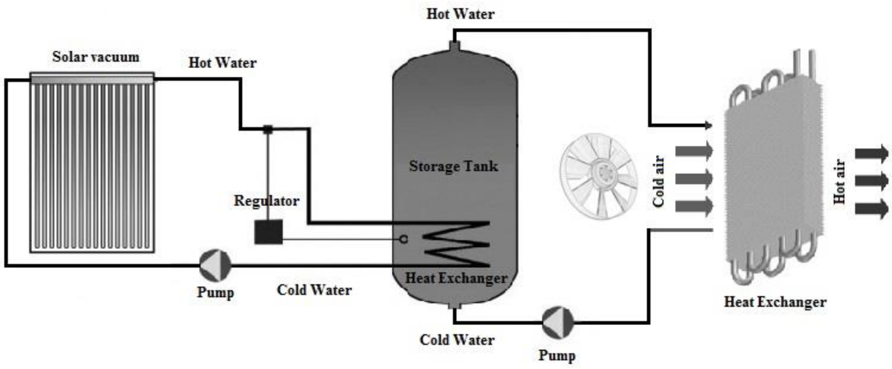

Figure 1: Solar heating system

The heating system sizing has shown that in order to satisfy the required air flow rates and temperature, the flat plate solar collector has to be sized based on the building category and the maximal water flow rate in the solar loop should be 1kg/s, accumulated in a water tank of 2m^3. Furthermore, the hot water circulates in the heat exchanger loop with a maximal flow rate of 0.5kg/s where the thermo-flow characteristics have been estimated based on the last established models in the literature [6]. The hourly solar irradiations in Ifrane city have been obtained from Meteonorm software and considered in the present dynamic simulations. In order to control the outlet air temperature, two hysteresis controllers have been used in the solar heating system. The first controller was configured in the solar loop based on an upper dead band of 10°C and lower dead band of 2°C while the second one was placed in the heat exchanger loop based on the high limit cut-out temperature with the aim to stabilize the outlet air temperature at 20°C and stop the heat exchanger blower when the ambient temperature exceeds 20°C. Nevertheless, regarding the intermittent behaviour of solar radiation an additional heater was necessary to compensate the possible energy deficit.

4. Results and discussions

4.1. Heat flow rate

The heat losses from a space of 750 m^3 has been calculated for different building categories based on the thermal transmittance for each one and compared with the total heat flow rate provided by the solar heating system.

Figure 2 shows a comparison between the total heat flow rate, provided by a solar collector of 5m^2, and the heat losses from a Hotel space. It can be seen that the considered system is able to produce more than 26 kW that is enough to cover the maximal required heat which is around 21 kW. In the worst case, the additional heater contributes with not more than 2.4 watts which represents 0.01% of the maximal heat flow rate.

Figure 3 illustrates that a hospital space of 750 m^3 requires a solar collector area of 7 m^2 providing a maximal thermal flow rate of around 29 kW in order to cover the maximal heat losses of around 26 kW. Only 0.005% of the maximal heat flow rate is covered by the additional heater generates.

Figure 4 shows that the total thermal flow rate generated by the solar heating system satisfy the required heat in the administrative and public school spaces using a solar collector area of 10 m^2. In this estimation, an air flow rate of 1.3 kg/s has been considered to compensate the maximal heat losses from the heated space which is estimated by around 32 kW.

As it can be observed in the previous figures, the solar heating system generates higher power in some periods which can be adjusted by controlling the air flow rate according to the required thermal flow rate. Generally, the heat generation is stopped in two cases, the first one is when the ambient temperature is more than 20°C as it has been configured in the controller of the heat exchanger loop and the second one is from 6pm to 8am when heating is not required by administrative and public school buildings.

