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Development of an advanced simulation model for solar cooling plants

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Abstract

Solar Cooling systems represent an effective solution to increase the use of solar energy in buildings, satisfying cooling demand in a sustainable and efficient way. Although the reference technologies are mature (solar collectors, absorption chillers, adsorption chillers, etc.), these systems often require detailed studies to define control techniques, management integration systems and energy optimization [1,2]. This work has been focused on the development and calibration of a dynamic simulation model of a solar cooling system in order to create an efficient and robust tool to support the phases of planning and management. The model was developed in Matlab-Simulink ambient taking as a reference the system installed at the building F-51 of ENEA Research Center "Casaccia" in Rome. The calibration carried out made the model representative of reality with an average error of 10% and it has allowed us to quantify the benefits obtained by some optimization measures in order to make the maximum primary energy savings in the overall operation of the system. The simulation model can help to increase the commercial deployment of solar cooling systems when used to identify the layout of plant and the associated control strategies that maximize the system's efficiency and profitability of the investment.

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1. Introduction

The solar heating and cooling systems allows to achieve considerable energy savings compared to conventional plants. The better choose of the system layout configuration and of the right size requires the use of dynamic simulations to investigate the indoor climatic conditions in a building. The paper presents the use of the Matlab-Simulink package to implement a model of the solar heating and cooling system and its calibration by the use of data of the summer working period. The technology of solar cooling for the air conditioning of the buildings has a high potential and induces considerable advantages: the cooling loads and the availability of solar energy are in phase; furthermore, the use of a renewable source allows to obtain a primary energy savings [3]. The model was calibrated with data of summer 2013 from the plant installed in ENEA Research Center “Casaccia” in Rome.

2. Description of solar heating and cooling installation

The installation of solar heating and cooling made in the building F-51 of the ENEA Research Centre has been integrated with the existing air conditioning system. The retrofit was made in 2009 with components, appliances and commercial machines easy to find on the market to ensure an easy replicability of the plant. The system is composed of:

- a solar field consisting of 30 evacuated tube solar collectors inclined at 40 °, facing south, for a total gross area of 112 m²; the collectors are anchored by steel structure in the roof plan 'building (Fig. 1a);
- a thermal storage system consisting of two tanks of 1500 liters each, connected with the solar circuit through a heat exchanger. The control logic considers alternately an accumulation priority than the other for the exchange with the solar field and the remaining accumulation has therefore priority to supply the load (Fig. 1b);
- an absorption chiller with a solution of $LiBr/H_2O$ of 70 kW with cooling tower (Fig. 2a);
- a chilled water storage of 2000 liters connected whit the absorption chiller (Fig. 2b);
- network of sensors connected to the control system and data acquisition (Fig. 2c-d).

Fig. 1. (a) solar field in the roof of building; (b) hot thermal storages.

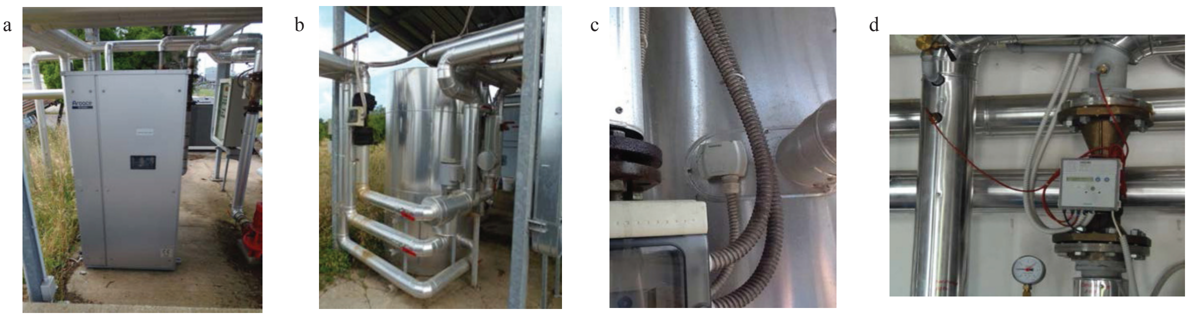

Fig. 2. (a) absorption chiller; (b) storage of chiller water; (c) thermocouple in the tank; (d) energy meter.

