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Experimental characterisation and technical feasibility of a closed two-phase vs a conventional solar water heating thermosyphon

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The present paper deals with Domestic Solar Water Heating Systems (DSWHS) for sanitary purposes. A Phase Change System (PCS) was designed and built. The PCS consists of a solar collector – thermo tank set that use a working fluid to indirectly transfer heat to the water. In some regions of Mexico, the high concentrations of minerals in the water accumulate to obstruct the pipes, preventing the solar collector from working. Using a suitable working fluid (different from water) avoids this problem, as well as freezing, corrosion, fouling and scaling, usually presented in conventional DSWHS. A conventional DSWHS with the same dimensions and geometry than the PCS was installed to compare their performance in simultaneous tests. Tests in the PCS were performed using three working fluids: R134a, R410A and acetone, under the actual field conditions of Temixco, Mexico. The technical feasibility of the three working fluids was investigated. Experimental data indicate that the PCS, loaded with either R134a or R410A, has equivalent performance than the DSWHS. However, high pressures and some difficulties to load the working fluid have to be dealt with. Lower performance was shown using acetone, but with the advantages of an easy load and low working pressure.

1. Introduction

Using renewable energy reduces impacts to the environment as well as the inherent economic repercussions. A growing awareness of the importance of using renewable sources of energy is being developed all over the World.

According to the Energy Secretariat of Mexico [1], nearly 90% of the primary energy production in Mexico comes from hydrocarbons. Although Mexico has a great solar potential to generate energy, it is poorly exploited. Regarding solar collectors to heat water, there is an installed surface of 1.16×10^6 m^2 to produce 5.6 PJ/year with an average efficiency of 50% [1]. The encourage of solar production of energy will yield energetic, economic, social and environmental benefits. The Energy Saving Council of Mexico through the program PROCALSOL [2], expects to reach an installed surface of 1.8×10^6 m^2 by 2012.

As stated by the Government Secretariat [3], Mexico is considered one of the ten major producers of thermosolar energy; however, with a per capita yearly generation of 41 MJ, it is far behind countries like Brazil (380 MJ) or Israel (17,000 MJ) per capita per year [4].

Conforming to Alatorre Frenk [4], in an official domestic investigation, Mexico has an economic feasible potential of 35×10^6 m^2 of solar collectors that would provide 115 PJ/year equivalent to 2.5% of the total demand of energy in Mexico. In this frame, the investigation and improvement of the technology must be encouraged.

Solar heating of water prevents the emission of pollutants to the atmosphere, reducing the use of liquid gas, diesel and electricity, as well as carbon or wood. Kalogirou [5] concluded that, for the case of domestic water heating systems (with electricity or diesel backup), the emission savings of using solar energy instead of conventional systems could reach up to 80%.

Currently, the most common DSWHS are the thermosyphons, in which the water is heated in a flat plate solar collector and stored in a thermo tank. According to Soin et al. [6], problems like corrosion, fouling and freezing presented in this kind of systems are eliminated in two-phase systems. Soin et al. described an experimental set up to evaluate the performance of a solar collector with a phase-change working fluid. The system consisted of a collector, a vapour liquid separator and a condenser. They used acetone and petroleum ether in the primary circuit as working fluids, because of their high heat transfer coefficients. They demonstrated that the collector efficiency increases linearly with the working fluid load level in the primary circuit.

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Among the mentioned working fluids, several refrigerants have been tested like R11 [7], R113 [8,9] or R123 [10,11], and also mixtures of refrigerants [12]. In addition, different geometries of two-phase thermosyphons have been studied [13–15].

A refrigerant, trichlorofluoromethane (or R11), was used by Schreyer [7] to evaluate the energy recovery in a solar collector coupled to a heat exchanger, and the latter to a thermo tank. The fins of the collector and circulation tubes were made out of steel. The primary loop was passive and the secondary needed a recirculation pump. His system recovered up to 83% energy at low collector temperature difference.

Davidson et al. [8] and Walker and Davidson [9] studied a Self-Pumping Solar Water Heater. The experimental apparatus included a flat plate solar collector, a heat exchanger, a storage tank, and an upper and a lower accumulator of refrigerant, and they compared their system to a simulation model. The system was totally passive; during the heat transfer period, they recognised three phases in the operation of the system, a run phase, in which the refrigerant (R113) from the upper accumulator fed the collector by gravity and the fluid moved downwards to the condenser; at this stage, the heat was transferred to the water, and the liquid was collected in the lower accumulator; during the pressurising phase, the vapour was prevented from entering the condenser, increasing the pressure and temperature in the lower accumulator and in the collector; and a pump phase, in which the pressure in the lower accumulator exceeded the pressure in the upper accumulator and the liquid returned to it. They found that their system was cost effective and reliable as a solar heating system, yet the thermal losses were considerable at high temperature of the collector.