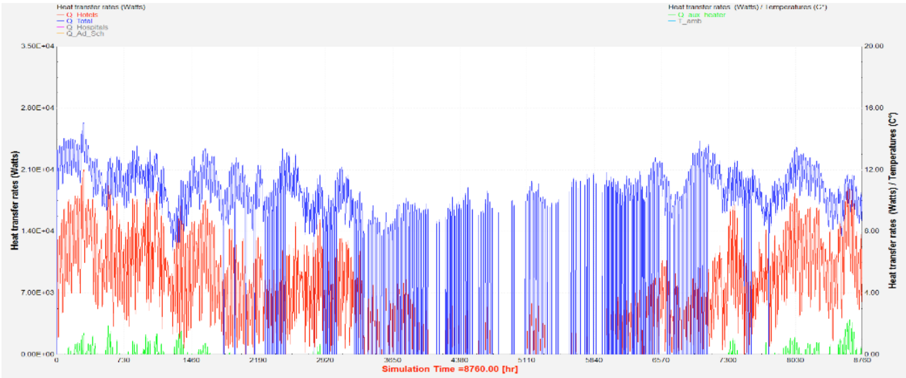

Figure 2: Heat flow rates in Hotels

Figure 3: heat flow rates in hospitals

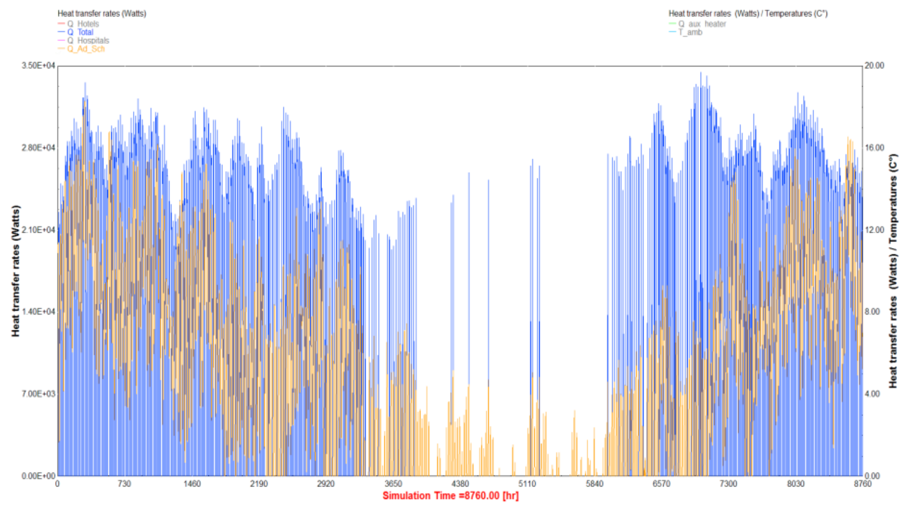

Figure 4: heat flow rates in administrative and public schools

4.2. Heating temperature

The air outside temperature (Tair_in), the air outlet temperature from the heat exchanger (Tair_out) and the final air outlet temperature provided by the whole system (Tair_Final), are plotted in figures 5, 6 and 6, respectively, for hotels, hospitals and administrative and public school spaces. The solar heating system increases the air from the ambient temperature (Tair_in) to the comfort temperature based on the hourly irradiation during the year. It can be seen that the final air outlet temperature is equal to 20°C when the ambient temperature is above the comfort temperature, however the solar heating system doesn't work when the ambient temperature is more than 20°C which means that the air temperature is equal to the ambient temperature or less if the place is equipped by a cooling system.

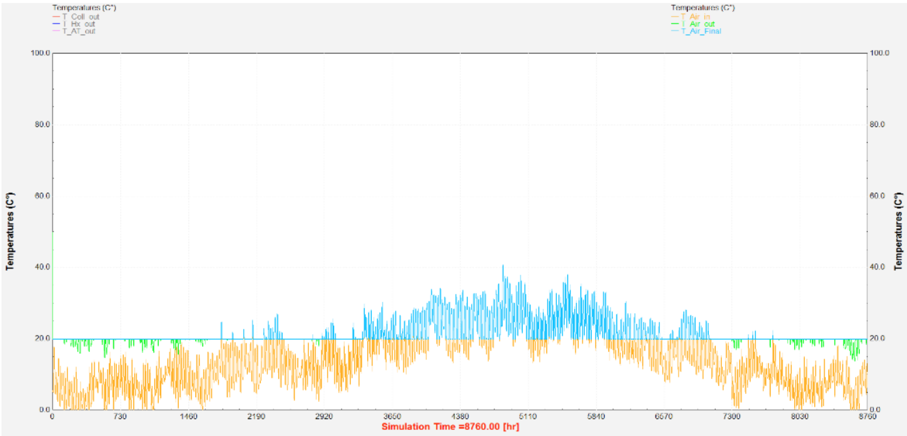

Figure 5: Air temperatures in hotels

Figures 5 and 6 illustrate that the additional heater is needed when the air ambient temperature is less than 1°C and -1°C, respectively, for hotels and hospitals.