The system was created with the aim of studying different configurations of integration to evaluate the convenience and practicality, so there are two systems integration: a natural gas boiler for the thermal energy input to the absorption chiller and an electrical reversible heat pump for the cooling demand. The schematic diagram of the system is shown in figure 3a, where red line indicates the components used in winter mode while blue line indicates components used exclusively in summer mode. For heating in winter operation mode, the absorption machine is clearly excluded and the hot water produced by solar panels with the integration of the gas boiler is sent directly to the fan coils serving the building. In the summer configuration the absorption machine is used. It receives the heat by hot water whit a temperature in the range 75-95°C and produces chilled water around 7-12 ° C in proportion to the temperature of the hot spring that feeds it [4,5]. In summer period, the system is more complex and the water heated by the panels is sent to the machine and not directly to users: the gas boiler integration started when hot water temperature doesn't reach the minimum temperature level. The seasonal regulation is done by changing the opening of the valves V3 and V4. When the irradiation is very high and the user does not require excessive power output temperature of the panels can reach high value and became difficult to manage, in this case a system is provided for heat dissipation.

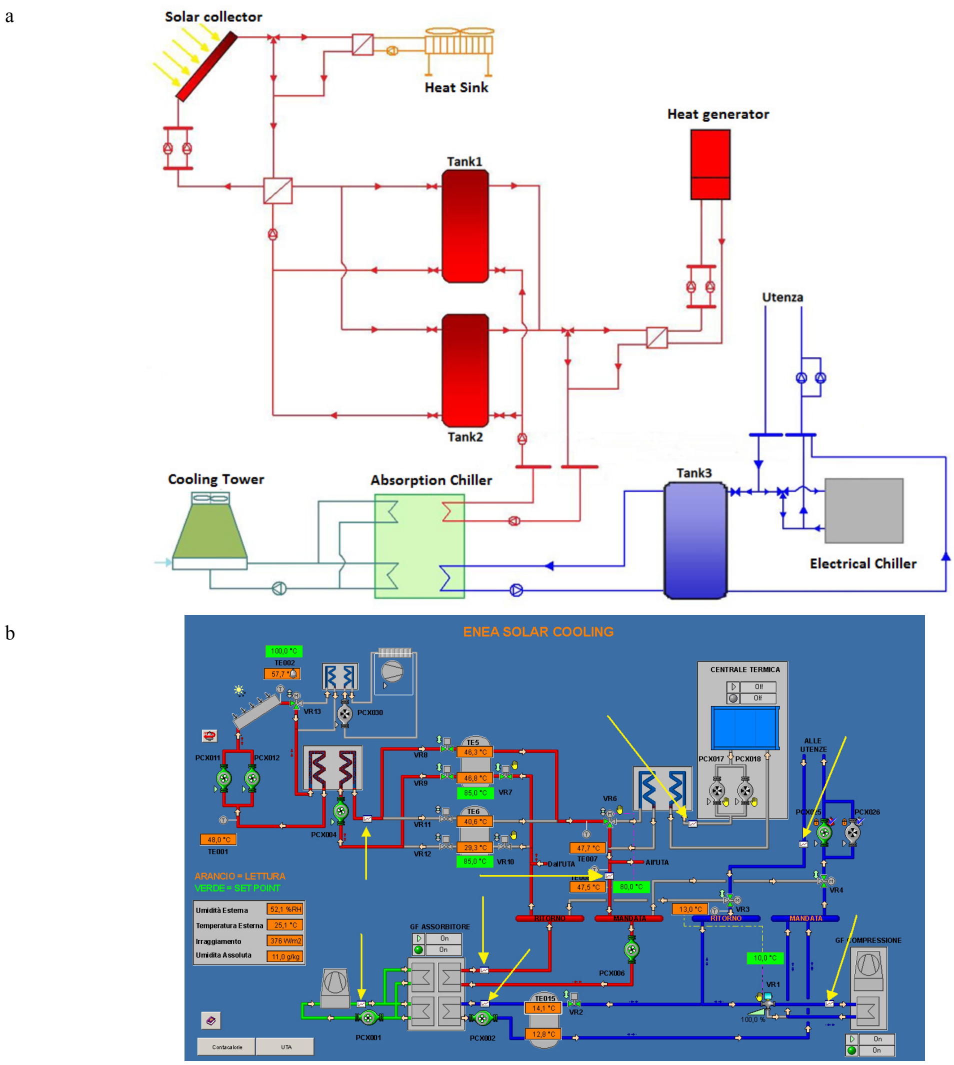

Fig. 3. (a) plant scheme of the solar heating and cooling system, (b) control interface of the management system.

