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Air-conditioning in residential buildings through absorption systems powered by solar collectors.

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Abstract

Over the past years, the scientific community has been exploring alternative solutions to the fossil fuels used for indoor air-conditioning. The solution here suggested is formed by absorption machines powered by solar panels used to air-condition small residential buildings. The study examined a small residential building and evaluated energy savings, reduction of CO_2 and the return on investment compared to a traditional solution. The results obtained might be considered as valid since the heat used was provided by a free energy source with a low environmental impact, devoid of CO_2 emissions.

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Keywords: absorption heat pumps; absorption chillers; solar collectors; air conditioning; Nearly Zero Energy Building; reducing emissions.

1. Introduction

Over the past few years the demand of air-conditioning in residential buildings has been increasing, in particular in the developed countries [1]. Traditional air-conditioning systems are usually powered by electrical energy [2-4], this is why the energy demand is higher. 50% of the energy consumptions in the residential sector [5,6] depends on air-conditioning systems and affects 12% of the total energy consumptions of the Country [7-9]. This growth might

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be controlled if we had a decrease in the electrical energy with a corresponding increase in the exertion of renewable sources [10-12].

In the summer, it is necessary to cool the environment because of the presence, during the day, of a high solar radiation, hence it might be useful to plan a system able to cool houses without any expenses, by using a renewable energy, as the sun. Nowadays the decision to power air-conditioning systems [13,14] through the energy generated using photovoltaics panels is too expensive, due to high installation costs [15,16].

The solution here suggested needs a system formed by absorption machines requiring a thermal energy source to function, in this case solar collectors. The system presents one machine with a heat transformer and an absorption refrigeration machine [17-19] powered by solar collectors. The heat transformer allows to increase the temperature of the heat taken from the collectors to improve the efficiency of the refrigeration machine (Fig.1).

Such combination might be a valid solution because it exploits the heat generated through a free energy source, that is the sun, with a low environmental impact devoid of any CO_2 emissions.

Nomenclature

A	absorber;
AR	absorption refrigerator;
C	condenser;
E	evaporator;
G	generator;
HT	heat transformer;
R	refrigerator fluid (H2O);
S	solution = refrigerator fluid (H2O) + absorbent salt (LiBr).
T_A	temperature absorber;
T_C	temperature condenser;
T_E	temperature evaporator;
T_G	temperature generator;
P	pressure;
x	concentration of fluid;
g	mass flow;
$r(T)$	refrigerator transformation heat;
$s(x,T)$	differential heat of solution;
m	g_s/g_r;
c_{PS}	specific heat of the solution;
c_{PR}	specific heat of the refrigerator;
L_{Ps}	solution pump work;
L_{Pr}	refrigerator pump work;
v	vapor
l	liquid

2. The system suggested

The solution here suggested is formed by evacuated tube solar collectors powering a heat transformer and an absorption refrigeration machine. The heat transformer, powered by solar collectors, while increasing the temperature of the fluid, improves the efficiency of the absorption refrigeration machine which in turn powers the air-conditioning system. The evacuated tube solar collectors allow to have higher temperatures than traditional glass panels. The temperature of the fluid in output was set to 75°C.

Fig. 1 and Fig. 2 report the diagram of the system suggested and the functioning conditions of each component of the machine. The absorption systems work with water and lithium bromide.

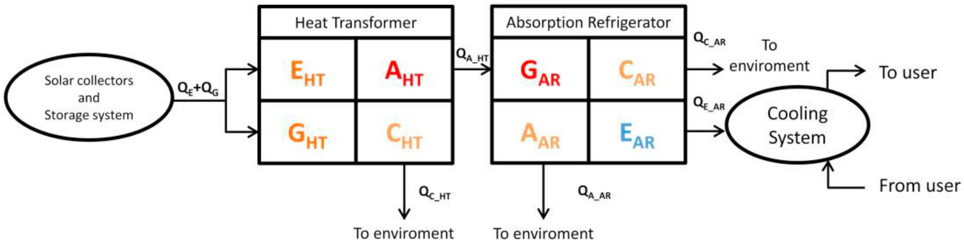

Fig. 1. Functional diagram of the air-conditioning system during the summer in low density residential buildings located in hot climates.

