Primary energy saving potential of a solar-driven ejector cooling system: a case study for a Portuguese residential building

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Primary energy saving potential of a solar-driven ejector cooling system: a case study for a Portuguese residential building

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Abstract. The seasonal energy performance of a cooling system based on an innovative variable-geometry ejector (VGE) is numerically investigated by using TRNSYS. The VGE-based system is mainly driven by solar energy, collected through solar thermal collectors, and is coupled to a residential building located in Porto. A biomass boiler is used as back-up heater. The energy performance of the investigated cooling system is compared with that of a conventional solution, based on a commercial air-to-water chiller. Results point out that, almost 75% of the generator heat demand can be supplied by solar collectors and about 90% of the overall energy input of the ejector-based system is satisfied by renewables. Moreover, numerical simulations confirm how the capability to vary the ejector geometry on the basis of current operating conditions allows to strongly improve the ejector seasonal efficiency. A second series of simulations aimed to further enhance the system performance. A master control logic which extends the VGE operation time in correspondence of favourable ambient conditions was introduced, in order to store additional cooling energy in the cold buffer tank. This strategy has proved to be effective, since the energy consumption of the biomass boiler could be reduced up to 35%.

1. Introduction

Nowadays, space cooling energy demand is growing rapidly and is mainly met by conventional vapor-compression units. Nevertheless, solar-driven ejector cooling is a relatively simple and low-cost technology and has high potential for space cooling applications, thanks to the intrinsic correlation between cooling load and solar irradiation [1]. Nevertheless, this kind of systems are characterized by low energy performance: the ejector Coefficient of Performance (*COP*) is typically lower than 0.3 and is strongly influenced by evaporator, condenser and generator temperature, as well by the working fluid properties [2]. In addition, ejector performance strongly depends on its geometry. In fact, under floating operating conditions, optimal ejector performance requires a variable ejector geometry (VGE) [3]. In this study, the seasonal energy performance of a cooling system based on the VGE proposed in [4] has been evaluated via dynamic simulations, by using the software TRNSYS. The key performance indicators of the ejector-based cooling system have been evaluated on a seasonal basis and compared to those of a reference cooling system based on a conventional air-to-water chiller.

2. Building and cooling system modelling

A solar-driven VGE system coupled to a single-family residential building recently built in Porto (Portugal) is modeled with TRNSYS. The building is characterized by an unheated basement and three conditioned floors, for a net floor area equal to 186.3 m^2. Figure 1 reports a view of the tri-dimensional model of the building, developed with TRNSYS3D plugin. Building envelope components present excellent thermal insulation properties. Relevant information about the building can be found in [5].

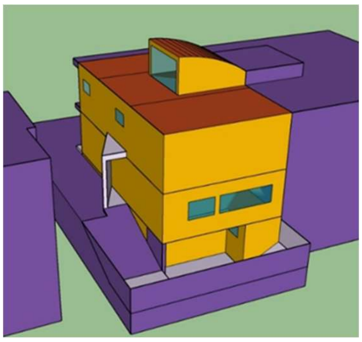

Figure 1. View of the building.

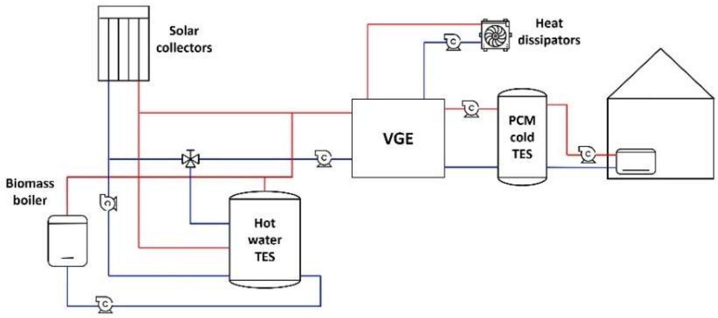

Figure 2. Layout of the ejector-based cooling system.