3. Development and calibration of the model

The simulation model was developed in Matlab-Simulink, a very popular modeling environment characterized by an approach to virtual modeling at the level of components and systems quite simple and intuitive. The various simulation blocks have been created from the physical understanding of the component to create a mathematical representation that allows to simulate different operating scenarios including the transient operation. Operation of blocks was then compared with the technical data provided by manufacturers to have an accurate and correct model. The plant being studied has a management platform, whose web interface is shown in figure 3b, which detects the main operating variables, performs control operations and storing the monitored data. The sensors used are temperature sensors (thermocouples) installed along the pipes and in the tanks, an external sensor for environmental temperature and humidity, energy metering systems (consist of a pair of temperature sensors and an ultrasound flow meter) and a solar station for the measurement of solar radiation components. The calibration of the simulation model was aimed at verifying the correspondence between the measured values and those simulated; this operation was make exporting data from the model via the block "*To Workspace*" which allows to save data as a text file. The process of exporting data is controlled by the number of the day to start the simulation a few days earlier than the actual start of the review period in order avoid possible initial transient phenomena. The time step of the simulation is 15 minutes. The plant was started on June 20, but many maintenance operations have made regular operation only since July 18. The data are considered representative up to August 8, after this date, the low occupancy of the building for the summer holidays has altered the profiles of employment provided. In the following graphs is showed the comparison between the values measured and simulated. The percentages present in the histograms refer to the error between the two values taking as reference the measured quantity (Figures 8 and 11).