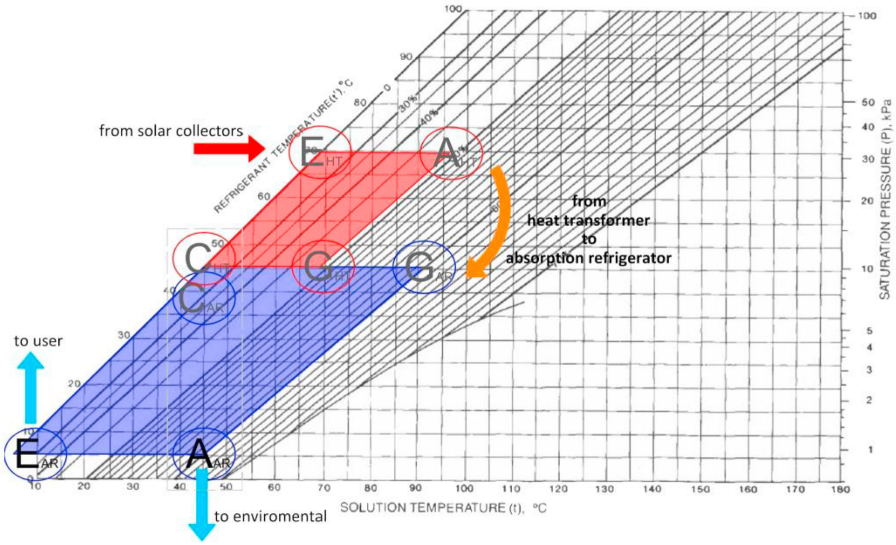

Fig. 2. Functioning conditions of each component of the machine here suggested.

The heat transformer is a machine whose functioning conditions depend on the chemical-physical properties of some absorbent-refrigerant solutions. While functioning the heat Q will be transferred from a temperature T_1 to a temperature T_2 ($T_2>T_1$). In the system suggested it collects thermal energy from the solar collectors and increases the energy quality (hence the temperature) of part of the heat provided by the absorber "A_{HT}". In this way, it is possible to power an absorption refrigeration machine that otherwise it would have not functioned if it was directly powered by the collectors. The coefficient of performance of a heat transformer, that is the ratio between the thermal output of the absorber and the total energy provided to the machine, is:

$$COP = \frac{Q_{A_{HT}}}{Q_{G_{HT}} + Q_{E_{HT}} + L_{PS} + L_{PR}} \tag{1}$$

where:

$$Q_{A_{HT}} = r(T_A) + s(x_A, T_A) - m \cdot c_{PS}(T_A - T_G)(1 - \alpha) - c_{PR.v}(T_A - T_E) \tag{2}$$

$$Q_{G_{HT}} = r(T_G) + s(x_G, T_G) - \alpha \cdot m \cdot c_{PS}(T_A - T_G) \tag{3}$$

$$Q_{E_{HT}} = r(T_E) + c_{PR,l}(T_E - T_C) - \alpha \cdot m \cdot c_{PR,v}(T_G - T_C) \tag{4}$$

