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Dynamic simulation of an integrated solar-driven ejector based air conditioning system with PCM cold storage

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HIGHLIGHTS

- A TRNSYS simulation of a SECS with PCM cold storage unit was performed.
- The ejector and steam generator were modelled using Fortran and EES.
- Only a small hot storage tank is recommended for high solar fraction.
- PCM cold storage offers an immediate energy supply and stable system operation.

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ABSTRACT

The development of a dynamic model using the TRaNsient System Simulation program (TRNSYS) for the performance assessment of a solar-driven air conditioning system with integrated PCM cold storage is presented. The simulations were carried out for satisfying the cooling needs of a 140 m^3 space during the summer season in Tunis, Tunisia. The model is composed of four main subsystems including: solar loop, ejector cycle, PCM cold storage and air conditioned space. The effect of varying the solar collector area (A_{sc}) and the hot storage capacity (V_{hs}) on the solar fraction are investigated. It was found that the application of a relatively small hot storage tank (700 l) led to the highest solar fraction (92%). A collector area about 80 m^2 is needed to assure a solar fraction of 70%. Increasing A_{sc} beyond this value has only a small effect on the overall system efficiency. The influence of applying cold storage is also investigated. The results without cold storage indicated that the comfort temperature was exceeded in more than 26% of the time. With cold storage the periods of high indoor temperatures reduced significantly. An optimal storage volume of 1000 l was identified resulting in the highest cooling COP and excellent indoor comfort (95% of the time with a room temperature below 26 °C). The maximum COP and solar thermal ratio (STR) were 0.193 and 0.097, respectively.

1. Introduction

According to the International Energy Agency [1], space cooling is the fastest growing end use of energy in buildings (4% per year since 1990), mostly in the form of electricity. In order to counteract this tendency and the corresponding negative environmental impact, there is a need for broader use of renewable energies for running air-conditioning systems. Solar cooling is particularly interesting because of the strong correlation between the demand and the availability of the energy source. Existing technologies can be either heat driven, e.g. sorption and ejector cycles, or electricity driven, e.g. thermo-electric and vapour compression systems [2,3]. Solar driven ejector cooling (SECS) has a great potential for air conditioning applications due to its ability to produce evaporator temperatures in the range of 5–10 °C from a low grade energy source [4].

Ejector refrigeration is a low cost and simple technology when compared to e.g. an absorption cooling cycle. The ejector itself has no moving parts and thus requires little maintenance. In addition, an ejector cycle can be designed for a wide range of refrigerants that can be selected based on their low environmental impact and local availability [5]. The main drawback of ejector cooling is associated to its moderate COP [2,3,5–10], typically lower than 0.3 [2]. In general, system performance can be improved by applying higher generator and evaporator, and lower condenser temper-

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Nomenclature

Abbreviations

COP	coefficient of performance
ETC	evacuated tube solar collector
HTF	heat transfer fluid
PCM	phase change materials
SECS	solar ejector cooling systems
STL	standard TRNSYS library
TMY	typical meteorological year

Symbols

A	area (m^2)
C_p	specific heat capacity ($kJ\,kg^{-1}\,°C^{-1}$)
dT	dead-band (°C)
I	incident radiations ($kW\,m^{-2}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	pressure (kPa)
P_c^*	critical back pressure (kPa)
N°	number
Q	energy (kJ)
$\dot{Q}$	power (kW)
SF	solar fraction
SF*	typical solar fraction
STR	solar thermal ratio
T	temperature (°C)
V	volume (m^3)