Trade-offs of replacing working fluids of ozone depletion promoting chlorofluorocarbons, were made by Calm and Didion [16]. They balanced the role of a number of fluids, the R134a included. R134a has a high latent heat of vaporisation, does not contribute to ozone depletion but, yet low, does have impact on global warming. Also, they concluded that there is no perfect fluid to prevent every environmental impact.

Ong and Haider-E-Alahi [17] studied the performance of a heat pipe loaded with R134a, and found that the heat flux transferred increased with high refrigerant flow rates, high fill ratios and greater temperature difference between evaporator and condenser.

Hussein [18] studied a two-phase closed thermosyphon flat plate solar water heater. He carried out both experimental and numerical tests and set some dimensionless variables to determine adequate store dimensions for the tank to improve the solar energy gain; the working fluid used was distilled water [19].

The thermal performance of a two-phase thermosyphon flat plate solar collector, under sky clear conditions, using different refrigerants was investigated by Esen and Esen [20]. They constructed three small-scale solar water heating systems, and evaluated R134a, R407C and R410A as working fluids. They found that the latter offered the highest solar energy collection.

In Mexico, technical problems with conventional thermosyphon systems arise when some particularities are considered, like the particles of minerals (like calcium oxides) in the water, that accumulate to obstruct the pipes. Also, these minerals cause corrosion and scaling, degrading the lifetime of the system. In some regions of Mexico, another problem emerges with the weather; when below zero temperatures are reached, water freezes and expands to break the tubes to the detriment of the collector. Using a suitable working fluid, rather than water, with low freezing point and not aggressive to the tubing, will prevent these technical problems and, consequently, increase the lifetime of the system.

The aim of this work is to evaluate a closed two-phase solar thermosyphon to heat water, using different working fluids, and compare it to a traditional system. Through these comparisons, the technical feasibility of the PCS will be assessed, as an advance to its further use, with equivalent performance to the DSWHS, and with the advantages that the problems mentioned earlier of freezing, corrosion, scaling, and particles embedded, are avoided. In addition, the phase-change phenomenology of the PCS is investigated to obtain information that will lead to its further improvement. For the purposes of the investigation, two refrigerants, R134a and R410A, and acetone (industrial-degree) were chosen as working fluids because of their physical properties, low impact to the environment, availability and relatively low cost. Also, they were previously used by other authors in comparable applications.

In order to assess the role of the different working fluids, several considerations must be taken into account. Regarding the refrigerants, R134a and R410A, they have low boiling points (as seen on Table 1); this means that, soon after the PCS starts to operate, the fluid in the collector will vaporise and move to the coil in the thermo tank to be condensed in a recirculation cycle. Contrastingly, acetone has a higher boiling point; this means that it will take longer to the PCS to start the evaporation–condensation cycle and hence, the major heat transfer towards the water (on the understanding that some minor sensible and latent heat can be transferred before the PCS reaches the conditions to have a continuous cycle). With respect to their latent heat of vaporisation (Table 1), acetone is, at least, twice as much as the other working fluids (that are closer to each other); this means that, in a cycle with the same saturation conditions and mass flow rate, more energy can be transferred with acetone than with other fluids. Therefore, these factors (boiling point and latent heat of vaporisation) must work together in combination to produce the best result. Another issue to consider is the pressure; while the PCS with acetone works close to the atmospheric pressure, high pressures have to be dealt with the refrigerants. Concerning the load, acetone is found in a liquid state at atmospheric conditions, while the refrigerants are found in a gaseous state. Due to these conditions, load of acetone can be easily controlled; in the case of R134a or R410A, special care is required in the injection because the volume cannot be accurately controlled.

Some improvements are introduced in the present paper (compared to those cited in the technical literature review) in order to obtain useful working information of these systems:

(a) The PCS is compared to an actual commercial DSWHS with exactly the same size, geometry and materials, except for the coil presented in the thermo tank of the PCS; therefore, the comparison is in real time under the same working and weather conditions;
(b) Previous research with refrigerants R134a and R410A was performed in heat pipes or small prototypes [17,20]; in this study, the refrigerants are evaluated in the real commercial-size PCS;
(c) Previous research with acetone [6] was performed under controlled conditions of flows and temperatures; the PCS proposed here worked with no human intervention or manipulation during the test, in real operating conditions;
(d) Not only is the performance of the systems evaluated, but also its technical feasibility in real operating conditions;

Table 1
Properties of the working fluids used in the PCS.

Working fluid	$T_{freezing}$ @p_{atm} [°C]	$T_{boiling}$ @p_{atm} [°C]	h_{fg} @0 °C [kJ kg^{-1}]	h_{fg} @50 °C [kJ kg^{-1}]	p_{sat} @50 °C [bar]
R134a	−101	−26.1	198.6	151.8	13.2
R410A	(−136, −103)	−52.7	221.3	135.1	30.7
Acetone	−94.7	56.5	558.8	508.1	0.8

h_{fg}: Latent Heat of Vaporisation; *sat*: saturation; *atm*: atmospheric. Source: NIST [23].