$$L_{Ps} = \frac{m \cdot \gamma_S (P_A - P_G)}{\eta_p} \quad (5)$$

$$L_{Pr} = \frac{g_r \cdot \gamma_{Rl} (P_E - P_C)}{\eta_p} \quad (6)$$

For what concerns the air-conditioning in the building, the heat transformer will be connected to an absorption refrigeration machine. As the heat transformer, the machine exploits the thermo-physical properties of an absorbent-refrigerant solution, though presenting a different configuration of its components; this allows the refrigeration of the thermal vector fluid of the hydronic system of the building. The heat with a high temperature will be transferred from the absorber "A_{TC}" of the heat transformer to the generator "G_{MF}" of the refrigeration machine. Thanks to the energy provided, it is possible to have through the evaporator "E_{MF}" cold water whose temperatures are compatible with the cooling of domestic environments, realising degraded heat (with room temperature) into both the condenser "C_{MF}" and the absorber "A_{MF}". Through the evaporator of the refrigeration machine "E_{MF}" the refrigerated fluid will be provided to a hydronic system which guarantees the air-conditioning in the building when it is hot.

The coefficient of performance of an absorption refrigeration machine, that is the ratio between the thermal output of the evaporator and the overall energy provided to the machine, is:

$$COP = \frac{Q_{E_{AR}}}{Q_{G_{AR}} + L_{PS}} \quad (7)$$

where:

$$Q_{E_{AR}} = r(T_E) + c_{PR.l}(T_E - T_C) \quad (8)$$

$$Q_{G_{AR}} = r(T_G) + s(x_G, T_G) - \lfloor m(1-\alpha) + \alpha \rfloor \cdot c_{PS}(T_A - T_G) \quad (9)$$

$$L_{Ps} = \frac{m \cdot \gamma_S (P_A - P_G)}{\eta_p} \quad (10)$$

It was assumed a difference of 5°C for every heat exchanger used among the components of the system here suggested. The system examined requires electrical energy just for the circulator pumps to make the fluids flow into the system.

The configuration of the system can be easily applied in those environments characterized by a good solar radiation during the summer and in all those urban contexts where the population lives in low density houses with outdoor environments able to have solar collectors. Moreover, to have an efficient system the heat fluxes exchanged between the building and the outside must decrease, in this way the thermal power of the system will be reduced. This is possible if the building is properly planned while complying with the transmittance set by the regulations.

In this study, to evaluate the feasibility of the system suggested, the energy required for the cooling of small single family buildings (located in the north, center and south of Italy with different climatic conditions) was examined keeping in mind the current regulations [20].

3. Examined scenarios

In a previous study three low-density residential buildings were examined, they presented the same walkable surface and volume, though with a different S/V (ratio dispersion surface/air-conditioned volume) [21]. This study stressed that the building with the highest level of dispersion is the one with a ratio of the S/V of 0.82 m^2/m^3, hence this residential building was analyzed with a walkable surface of 112 m^2 and a volume of 384 m^3. The structure examined presented two communicating levels through an inside staircase and it was formed by: one living room, one kitchen, 2 bedrooms and 3 bathrooms. The building was set right on the ground isolated through an aired crawl space. The solar collectors were installed on the upper terrace. The number of glass surfaces characterizing the Northern side of the structure are reduced with respect to the Western and Eastern with a higher number of glass surfaces, as showed in Fig. 3.

The wall construction packages together with doors and windows complied with the thermal transmittance set by the current Italian regulations [20]: 0.23 $Wm^{-2}K^{-1}$ for the vertical walls; 0.22 $Wm^{-2}K^{-1}$ for the outwards horizontal slab; 0.27 $Wm^{-2}K^{-1}$ for the ground floor slabs and 1.40 $Wm^{-2}K^{-1}$ for glass surfaces.

Exposure	A_{opaque} [m^2]	A_{glass} [m^2]	A_{opaque}/A_{glass} [%]
North	48	0.00	0.0
East	43.68	4.32	9.9
South	46.56	1.44	3.1
West	43.68	4.32	9.9

Fig. 3. Geometric characteristics and planimetries assumed for the house examined on 2 communicating levels through an interior staircase.

Through the software TRNSYS [22] the thermal loads in a transient regime during a sample year were examined, with respect to the outdoor climatic conditions. Different Italian cities as Rome, Palermo, Milan, Pisa, Naples were examined, since they present different climatic conditions but we analyzed the building with the same transmittances. The maximum power required to cool the building according to the city considered was thus analyzed; the inside temperature was set to 26°C (Table 2).