Greek letters

δ	control function
ε	effectiveness
ζ	mass fraction ($kg\,kg^{-1}$)
η	efficiency

Subscripts

bl	building
c	condenser
cs	cold source
e	evaporator
ej	ejector
exp	experimental
G	global
g	generator
hs	hot source
in	inlet
max	maximum
num	numerical
out	outlet
sc	solar collector
sd	schedule
w	week

atures. In most studies, the generator temperature varied in the range of 85–95 °C, which resulted in COPs between 0.2 and 0.33 [3,11]. A relatively high COP (0.85) was reported for a pilot scale steam ejector operating at a high generator temperature of 200 °C [12]. Besides operating conditions, the selection of working fluid is also important since it influences both COP and system size. A review of previously applied refrigerants can be found in [13]. According to Smierciew et al. [9], for air-conditioning application, the highest system COP (0.38) can be achieved using isobutane as working fluid (at $T_g = 130$ °C) when compared to methanol (0.32), ammonia (0.31), water (0.25) and propane (0.19).

Despite the potentials, only a few solar driven ejector air conditioning pilot scale installations worldwide and long-term experimental performance data is not available from the literature. Research has been mostly focusing on numerical modelling, which is in fact generally true for solar air-conditioning applications. Amongst the few existing experimental works, Huang et al. [14] studied a 10.5 kW capacity ejector cooling cycle using R141b refrigerant and flat plate solar collectors to drive the cycle. Highest overall COP of 0.22 ($T_g = 95$ °C) and 0.12 ($T_g = 102$ °C) were obtained for an evaporator temperature in the air-conditioning ($T_e = 8$ °C) and in the refrigeration ($T_e = -6$ °C) range, respectively. A similar study was carried out by Yapici et al. [15] using R123, and the results showed a somewhat surprisingly high overall COP of 0.42 for generator and evaporator temperatures of 74 °C and 10 °C, respectively. Pollerberg et al. [16] investigated the performance of a small test rig equipped with a 1 kW capacity steam ejector chiller and 10.5 m^2 parabolic trough collectors. Experimental data revealed that high overall COP values can be obtained for low condenser pressures. Numerical simulations of the same authors for five different locations allowed for the estimation of the annual mean system performance under different climate conditions. An economic evaluation of the system was also performed; the cost of cold energy was estimated to be 0.619 €/kW h and 0.147 €/kW h in Germany and Egypt, respectively. Huang et al. [17] studied the performance of a solar assisted ejector cooling system. The test rig was composed of 26 m^2 vacuum tube collectors connected to a 5.6 kW cooling capacity hybrid ejector cooling and inverter type air conditioner system. The results showed that the overall COP of the system can be enhanced up to 43%. Zhang et al. [18] evaluated the efficiency of three types of solar collectors capable of supplying thermal energy to a 5 kW capacity ejector cooling cycle. It was concluded that the optimum collector field would have an area of 46.2 m^2 with heat pipe type collector to provide 16.7 kW heat with 53% efficiency. This configuration is merely sufficient to run the system without any auxiliary heating. A similar study was performed by Abdulateef et al. [19], and it was shown that a solar-driven combined absorption-ejector cooling system would have a 50% higher overall COP than a conventional absorption machine. The operating conditions and the system performance of the previously cited works are summarised in Table 1. The most important recently published numerical works are presented in Table 2.

One way to promote the deployment of solar cooling systems on the market is to optimise their year-round performance. With careful design and integration of a thermal energy storage (TES), the performance of the system can be improved. The application of TES can lead to two important benefits. First, it allows for the rationalisation of the heat supply capacity by providing the extra energy during peak hours. Second, it improves the cost effectiveness when there is a time shift between energy supply and consumption. In order to improve the thermal comfort, LHS using PCMs can be directly integrated into the building walls through PCM layers [20–22] or connected to the building through cold storage containers coupled with solar powered cooling systems [23,24]. The storage efficiency is known to be strongly dependent on the container geometry (e.g. cylindrical or rectangular geometries) [25], as well as on the internal heat exchanger (HEX) design (e.g. shell and tube [26,27] or helically coiled tubes [28]).

Until the date, solar driven ejector cooling systems are almost exclusively evaluated by their cooling cycle performance [29,30]. According to the authors' knowledge, only two numerical studies