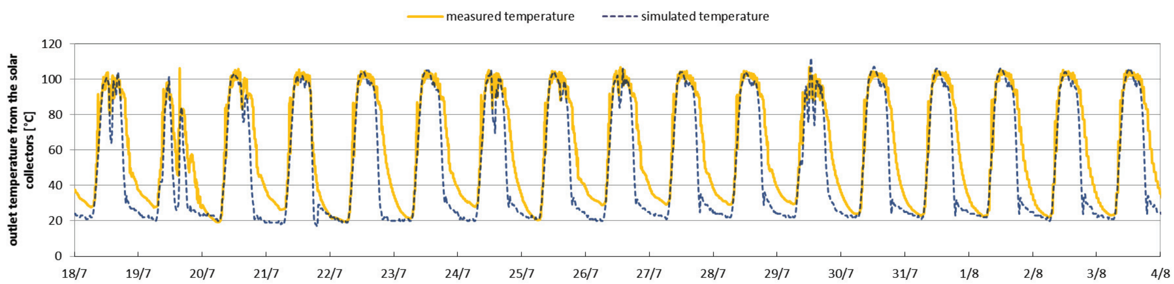

Fig. 4. comparison of the temperature at the outlet from the solar collectors

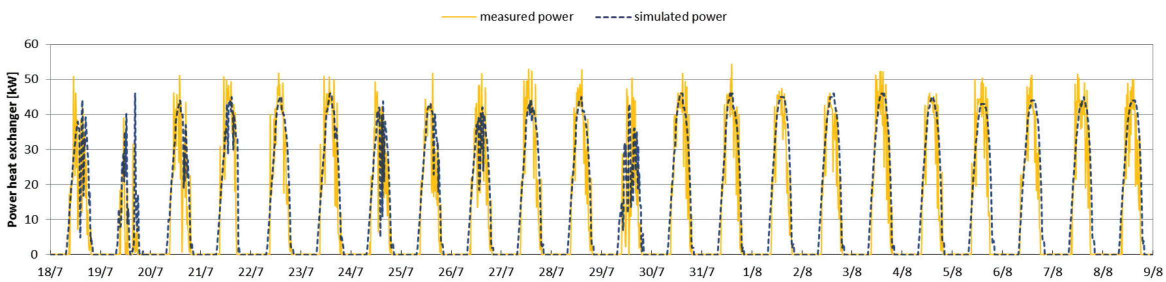

Fig. 5. comparison of the power at the outlet from heat exchanger

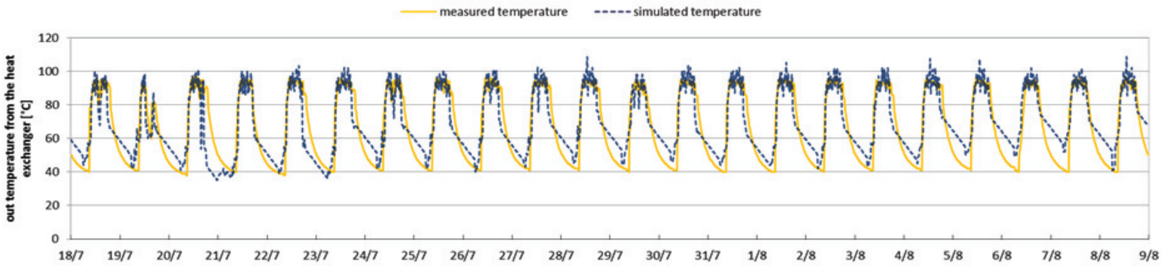

Fig. 6. comparison of the temperature at the outlet from the heat exchanger

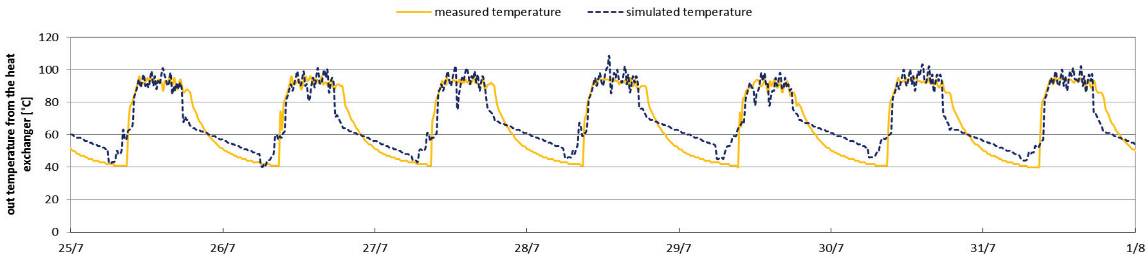

Fig. 7. focus on the comparison of the temperature at the outlet from the heat exchanger