4. Dimensioning of the components of the system and the area of the solar collectors.

The system was dimensioned while taking into consideration the maximum thermal power required to cool the indoor environment. In particular, it was possible to determine the maximum thermal power exchanged among the different parts forming the heat transformer (HT) and the absorption refrigeration machine (ARM). Moreover, the surface of the solar panels was also dimensioned together with the volume of the storage system during summer (April - October).

Tab. 1 reports briefly the planning specifications concerning the HT, AR and solar collectors.

Table 1. Solar tube collectors area necessary to cool the buildings during the summer in each city examined, volume of the storage system and thermal power of the components of the heat transformer and absorption refrigeration machine.

				Absorption refrigeration machine		Heat transformer		
City	Maximum thermal power [kW]	Solar collectors area m^2	Volume of the storage system m^3	Power of the generator [kW]	Power of the evaporator [kW]	Power of the generator [kW]	Power of the evaporator [kW]	Power of the absorber [kW]
Milan	1.81	4.7	0.55	2.05	1.81	2.09	2.06	2.05
Naples	2.17	3.85	0.2	2.45	2.17	2.51	2.47	2.45
Palermo	2.18	3.25	0.2	2.47	2.18	2.52	2.49	2.47
Pisa	2.01	3.5	0.25	2.27	2.01	2.42	2.29	2.27
Rome	2.00	3.45	0.2	2.26	2.00	2.31	2.28	2.26

5. Energy analysis of the system according to different climatic conditions

The energy required to cool an environment considered was examined thanks to the annual simulations in a dynamic regime. It was evaluated the amount of electrical energy necessary if a heat pump had to cool the indoor environment (Table 2) with a variable COP according to the temperatures of the condenser.

Table 2. Annual CO_2 non-emitted in the environment in the case study, annual thermal energy required by the building and annual electrical energy consumed.

City	Carbon dioxide tonne/year	$E_{building}$ [kWh/year]	$E_{electric}$ [kWh/year]
Milan	0.18	1,525.9	508.6
Naples	0.44	4,081.3	1,236.7
Palermo	0.6	5,818.1	1,711.2
Pisa	0.31	2,751.7	887.6
Rome	0.36	3293.5	1029.2

In order to estimate the amount of carbon dioxide and other gases damaging the environment, it was used the emission coefficient (mass of CO_2 for every kWh consumed); such coefficient, in Italy, is 0.3524 $kgCO_2$/kWh [24-26]. Table 2 reports the amount of gas that, thanks to the system suggested, was not emitted into the atmosphere, since traditional systems powered by electrical energy were not installed.

6. Economic feasibility: installation and energy costs

The commercial price of the system suggested depends on the price of the solar collectors and in particular on the price of the machine formed by the combination of the heat transformer and the absorption refrigeration machine once it will be available on the market.

After the quantification of the investment cost, it can be assessed the return on the investment of the different system solutions:

- Solution (A): exertion of a compressor heat pump powered by electricity:
- Solution (B): exertion of the solution here suggested.

In order to be able to compare these systems, it was taken as a reference point the costs of the low-voltage electrical energy (€/kWh) according to the national markets [27-29] (Italy: 0,1 €/kWh) together with the cost of the devices and the labour according to the official regional price list [30].

For what concerns solution (a) it was used an autonomous multisplit air-conditioning unit characterized by a highly efficient rotary hermetic compressor, thermal exchange battery and helicoidal fan. The cost of the functioning system is 4,400.00 €, this price includes installation costs and does not take into consideration exertion costs determined by the electrical energy used.

