Applied Thermal Engineering 100 (2016) 820–828

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Exploitation of humid air latent heat by means of solar assisted heat pumps operating below the dew point

Federico Scarpa *, Luca A. Tagliafico

DIME/TEC, Division of Thermal Energy and Environmental Conditioning, University of Genoa, Via All'Opera Pia 15 A, 16145 Genoa, Italy

HIGHLIGHTS

- The opportunity of humid air latent heat exploitation by DX-SAHP is investigated.
- A set of experimental tests confirms this opportunity and quantifies it as relevant.
- A parametric analysis is performed, via simulation, to deepen the subject.
- The energy gain is relevant during both night and daytime.

ARTICLE INFO

Article history:
Received 1 September 2015
Accepted 18 December 2015
Available online 2 March 2016

Keywords:
Solar thermal
Heat pumps
Bare panels
Vapor content
Dew point
Relative humidity

ABSTRACT

Nowadays, the exploitation of environmental exergy resources for heating purposes (solar energy, convection heat transfer from ambient air, moist air humidity condensation) by means of properly designed heat pump systems is a possible opportunity. In particular, the use of direct expansion solar assisted heat pumps (DX-SAHP) is investigated in this study, when a bare external plate (the solar collector) is kept at temperatures lower than the dew point temperature of ambient air, so that condensation takes place on it.

The potential of this technology is settled and an instrumented prototype of a small DX-SAHP system is used to verify the actual performance of the system, in terms of specific thermal energy delivered to the user, efficiency and regulation capabilities. Results clearly show that the contribution of the condensation is significant (20%–30% of the total harvested energy) overnight or in cloudy days with very low or no solar irradiation, and must be taken into account in a system model devoted to describe the DX-SAHP behavior. During daytime, the percentage gain decreases but is still consistent. By investigating along these lines, the heat due to condensation harvested by the collector is found to be a function of the dew-point temperature alone.

1. Introduction

Solar energy for water and space heating applications is mainly exploited in traditional plants by means of glazed solar panels in which the main concern is to avoid thermal dispersions to the environment due to convective and irradiative heat transfer. During normal operation, in traditional solar plants, the panel temperature is rather higher than the environmental one, so that the collector thermal efficiency (that is the ratio between the exploited thermal energy and the incident solar irradiation) is low, due to thermal losses. To minimize these losses, commercially available collectors adopt single or double glazed covers or even expensive evacuated tube solutions.

Coupling the solar collectors with the cold side (evaporator) of an heat pump, having its hot side (condenser) connected to the user thermal load, it is possible to realize a “thermal upgrading” that can guarantee energy savings higher than those typical of traditional systems for water and air heating, even if compared with conventional air–water or geothermal heat pumps [1,2]. A lot of literature is available about Direct Expansion Solar Assisted Heat Pumps (DX-SAHP) concerning the issues to be faced to determine the best control strategy needed to optimize the collector temperature, that is to balance the collector efficiency (which asks for low panel temperatures) and the coefficient of performance (COP) of the inverse cycle (which asks for high panel temperatures) [3–5]. This kind of compromise can be achieved by means of optimal DX-SAHP control [6,7], driving heat pump refrigeration capacity and panel temperature toward some kind of optimized values, based on proper thermodynamic analysis.

The simplest operating scheme of a DX-SAHP system is sketched in Fig. 1, in its basic configuration, where the temperature T_p of a

* Corresponding author. Tel.: +390103532861; fax +39 010311870.
E-mail address: fscarpa@ditec.unige.it (F. Scarpa).

http://dx.doi.org/10.1016/j.applthermaleng.2015.12.077
1359-4311/

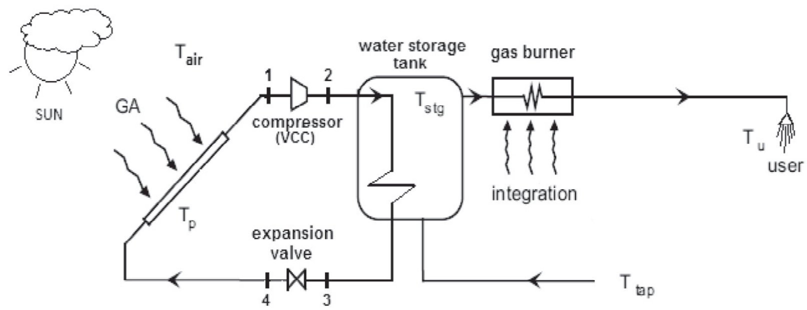

Fig. 1. Basic DX-SAHP (Direct eXpansion Solar Assisted Heat Pump) operation layout; a possible application as Domestic Hot Water (DHW) heater.

bare solar panel is controlled by means of a vapor compression refrigeration cycle. The load of the system can be for instance represented by the heating of a storage tank for Domestic Hot Water (DHW) purposes. Optimized working conditions can be guaranteed as a function of the environmental parameters and user demand, by a proper control of the variable speed compressor and electronic expansion valve [8,9].

