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Design and evaluation of a heat exchanger that uses paraffin wax and recycled materials as solar energy accumulator

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ABSTRACT

Soft drink cans filled with paraffin wax mixed with 5% w/w aluminum wool, obtained from disposable cans, doubled the thermal conductivity of cans filled only with paraffin wax. Thermal conductivity of the systems was determined by two ways: directly using a thermal conductivimeter, and indirectly based on temperature profiles and on the analytical solution of a cylinder.

We designed, built and evaluated a heat exchanger for solar energy accumulation, composed by 48 disposable soft drink cans filled with a total of 9.5 kg of paraffin wax mixed with 5% w/w aluminum wool. In sunny days, the wax melted completely in 3 h. The accumulated energy of 3000 kJ, allowed increasing the temperature of 3.5 m^3/h air flow rate from 20 to 40 °C during a period of 2 h. This application will allow extending the use of solar energy in drying processes or could be used as household calefaction system.

The progress of the phase change front in time during the energy discharge period was simulated with COMSOL, whereas the effect of the number of cans and thermal conductivity of the paraffin wax on the air temperature increase was simulated with MATLAB.

1. Introduction

The energy required in different processes usually comes from hydrocarbons, whose price is raising continuously. Besides the use of fossil fuels has a negative impact on the environment because of contaminant emissions, such as CO_2 [1].

On the other hand, food and beverages packaging produce pollution problems, since the garbage ultimately is buried in a landfill or burned, and never used again. For example, in 2012, around 300 billion of aluminum disposable cans for soft drinks were manufactures, and the production is augmenting at a 3% annual rate. Cans recycling reduce the trash and turn them into new products. In this way, cans recycling allows energy savings, reduction of greenhouse gas emissions that contribute to global climate change, and also helps to create new jobs.

Solar energy appears attractive as a non conventional and non polluting alternative. However, the daily and seasonal fluctuations in the irradiation level are a drawback [2]. Thermal energy can be stored as a change in internal energy of a material as either sensible heat, latent heat or thermal-chemical heat [3]. The storage of sensible heat is the most popular technology, and there are a large number of low-cost materials available with this purpose. However these materials have the lowest heat storage capacity, thus requiring large equipment [4]. The storage of latent heat by means of phase change materials (PCM), is particularly attractive since PCM provide a high-energy storage density and have the capacity to store energy at a constant temperature, which is the temperature that corresponds to the phase transition temperature of the PCM [5–9]. Nevertheless the use of PCM demands consideration of price and other indirect costs, together with the need of improving some thermo physical properties of PCM. Additionally, the heat transfer rate from the PCM must be improved to facilitate the energy withdrawal by the fluid [9–11].

Kenisarin and Mahkamov [13], Dutil et al. [9], and Tigui et al. [12], mention the need of improving performances sufficiently to justify costs related to additional systems and/or controls needed.

PCMs can be classified into three categories: (1) organic materials such as paraffin; (2) inorganic materials, such salt hydrates and metallic materials; and (3) eutectic materials, containing various combinations of inorganic and organic materials. Inorganic compounds have a high latent heat per volume unit and high thermal conductivity. Additionally they are non-flammable and have low in cost in comparison to organic compounds. However, they are corrosive to most metals and are chemically unstable, which can affect their phase change properties [2].

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Nomenclature

A	heat exchanger exposed area (m^2)
Bi	Biot number
C	specific heat (Joule/kg°K)
k	effective thermal conductivity (W/mK)
Fo	Fourier number ($Fo = \alpha\, t/R^2$)
J_0	Bessel function
J_1	Bessel function
M	paraffin wax mass (kg)
R	cans radius (m)
r^*	dimensionless radio (r/R)
T	drying air temperature (°C)
t	time (s)
v	air velocity, inside of the chamber (m/s)
w	air flow mass (kg/s)

Greek letters

α	thermal diffusivity (m^2/s)
ε	porosity of aluminum wool bed
φ	inclination angle of the heat exchanger
ρ_p	density of dry solids (kg/m^3)
λ_i	first root of transcendental eigenconditions
λ	latent heat of fusion (Joule/kg)
η	efficiency
∞	ambient conditions

Most organic PCMs are non-corrosive and chemically stable, are compatible with most building materials and have a high latent heat per weight unit and low vapor pressure [2,14]. Although they show low thermal conductivity, volume changes during melting and solidification, and also flammability [16], a serious drawback of this material. One of the most popular organic PCM is paraffin wax, since it is inexpensive and exhibits moderate thermal storage densities and a wide range of melting temperatures depending on its composition [14,15].