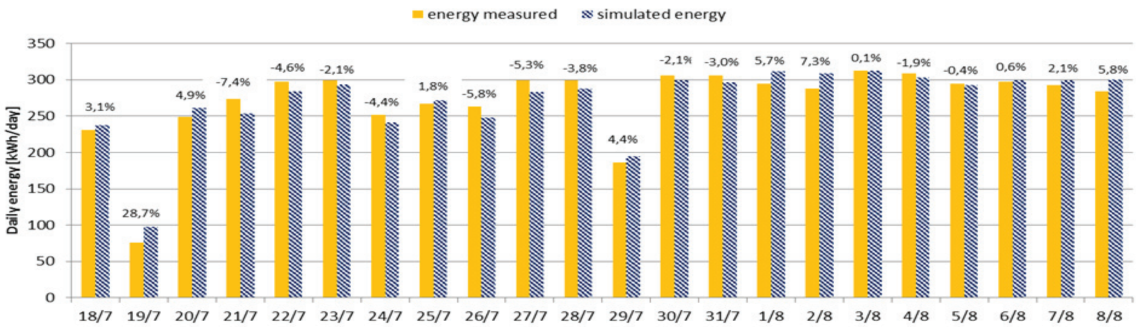

Fig. 8. comparison of the energy at the outlet from the heat exchanger

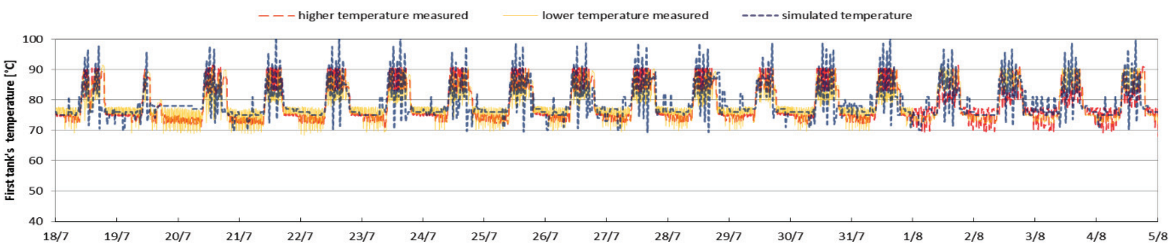

Fig.9.comparison of the temperature in first tank

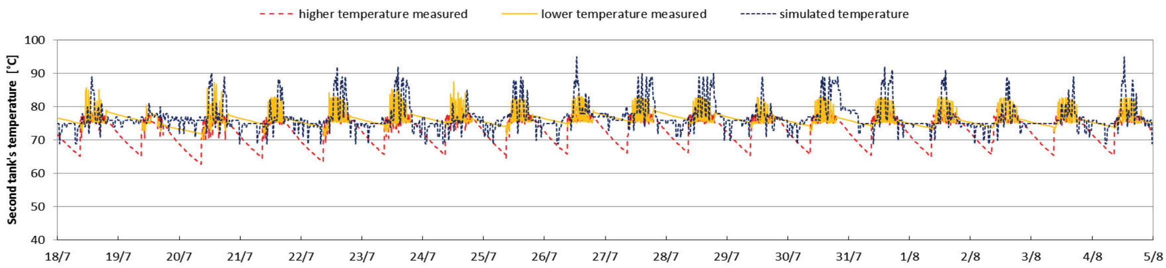

Fig. 10. comparison of the temperature in second tank

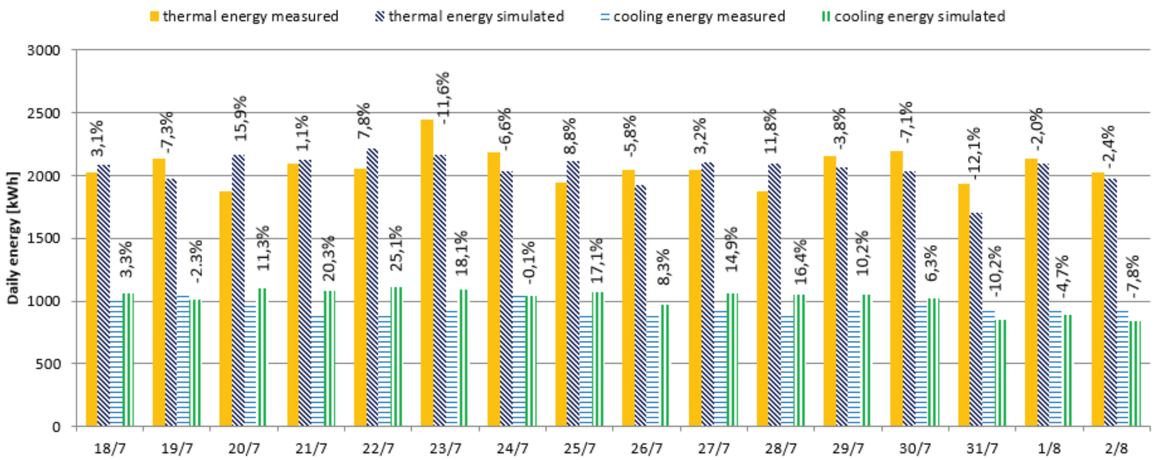

Fig. 11. comparison of the input and output energy in the absorption chiller

4. Simulations of plant optimization

In order to identify possible interventions aimed at improving the functioning of the solar plant and increase its efficiency the simulation model has been used to quantify the energy benefit achievable considering some changes in the system as listed below:

- use of the design flow rate in the solar circuits;
- extension of the solar area;
- use of low difference temperature system for cooling the offices (like radiant celling system).

These simulations were also conducted in order to assess the robustness, usability and reliability of the model in the case of configurations change in of same characteristic parameters of the plant.

4.1. Case A: simulation with design flow

In this first case was used the simulation model to quantify the benefit obtainable whereas to operate with the design flow rates, compared to the lower flow rate actually used (Figure 12), in the primary and secondary side of the heat exchanger placed between the solar collectors and the hot tanks. Specifically, the flow rate was increased in the primary side from 0.6 l / s to 1.6 l / s, the secondary side from 0.97 l / s to 3.1 l / s. This, in addition to increasing the usable power from the solar field and then the solar fraction, enables better management of the entire system because, with the increase of flow rate to the secondary, the charging time of the hot tank is faster than in the previous case. In addition, there is also an increase of the efficiency of the heat exchanger, from 0.84 to 0.88. The results show an increase in the energy supplied by the solar field of about the 8%, and an increase in solar fraction of 1.6 % (Figure 13 and Table 1).