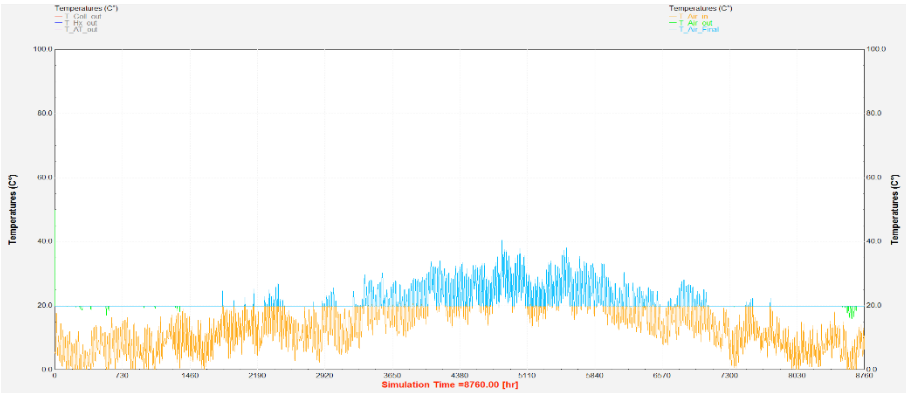

Figure 6: Air temperatures in hospitals

As it can be seen in figure 7, the additional heater doesn't participate in heat generation during the year in administrative and public school buildings thanks to the enough heat produced by the solar loop. Outside the required heating period determined by the control function, the air temperature is equal to the air ambient temperature.

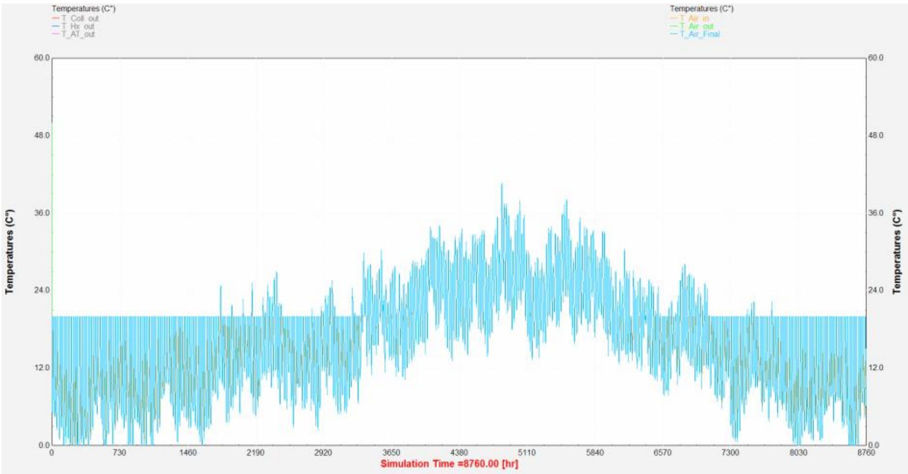

Figure 7: Air temperatures in administrative and public schools

5. Conclusion

Solar air heating is a solar thermal technology where radiations are captured and then transformed by a conversion system to heat the air. It is a renewable energy technology used for heat and cooling generation whether in residential or tertiary sectors. In the present study, the heating system has been designed to ensure a comfort temperature of 20°C and to compensate the thermal heat losses inside a volume of 750 m^3 in tertiary sector. Simulation results have shown that the system can compensate the thermal losses and thus ensure the comfort temperature for the different building categories of the tertiary sector. The sizing of the system differs from one case to another, it depends on the required thermal power and the considered heating period. In this case, the maximal estimated thermal power is around 21 kW, 29 kW and 32 kW based on a solar collector areas of 5 m^2, 7 m^2 and 10 m^2, respectively, for hotels, hospitals, administrative and public-school spaces. This calculation is based on the minimal thermal transmittance recommended by the Moroccan regulation using the TRNSYS environment.

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