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Thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants

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Abstract

A solar cooking system using vacuum-tube collectors with heat pipes containing a refrigerant as working fluid has been fabricated, and its performance has been analysed experimentally. The experiments were conducted during clear days in July and August of 2002 in Elazığ, Turkey under similar meteorological conditions for three refrigerants and water. Detailed temperature distributions and their time dependences were measured. The maximum temperature obtained in a pot containing 7 l of edible oil was 175 °C. Also, the cooker was successfully used to cook several foods. The cooking processes were performed with the cooker in 27–70 min periods.

Keywords: Solar cooker; Vacuum-tube collector; Heat pipe; Refrigerant

1. Introduction

Solar cooking systems using evacuated tube collectors have several advantages. They provide high thermal power and temperatures without tracking and allow cooking in the shade or even in conventional kitchens because of the spatial separation of collecting part and oven unit. An effective heat transfer system between solar collector and oven plate is necessary to take maximum advantage of all these potentials. For this purpose heat pipes seem very appropriate. Their thermal conductance is extremely high and the heat transfer between evaporator and condenser unit is nearly isothermal. There are only a few publications relevant to the application of heat pipes in solar cookers. The first attempt to use a two-phase thermosyphon in a solar cooker was made by Bhattacharya and Kapur (1978). They proposed the use of one thermosyphon leg in outdoor collectors. Swet (1974) described similar conceptual designs. More recently testing of a heat-pipe cooker at the Brace Research Institute (1983) resulted in an inconclusive performance. Different inner structures in thermosyphon tubes, intended to be used as absorbers in CPC-type collectors, have been investigated by Collares-Pereira et al. (1991). Their experimental tests were restricted to temperatures up to 85 °C. Morrison et al. (1993a,b) reported on a sophisticated steam driven cooker, where steam generated in an evacuated tubular absorber was transferred via a long pipe system into a storage vessel and the cooking plates. Balzar et al. (1996) reported a solar cooking system using vacuum-tube collectors with integrated thermosyphon-type heat pipes leading directly to the oven plate. Detailed temperature distributions and their time dependences were measured, and the maximum temperature obtained in a pot containing 5 litres of edible oil was 252 °C. Stumpf et al. (2001) presented the measured and calculated properties of three different collector-based solar cooking systems. Two of them had a direct single-stage heat-pipe coupling between collector and oven plate. The first one was

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Nomenclature

I	instantaneous incident solar radiation on the tilted plane (W/m^2)	T_2	inlet heat pipe temperature of condenser unit (°C)
GWP	global warming potential	T_3	outlet heat pipe temperature of condenser unit (°C)
ODP	ozone depletion potential	T_4	hot plate temperature (°C)
T_a	ambient air temperature (°C)	T_5	pot content temperature (°C)
T_1	heat pipe temperature of collector section (°C)		

heated by a flat-plate collector with 2.33 m^2 aperture area, while the second system was heated by one module of a Sydney vacuum-tube collector with 1.085 m^2 of aperture area. The third system with a double-stage thermal coupling was heated by two Sydney modules. On clear days the shortest heat-up times from 40 to 99.5 °C for 5 kg water were 36, 32 and 17 min corresponding to an average thermal power of 580, 653 and 1220 W for the three systems, respectively.

Also, the use of heat pipes was proposed by a number of other investigators. Khalifa et al. presented solar cookers for indoor and outdoor uses (1985), cookers for solar homes (1986a), and split-system solar cookers with heat pipes (1986b), as well as indirect hot box ovens in which the cooker is heated indirectly by means of steam flowing through heat pipes, which are enclosed in a flat-plate collector. The flat-plate collector, which may use booster plane reflectors or concentrators, is placed outdoors and the oven in the kitchen.

So-called "solar steam cookers", working at atmospheric pressure, never quite reach 100 °C (Telkes, 1958; Burkhardt, 1982; Garg et al., 1978; Osman, 1980; Whillier, 1965). Also, Khalifa et al. (1984, 1986c, 1987) introduced several novel concepts by developing insulated solar ovens that contain vapour-tight and, hence, spill-proof pots.

Refrigerants or phase change fluids are commonly used as the heat transfer fluid in refrigerators, air conditioners, and heat pumps. They generally have a low boiling point and a high heat capacity. This enables a small amount of the refrigerant to transfer a large amount of heat very efficiently. Refrigerants respond quickly to solar heat, making them more effective on cloudy days than other transfer fluids. Heat absorption occurs when the refrigerant boils (changes phase from liquid to gas) in the solar collector. Release of the collected heat takes place when the now-gaseous refrigerant condenses to a liquid again in a heat exchanger or condenser. For years chlorofluorocarbon (CFC) refrigerants, such as Freon, were the primary fluids used by refrigerator, air-conditioner, and heat pump manufacturers because they are non-flammable, low in toxicity, stable, no corrosive, and do not freeze. However, due to the negative effect that CFCs have on the earth's ozone layer, CFC production is being phased out, as is the production of hydrochlorofluorcarbons (HCFC). The few companies that produced refrigerant-charged solar systems have either stopped manufacturing the systems entirely, or are currently seeking alternative refrigerants. For instance, as R-22 is gradually phased out, non-ozone depleting alternative refrigerants are being introduced. Various substitutes to R-22 have been proposed. The refrigerants used in this study were Freon 22, Freon 134a, and Freon 407C.

The objective of the present experimental study is to demonstrate the feasibility of using refrigerants in a solar cooking system which consists of a vacuum-tube solar collector with integrated long heat pipes leading directly to the oven plate, to cook and/or to keep food warm in the late evening.

2. Description of the solar cooking system

Fig. 1 shows a general view of the solar cooking system. It consists of the three main components: collector, heat pipes, and oven section. The collector is made up of six evacuated double-wall (concentric) glass tubes (length 1 m, outer diameter of inner tube 25.4 mm, outer diameter of outer tube 37.6 mm) mounted on parabolic concentrating chrome–nickel reflectors (thickness 0.4 mm). All the evacuated glass tubes with heat pipes and reflectors were housed in a flat-plate collector case of 0.96 m^2 of aperture area (120 cm length, 80 cm width), and 20 cm thickness. The sides of the collector were thermally insulated with a 5 cm thick layer of polyurethane. The heat pipes were made of copper with an outer diameter of 6.32 mm and a length of 1 m. The exposed surface of each copper heat pipe was painted with mat black paint. They are differently bent and lead directly to the oven unit via an insulated adiabatic section of about 0.5 m. In order to increase the heat transfer area of the heat pipes embedded in heat transfer liquid in condenser section, each pipe was formed in