Fig. 12. primary flow measurement with a portable ultrasonic flowmeter

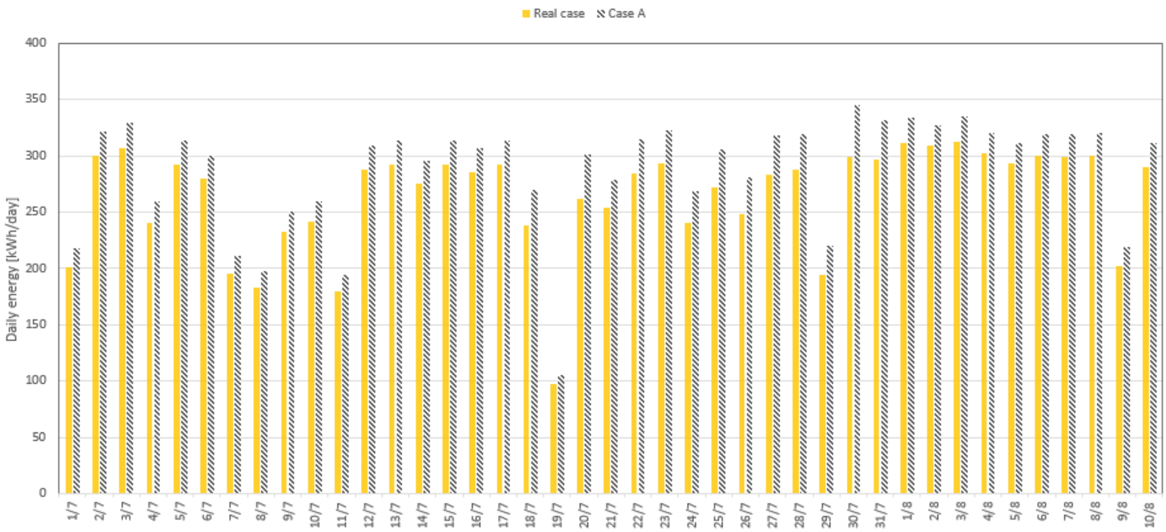

Fig. 13. increase the solar energy usable for case A

4.2. Case B:simulation with extension of the solar area

Another intervention that allows to make a better use of the system is the increase of the solar field collector area .An increase of 50% has been compared to the current situation, the area was been increased from 100 to 150 m² (net area) and thus reach a value of about 2.15 m² / kWcool than the previous 1.43 m² / kWcool. This choice has been made by some practical considerations relating to the real possibility of implementation in the real case study. In the building roof we can find the space for a third row of collectors connected in parallel to the two already installed without causing any shading problems on the other collectors and with no need of structural interventions. The flow rates were increased based on the data provided by the manufacturers. The results show that, compared to the based situation, an increase in energy provided by the solar field of 28% produce an increase of the solar fraction of 10%. (Figures 14 and Table 1).