As pointed out by Figure 2, the cooling system is composed by several devices. The VGE is the main element of the system. The ejector operates with R152a and has the capability to adjust its geometry according to current operating conditions with two degrees of freedom. In particular: the nozzle throat area is changed by means of a movable spindle, while the relative position of the primary nozzle with respect to the entrance section of the ejector throat is varied by changing the nozzle exit position. Both the spindle and the nozzle position are adjusted to maximize the ejector *COP* and the secondary stream mass flow rate. The VGE evaporator is coupled to the building distribution loop by means of a 500 liters buffer tank, in which cold water can be stored. The thermal storage contains 30% in volume of encapsulated PCM (ATS15, melting temperature of 15°C) to increase its storage capacity. Heat from VGE condenser is dissipated to the outdoor ambient by using two commercial dissipator units (BAXI UL217), connected in parallel. VGE generator is mainly driven by solar energy. Nine flat plate solar collectors are installed on the building roof, facing South and having an inclination equal to 35°. Absorber area of each collector is equal to 2.1 m^2, while optical efficiency η_0, 1st and 2nd order heat loss coefficients are equal to 0.73, 1.68 W/m^{2}K and 0.01 W/m^{2}K^2, respectively. On the basis of solar energy availability and VGE operation, the solar collector field can directly heat up the VGE generator or charge a 1000 liters hot water buffer tank (TES). In addition, a biomass boiler characterized by a nominal heating capacity of 12 kW is used as back-up heater when low values of solar irradiation are present. As pointed out by Figure 2, six pumps are installed within the circuit.

Numerical models of VGE and biomass boiler are both based on a performance-map approach. VGE performance data are evaluated as a function of generator, condenser and evaporator temperatures, while the boiler efficiency depends on the part load factor and the inlet water temperature. VGE and biomass boiler performance data are not reported in this paper for sake of brevity and can be found in [6].

In order to evaluate the energy savings achievable with the proposed ejector-based cooling system, the dynamic model of a conventional solution has been also implemented. The traditional configuration consists of an air-to-water mono-compressor chiller, coupled to a 500 liters cold water buffer tank. Cooling capacity and electric power input of the unit at rated conditions (7°C/12°C - 35°C) are equal to 11.3 kW and 3.37 kW, respectively.

Both the control logics of individual components and the master control strategy of the whole system have been implemented in the dynamic model. Thermal energy can be collected by solar collectors when the solar field outlet temperature ($T_{out,col}$) is higher than a fixed threshold value (i.e. 20°C) and, simultaneously, larger than the water temperature in the lower part of the hot water TES. Moreover, solar field circulating pump is switched off for safety reasons when $T_{out,col}$ is higher than 110°C.

VGE operation is managed on the basis of different conditions. First, the water temperature at the generator and condenser inlet must be higher than 70°C and lower than 40°C, respectively. Cooling energy request is enabled when the temperature in the lower part of the PCM storage $T_{PCM,bot}$ increases above a defined threshold (SC_{on}=11.5°C). VGE is then switched off once the temperature in the upper part of the cold storage $T_{PCM,top}$ decreases below another threshold parameter (SC_{off}=17.5°C). Moreover, in correspondence of high values of solar irradiation the by-pass connection between solar field and VGE is activated to improve the system *COP*. Specifically, the by-pass is operated when $T_{out,col}$ is higher than a threshold value ($T_{set,bp}$), equal to 85°C. Finally, the biomass boiler is activated when cooling energy is required and the water temperature in the top part of hot TES is below 75°C.

Simulations have been performed to evaluate the efficiency of the system with a timestep equal to 1 minute. The considered cooling interval ranges from the 1st of May until the 26th of October (179 days). The solar fraction (*SF*) is selected as the main KPI of the system. It is defined as the ratio between the useful heat collected by solar field and the thermal energy delivered to the generator to drive the cycle. *SF* is expressed as a function of E_{bb}, the thermal energy provided by the biomass boiler, and E_{gen}, the total heat input of the VGE generator:

$$SF = 1 - \frac{E_{bb}}{E_{gen}} \tag{1}$$

3. Results and discussion

As first step, the seasonal performance of both the configurations (i.e. ejector-based and chiller-based solution) has been determined. About 90% of the total primary energy need for VGE system is linked to renewable energy, mainly solar and biomass sources. Furthermore, the electric energy consumption of the ejector-based system decreases up to 78% with respect to the conventional system. More in detail, electric energy need for the proposed solution is linked only to circulating pumps operation, since the VGE is thermally-driven by solar collectors and biomass boiler. It is important to highlight that, in this case, electric energy demand is limited to 5% of the building space cooling need. Nevertheless, due to the higher number of circulating pumps, pumping energy increases up to 53% in the VGE-based solution, if compared to the chiller-based system.

Numerical simulations show that the solar fraction of the ejector-driven cooling system is equal to 73.5%. The largest share of generator energy need is supplied by solar energy, with the biomass boiler operated as back-up heater for a limited part of the season. In fact, only 26.5% of the VGE thermal energy input is supplied by the boiler. Moreover, it is important to stress that the biomass typology can be selected on the basis of the system location, in order to minimize the overall environmental footprint of the VGE-based solution. Performed simulations confirm that the potential to vary the ejector geometry on the basis of current operating conditions allows to significantly increase the system efficiency. In fact, the ejector seasonal *COP*, equal to 0.67, is almost doubled with respect to typical values reported in other published works ([2]-[3]).