Several methods to enhance heat transfer processes in a latent heat thermal storage unit have been proposed, such as the use of finned surface embedded into the heat storage medium and the introduction of matrix structures with a high heat conductivity into the heat storage medium (or impregnation of heat storage medium into a porous matrix structure) [2,10,13,17–19]. Nevertheless, the potential use of these alternatives is somewhat limited owing to their high costs.

Mettawee and Assassa [20] reported a method of improving the thermal conductivity of paraffin wax by embedding aluminum 80 μm particles in it. The mass ratio of aluminum particles to wax used in the experimental work was 0.5. They concluded that the charging time of energy decreased by 60% for composite than pure paraffin wax. The mean daily efficiency for paraffin wax fluctuated between 32% and 54.8%; while it varied from 82% to 94% for the aluminum–wax composite material.

Another aspect to consider, in addition to the low conductivity of organic PCM, is to increase the heat transfer rate from the PCM to the surrounding fluid. This aspect enhances the thermal efficiency during the energy discharge process.

In a first stage of this work we determined the thermal conductivity of pure wax blocks and blocks containing wax plus 5% w/w aluminum wool in a thermal conductivimeter. Then, in a second stage, the thermal conductivity of aluminum cans filled with pure wax and wax plus 5% w/w aluminum wool was estimated considering that the cans had a geometry similar to an infinite cylinder. Finally, we designed and built a heat exchanger that contains paraffin wax mixed with aluminum wool in cans that was used as a solar energy accumulator.

2. Materials and methods

2.1. Aluminum wool

Aluminum wool was obtained by opening vertically 350 mL soft drink cans (obtaining a 10 cm × 20 cm sheet) and then cutting them in strips (0.4 cm wide and 10 cm length) using a paper-cutter (Fig. 1). Once cut, the strips acquired a curly shape. The packing conformed by these strips is the aluminum wool.

2.2. Wax blocks

We built pure paraffin wax blocks and also wax blocks containing 5% w/w (equivalent to 1.5% v/v) aluminum wool. The blocks size was 10 cm × 5 cm × 3 cm. Thermal conductivity of the blocks described above was determined in triplicate with a thermal conductivimeter (CT Metre) exhibiting a 5% precision and a 2% repeatability (Fig. 2).

We used commercial paraffin wax whose properties are given in Table 1.

2.3. Thermal conductivity of filled cans

We studied the thermal behavior of pure paraffin wax as well as wax mixed with 3% and 5% w/w aluminum wool contained in the cans (6.72 cm diameter and 12 cm height). The phase transition from solid to liquid and from liquid to solid, including the necessary heating periods from ambient temperature to 80 °C, was measured.

Three cans were electrically isolated by coating them externally with Teflon tape. Then the can was wrapped with an electric resistance of 19.2 W. The resistances were then thermally isolated, to

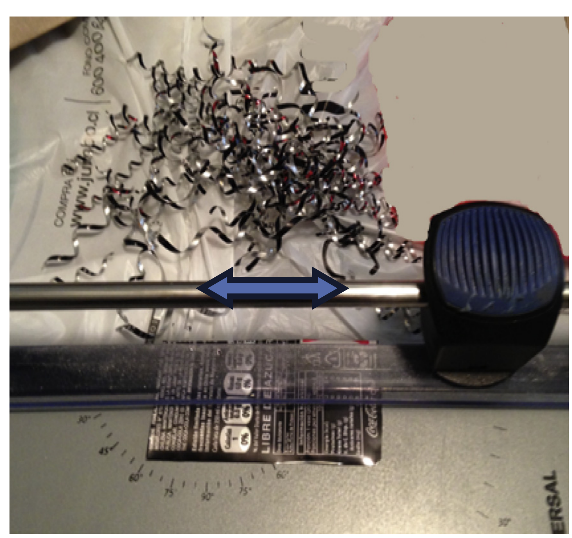

Fig. 1. Obtainment of aluminum strips.