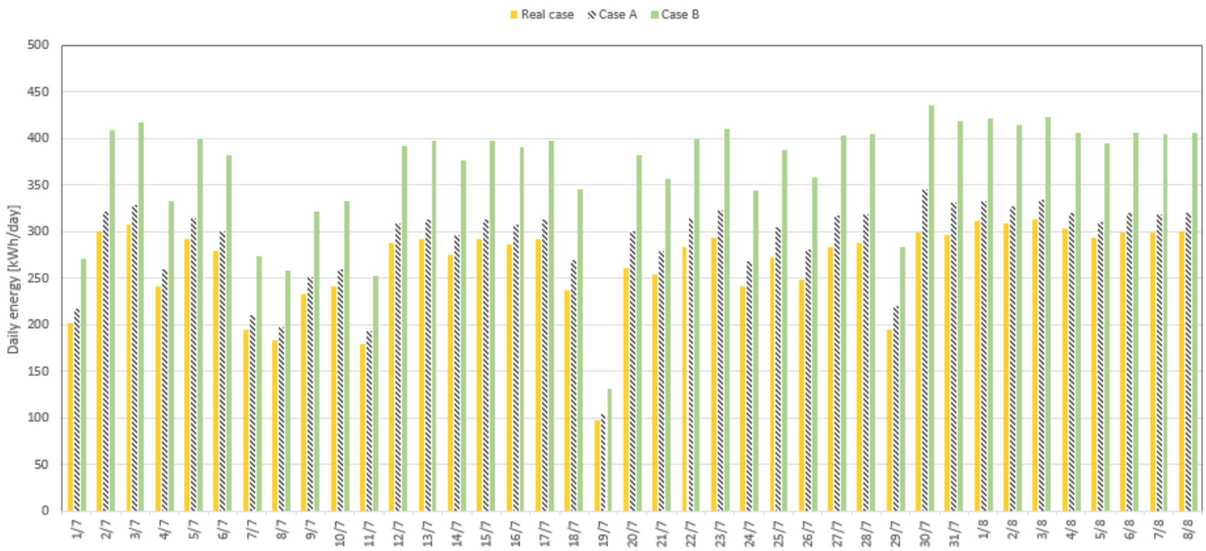

Fig. 14. increase the solar energy usable for case B

4.3. Case C: simulation with radiant system

In this case, it is assumed to use radiant ceiling system in place of the existing fan coils. The results show how the use of the radiant system is enough to satisfy the cooling requirements of the building maintaining the indoor temperature in the defined range. The use of radiant system requires a higher temperature level of the cold tank. With a consequent improvement of efficiency in the operation of the machine due to the increase of the COP because it can works with high temperature of evaporation [2,6]. Finally radiant systems characterized by a thermal inertia higher than fan coils [7,8]; allow a better adaptation to the discontinuity that may result from supply by renewable sources, such as solar radiation (Table 1).

4.4. Case D: simulation with extension of the solar area and radiant system

Case D simultaneously considers the interventions of cases B and C, then it is assumed to increase the area of solar and, at the same time, use a terminal radiant in offices (Table 1).

4.5. Results

The simulations were carried out for a total period of two months (July and August) with the climate data of 2013, considering the typical profiles of employment and using both sources of integration in the system. To compare the different cases, were considered the following parameters:

- efficiency of the heat exchanger as defined by the method ε-NTU;
- solar coverage calculated as the ratio of the energy from the solar collectors and the total thermal energy that feeds the absorber chiller;
- average daily COP of the absorber chiller;
- absorber coverage calculated as the ratio between the cooling energy produced from the absorber and the total cooling demand.

Table 1. Results of optimization of the plant.

Reference variable	Real case	Case A	Case B	Case C	Case D
Collectors number	30	30	45	30	45
Primary flow [l/s]	0.6	1.6	2.5	1.6	2.5
Secondary flow [l/s]	0.97	3.1	4.8	3.1	4.8
Output terminal	Fan coils	Fan coils	Fan coils	Radiant ceiling	Radiant ceiling
Exchanger efficiency	0.84	0.89	0.89	0.89	0.89
Solar coverage	33.2%	34.8%	45.1 %	43.9%	54.9%
COP absorber chiller	0.72	0.72	0.72	0.74	0.74
Absorber coverage	44.1%	44.3%	46.8%	73.3.2%	79.6%

5. Conclusions

The main purpose of this work is the calibration of a dynamic simulation model of a solar heating and cooling system developed in Matlab-Simulink, using real data from the plant installed in the ENEA Research Centre "Casaccia" in Rome. The calibration of the simulation model has given satisfactory results, particularly as regards the part relating to the solar collection and energy storage mainly through a high degree of detail of the models of the individual components (solar collector, heat exchanger, thermal storage), the accuracy of the technical data used and most importantly, thanks to the inclusion of climatic data actually measured. Very realistic simulations have been made, highlighted by the low error between simulated values with those measured.

The model developed allows possible improvements and optimization in plant assessment and shows its capability to identify vulnerabilities and possible weaknesses in plant operations.

The model can also be used as a valid tool to support the design and dimensioning of a new plant in simulating various behaviors of the system due to different management logics of the components and in researching the best control strategy to achieve maximum performance and primary energy savings.

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