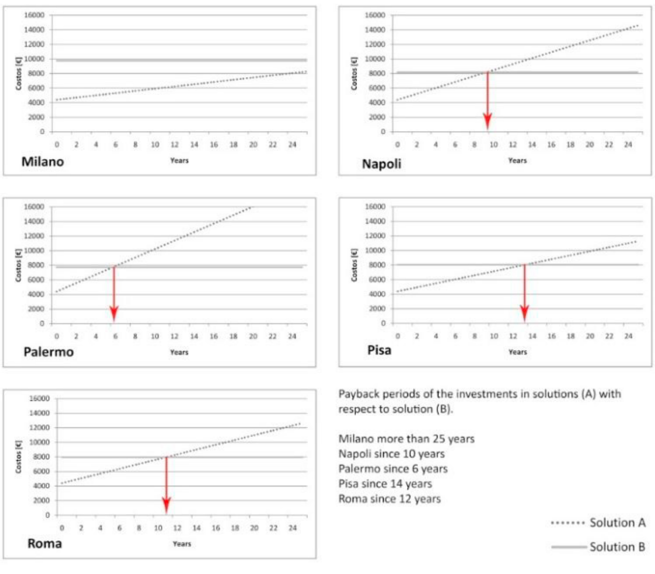

Fig. 4. Payback periods of the investments in solutions (A) with respect to solution (B).

For what concerns solution (b) the cost of the solar collectors together with the storage system (including installation costs) were evaluated. A maximum cost of the machinery here suggested was assessed. The cost of the solar collectors and their installation, while considering the regional price list [30], is 650 €/m^2. On the other hand, for the storage, the regional price list reports 3,11 €/liters. The machine here suggested, formed by a heat transformer and an absorption refrigeration machine, not being on the market, was assumed to have a maximum cost of 5,000 €. For both solutions, the cost of the distribution system inside the building was not estimated.

The return on investment is reported in Fig. 4. The solution can be considered advantageous if the return on investment, with respect to a traditional system, does not exceed 20 years.

While observing Fig.4 it can be noticed that it is not possible to have an amortization of the solution (b) in every city examined. In Milan, whose climatic zone is E [23], the solution suggested is not advantageous because the amortization period exceeds 20 years.

Solution (b), though presenting higher installation costs than solution (a), during the exertion does not present extra energy expenses, since it exploits the solar energy to make them function. They do not depend on the national electrical grid being a zero-carbon dioxide emissions solution.

7. Conclusions

The solution suggested, in order to achieve a thermal comfort in low-density residential buildings, without weighing on the exhaustible energy sources, is characterized by absorption machines exploiting absorbent-refrigerant solutions (H_2O and LiBr) for the refrigerant production (absorption refrigeration machines) or to ennoble, thermally speaking, part of the energy they use (heat exchangers). This study suggests a machine that thanks to the combination of these characteristics can exploit the solar heat to air-condition small residential buildings.

What has been showed was the possibility to have a proper powering system, through solar collectors and storage systems, of these thermal machines. It was assessed the annual energy demand in different Italian cities (Rome, Palermo, Milan, Pisa and Naples) together with the amount of non-emitted carbon dioxide into the atmosphere thanks to the solution here suggested. This solution was then compared (in terms of installation costs and return on investment of the higher expense due to their realization) with a traditional solution formed by a heat pump powered by the national electrical grid.

If it was assumed a price of about 5,000 euro for the installation of the machine suggested (it is not available on the market), it can be noticed that the return on investment is almost for every city less than 14 years. Milan, whose climatic zone is E according to the current regulations [23], reports a return on investment exceeding 30 years. It can be stated that the solution here examined can be advantageous for the following climatic zones: A, B, C and D. If future scenarios will present lower realization costs with an increase in the value of the electrical energy, such solution might become even more interesting in those areas where nowadays it is not advantageous. While functioning, the system does not emit greenhouse gases, hence it complies with the recent international agreements about climate.

Future scenarios might extend this study to the functioning of the system during winter while using heat exchangers to increase the temperature of the fluid provided by solar collectors to power a heating system [31-33].

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