If the panel temperature T_p is made an independent variable, it will be possible to drive additional heat transfer rates from the ambient, keeping the panel temperature lower than the air dew point, exploiting also the energy available as latent heat from the condensation of the air vapor content.

For the same user load, condensation on the panel surface allows it to be maintained at a temperature higher that that needed in case of low relative humidity condition thus granting better COP operating values.

Furthermore, in some circumstances, the requested load should require a collector temperature lower then 0 °C, in absence of the condensation phenomenon, thus posing some concerns about the correct operation if the system is a water source heat pump. In fact, despite the present work is primary focused on direct expansion SHAP, many findings can be applied to simple heat pumps in heating mode.

In the literature, the condensation of humid air has been investigated in relation to heat-pump drying [10], ambient air dehumidification [11], greenhouse environment control [12], and in general in contexts where air humidity is an undesirable factor. The exploitation of latent heat from the external humid air has not to be confused with the practice of using the latent heat associated to the phase change of a substance (i.e. PCM material) to store and retrieve energy [13], since this process is internal to the system and it is used to optimize the dynamics of the heating delivery. Conversely, in the present investigation, latent heat comes from the environment and sums up to the other external energy sources.

The aim of the present study is to investigate the effect of the condensation on the total energy harvested by a solar assisted heat pump. If the contribution will be found relevant, further work will be devoted to deepen the role of the optimal collector temperature, in respect to the dew point temperature, to maximize the overall system performance.

To the best of authors' knowledge, the present study is the first contribution presenting a detailed investigation devoted to specifically analyze, both theoretically and experimentally, the potential benefit of humid air latent heat exploitation.

2. The condensation process

Several studies are available for the calculation of heat transfer due to condensation of water vapor on a cold surface. Most of the literature refers to pure vapor condensation or to saturated moist air, starting from the famous liquid film theory for film wise condensation by Nusselt, and evaluating separately the thermal resistances encountered by the heat flux to pass from the ambient air to the cooled solid interface.

According to this theory the simplest form for the evaluation of the condensation heat transfer coefficient h_c is given by (see for instance [14]):

$$Nu = \frac{h_C \cdot L}{k_f} = 0.943\left[\frac{h_{fg} g \cos(\theta) \cdot L^3}{k_f \cdot (T_{sat} - T_p) v_f}\right]^{0.25} \qquad \delta \cong \frac{k_f}{h_C} \tag{1}$$

Which explicitly represents the dependence of the liquid film Nusselt number on the Prandtl and Grashof numbers, L is the plate length in the condensate flow direction, $g\cos(\theta)$ is the gravity acceleration component parallel to the plate plane, with h_{vl} the latent heat of vaporization of the liquid film at the condensate temperature T_{sat}, δ is the average liquid film thickness. The coefficient 0.943 is usually augmented by a 20% in later works to account for the influence of waves, if they are present.

However, when heat transfer from moist air in atmospheric conditions has to be studied, as it is the case in the application here presented, a very dilute water vapor in air is present, so that the main thermal resistances will be on the air–liquid film interface, where also a drop of the vapor pressure takes place, rather than at the liquid film–solid interface, as shown in Fig. 2.

Various authors, like Sparrow and Eckert [15] or Minkowycz and Sparrow [16] contributed to the subject of heat transfer and condensation rate in presence of incondensable. An approach is to calculate the mass-transfer coefficient for the condensation of very dilute systems on a cold surface, on the basis of the heat-mass transfer analogy, starting from the knowledge of the convective heat transfer coefficient at the air–liquid film interface. Just like the convective Nusselt number is correlated to Reynolds (or Grashof) and Prandtl numbers for heat transfer calculations, in the same way the Sherwood number can be calculated as a function of Reynolds (or Grashof) and Schmidt numbers for mass transfer calculations. As a result the mass transfer coefficient h_M can be expressed, in its simpler form, according to the equation [17]:

$$h_M = \frac{h_{air}}{c_{p,air}\rho R_{1v} T} \frac{p_{air}}{\bar{p}_{dry}} \tag{2}$$

where h_M [kg/Ns] is the mass transfer coefficient, h_{air} [W/m^{2}K] is the convective heat transfer coefficient, ρ [kg/m^3] is air density, T [K] is air temperature, and R_{1v} [J/kgK] is the gas constant of water vapor.

The last term, near to 1.0 in the considered context, is given by the ratio between the humid air total pressure and the logarithmic average dry air pressure that is