Nonetheless, in order to further improve the seasonal performance of the VGE-based system, an enhanced master control logic has been tested via dynamic simulations. More in detail, the value of parameters introduced for VGE operation (i.e. SC_{on} and SC_{off}, used for activation and de-activation, respectively) are decreased when the solar field outlet temperature or the water temperature in the upper part of TES are higher than specific threshold values, $T_{set,col}$ and $T_{set,TES}$, respectively, defined by the master controller. In this way, the VGE can operate for a longer time with higher generator temperatures, by storing a larger amount of cooling energy within the PCM buffer tank. The stored cooling energy can then be used in periods characterized by lower solar irradiation, thus reducing the activation time of the biomass boiler. The potential of the proposed logic has been evaluated for several combinations of control settings. In Figure 3 the main results of numerical simulations are reported.

It is evident from Figure 3 that, when SC_{on} and SC_{off} are decreased of 4 K and 7 K, respectively, the share of solar energy on the total energy input increases up to 13% with respect to the reference case.

Moreover, solar fraction presents a maximum for $T_{set,col}$ ranging between 90°C and 95°C. In fact, when $T_{set,col}$ is lower than 90°C, the VGE is called to operate even for low-intensity solar irradiation and, consequently, it is not possible to exploit the maximum storing capacity of the cold tank. On the contrary, if $T_{set,col}$ is fixed higher than 95°C, the system performance is not optimized for two reasons: i) solar field outlet temperature is lower than 95°C for a significant part of the season; ii) the VGE is called to operate when the solar collectors outlet temperature is close to the maximum allowed limit (110°C) and it is not possible to exploit the maximum storing potential of the cold storage.

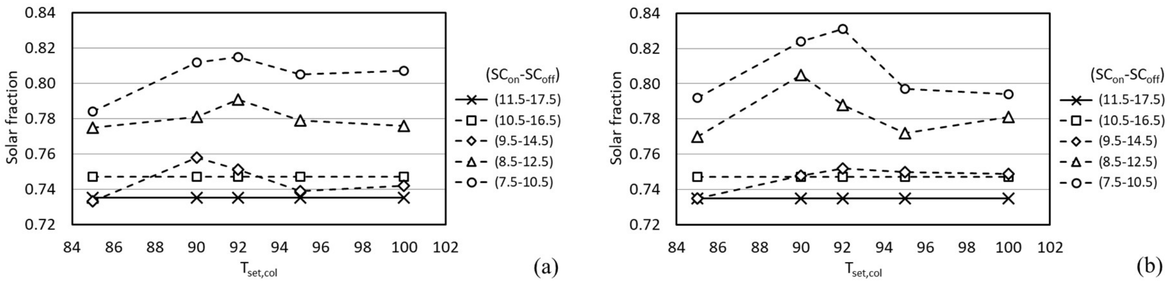

Figure 3. Solar fraction achieved with the proposed logic as a function of control settings. Data reported for $T_{set,TES}$ = 90°C (a) and $T_{set,TES}$ = 95°C (b).

In addition, data reported in Figure 3 point out that the maximum values of solar fraction can be achieved when $T_{set,TES}$ is set equal to 95°C. In this way, the generator can be loaded by the hot water TES for a longer time and the VGE operation is optimized to store cold water within the cold buffer tank. By setting SC_{on} and SC_{off} equal to 7.5°C and 11.5°C and $T_{set,TES}$ and $T_{set,col}$ equal to 95°C and 92°C, the biomass boiler energy consumption is reduced of 34.4% and, consequently, the solar fraction increases from 73.5% to 83.1%.

4. Conclusions

In this study, the seasonal performance of a cooling system based on a variable-geometry ejector (VGE), mainly driven by biomass and solar energy, has been numerically assessed by means of TRNSYS. Numerical results show that the VGE-based system allows to optimize the exploitation of renewable energy with respect to a conventional solution, based on an air-to-water chiller. Almost 75% of the generator heat demand is loaded by solar energy, while the overall renewable quote of this innovative cooling system is equal to 89.6%. This value is particularly high if compared to that obtained for the traditional configuration (19.4%), confirming the strong energy saving potential of ejector systems.

The system performance can be further improved by optimizing the VGE operation and the cold storage charging. The capability to exploit the stored cooling energy during the less favorable hours of the day allows to reduce the biomass boiler energy input of almost 35% along the season and, consequently, to increase the seasonal solar fraction of the system up to 83%.

Acknowledgments

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