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Exergy analysis of the solar cylindrical-parabolic cooker

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Abstract

For the first time the simple solar parabolic cooker (SPC), of the cylindrical trough shape, is analysed from the exergy viewpoint. The paper presents the methodology of detailed exergy analysis of the SPC, the distribution of the exergy losses, and, on the example of the cooker surfaces, explains the general problem of how the exergy loss on any radiating surface, should be determined, if the surface absorbs many radiation fluxes of different temperatures. An imagined surface was used in the considerations to close the system of the cooker surfaces. It was shown that optimization is needed, to increase the energy and exergy efficiencies of the cooker.

Equations for heat transfer between the three surfaces: cooking pot, reflector and imagined surface making up the system, were derived. The model allowed for theoretical estimation of the energy and exergy losses: unabsorbed insolation, convective and radiative heat transfer to the ambient, and additionally, for the exergy losses: the radiative irreversibilities on the surfaces, and the irreversibility of the useful heat transferred to the water.

The exergy efficiency of the SPC, was found to be relatively very low (∼1%), and to be about 10 times smaller than the respective energy efficiency which is in agreement with experimental data from the literature. The influence of the input parameters (geometrical configuration, emissivities of the surfaces, heat transfer coefficients and temperatures of water and ambience) was determined on the output parameters, the distribution of the energy and exergy losses and the respective efficiencies.

Keywords: Exergy; Radiation; Solar cooker

1. Introduction

The presented analysis was inspired by publication of Ozturk (2004), in which for the first time the exergy efficiency was determined experimentally for the solar parabolic cooker (SPC) of the cylindrical trough shape. The SPC is the example of the devices driven by solar radiation, which generally have, especially as compared to the energy efficiency, very low exergy efficiency and there is practically little one can do in order to improve their performance. Another example of processes driven by solar radiation can be a plant vegetation process which also has low energy and exergy efficiencies as discussed e.g. by Szargut and Petela (1968). The performance of the SPC can be improved only a little by appropriate design of geometrical configuration and optical properties of the surfaces exchanging heat by radiation. This aspect is analysed in the present paper.

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Nomenclature

A	surface area, m^2
B	radiation exergy, W
c	specific heat of water, $\mathrm{W\,kg^{-1}\,K^{-1}}$
σ	the Stefan–Boltzmann constant, $\sigma = 5.667 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
D	outer diameter of cooking pot, m
E	emission energy, W
h	convective heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
I	insolation, W
J	radiosity, W
k	heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
L	SPC length, m
L_c	crossed string length, m
L_D	distance of cooking pot from the reflector bottom, m
L_n	not crossed string length, m
L_s	intersection ordinate, m
m	water mass flow rate, $\mathrm{kg\,s^{-1}}$
Q	heat delivered or extracted from surface, W
r	exergy/energy ratio
S, S'	tangency points
S_cir	length of circle arc, m
SPC	solar cylindrical-parabolic cooker
x_s, y_s	coordinates defining shape and size of the reflector, m
x_2, y_2	coordinates of tangency point S, m

T	absolute temperature, K

Greeks

α	absorptivity
β	percentage energy loss
δB	exergy loss, W
η	energy efficiency of the SPC
η_B	exergy efficiency of the SPC
φ	radiation shape factor
ε	emissivity
ψ	maximum efficiency ratio
ρ	reflectivity
ξ	percentage exergy loss
τ	transmissivity

Subscripts

i	initial or successive number
j	successive number
0	ambient
Q	heat
S	solar
w	water
1	imagined surface making up the SPC surfaces system
2	inner surface of reflector
3	outer surface of cooking pot

The principles of radiative heat transfer applied in the present paper are presented e.g. by Holman (1997). Szargut and Petela (1965, 1968) as well as Szargut et al. (1988), present the concept of exergy and its application to the analysis of processes. Extensive review of the problems of radiation exergy is provided by Bejan (1997). Some clarifications regarding exergy of thermal radiation are discussed by Petela (2003).

An analysis of the conversion process of energy, which conserves itself totally regardless of its quality, serves rather well for design calculations, whereas the exergy analysis, which takes into consideration the quality of energy, serves mostly for practical estimation and analysis of the process.

The main reason of low efficiency of devices driven by solar radiation lies in the impossibility of full absorption of the insolation. To obtain high quality energy, at high temperature, the absorbing surface has to be at high temperature, which produces a large loss of energy by emission from the surface. This factor influences both the energy and exergy efficiencies. The exergy consideration of the optimal temperature of the absorbing surface which converts solar radiation into heat is presented by Petela (2003).

In relation to the exergy efficiency there is an additional reason which makes this efficiency significantly lower than the energy efficiency. A low exergy performance efficiency of SPC, and of other devices driven by solar radiation, is caused by the significant degradation of energy. The relatively high temperature (~6000 K) of solar radiation is degraded to the relatively low temperature e.g. to the temperature T_w of heated water, which is not much larger than the ambient temperature T_0, ($T_\mathrm{w} \approx T_0$).

The effect of such degradation, which causes the significant difference between energy and exergy efficiencies, can be illustrated by simple consideration of the ratio r of the exergy growth to the energy growth of water which is preheated from initial temperature T_wi to the higher temperature by $\Delta T = 20$ K. The ratio r can be presented as follows:

$$r = \frac{mc\left[(T_\mathrm{wi} + \Delta T - T_\mathrm{wi}) - T_0 \ln \frac{T_\mathrm{wi}+\Delta T}{T_\mathrm{wi}}\right]}{mc(T_\mathrm{wi} + \Delta T - T_\mathrm{wi})} = 1 - \frac{T_0}{\Delta T} \ln\left(1 + \frac{\Delta T}{T_\mathrm{wi}}\right) \qquad (1)$$

where m and c are the mass and specific heat of water, respectively. The results from Eq. (1) and for the values