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Analytical modelling using Green's functions of heat transfer in a flat solar air collector

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Abstract

We have developed a purely analytical model to simulate the thermal behaviour of a flat solar air collector operating in forced convection.

The mathematical model developed is based on a direct solution using Green's functions of the linear equation for heat propagation in the air flowing through the rectangular flow path, interacting with the solid walls of the solar collector. Given the speed of the air flow and the mean solar heat flux, this approach can be used analytically to determine the two-dimensional temperature profile throughout the fluid.

This analytical model is confirmed experimentally, and can determine the local and mean temperature field in the fluid and, in particular, the surface convective heat flow. It is also used to identify changes in the convective heat exchange coefficient as a function of position and air temperature at the solar collector outlet.

Keywords: Forced convection; Solar collector; Analytical methods; Internal flow; Green's functions

1. Introduction

The Sun is the source of life on Earth, and sustains it with a constant energy supply. Today, the conservation of energy resources has become a global priority. Spiralling energy demands have compelled energy experts to seek new technologies, such as renewable energy sources (solar, wind, and geothermal).

The production of thermal power from solar energy using flat solar collectors is currently used in many applications because of the many economic and environmental advantages of this system.

This paper discusses the analytical modelling of convective heat exchange in a flat solar air collector. The heat collector is a device that converts solar energy into thermal energy. It can be used in many applications where low or moderate temperatures are required, for example to heat buildings or swimming pools, or to dry agricultural products, wood, or medicinal plants.

Given the difficulty of using numerical methods, in this study we have chosen to use an original analytical method to study the heat transfer mechanism by forced convection in air flow through a horizontal rectangular flow path. The

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Nomenclature

a	thermal diffusivity of the fluid, $m^2\,s^{-1}$
c	length of channel, m
c_p	specific heat capacity of the fluid, $J\,kg^{-1}\,K^{-1}$
D_h	$2\,L_1$, hydraulic diameter, m
E_s	solar heat flux, $W\,m^{-2}$
G	Green's function
h	convective heat exchange coefficient, $W\,m^{-2}\,K^{-1}$
L_1	thickness of the moving air flow path, m
L_2	width of channel, m
q_v	volume flow rate, $m^3\,h^{-1}$
t	time, s
T	temperature, °C
T_∞	ambient temperature, °C
U_∞	velocity, $m\,s^{-1}$
x, y, z	space variables, m

Greek symbols

λ	thermal conductivity of the fluid, $W\,m^{-1}\,K^{-1}$
ϕ	convective heat flow density, $W\,m^{-2}$
Φ	convective heat flow, W
β_m	eigenvalues
ψ_m	eigenfunctions
η	thermal efficiency
η_{op}	$\tau_v\alpha_a$, optical efficiency
α_a	absorptivity of the absorber
τ_v	transmission coefficient of the glass
ρ	density of the fluid, $kg\,m^{-3}$
v	cinematic viscosity, $m^2\,s^{-1}$

Indices and exponents

e	inlet
s	outlet
p	wall

Dimensionless numbers

Re	D_hU_∞/v, Reynolds number
Pr	v/a, Prandtl number
Pe	Re Pr , Peclet number
Nu	hD_h/λ, Nusselt number
x^*, z^*	x/c, z/L_1, dimensionless space variables
μ_m	dimensionless eigenvalues
T^*	$(T_p - T(x,\,z))/(T_p - T_e)$, dimensionless temperature
ϕ^*	$D_h\varphi/\lambda(T_p - T_e)$, dimensionless convective heat flow density

Green's functions method has been adapted to solve the energy equation in the air flowing through the rectangular flow path by imposing a boundary conditions at the upper wall of the collector (absorber), a local temperature (variable in the direction of air flow).

The aim of this work is to determine the local and mean temperature field in the fluid, the surface temperature of the walls and, in particular, the surface heat flow, and to identify how the coefficient of heat exchange varies as a function of position and the air temperature at the outlet of the rectangular channel.

The results obtained analytically by the Green's functions method are compared to experimental results.

2. Bibliography

Several types of air collector have been built and tested all over the world, mainly with the aim of collecting the greatest possible quantity of solar energy at minimum cost. To achieve this goal, various avenues are currently being explored. Below, we present a few studies available in the literature which discuss the energy efficiency of flat solar air collectors.

This research includes the work carried out by Rommel and Moock (1997). These authors study the effect of the height of the rectangular channel on the efficiency factor of the absorber. They showed that this factor could reach a maximum value (0.98) when the channel height was between 3 and 6 mm.

Njomo (1998) performed a study on a flat solar air collector with a combination plastic–glass cover, and analysed the effect of various parameters on the thermal behaviour of the collector. This author showed that the outlet temperature of the coolant fluid and the daily heat output of the collector decrease as the air flow increases and does not increase significantly with increasing inlet temperature.

A study concerning selective coatings was carried out by John Wiley (2003a) and Michaelides (2003b). These authors showed that the application of selective coatings increases the efficiency of the flat solar collector when the temperature of its absorbent surface reaches 60–70 °C.

Youcef-Ali (2005, 2006) introduced rectangular fins into the air flow path of a solar collector. The main purpose of this study was to increase the total exchange surface to improve the thermal performance characteristics. Better thermal performance is obtained with the fins, whilst the increased pressure loss is only slight.

Ammari (2003) suggests a mathematical model to calculate the thermal performance of a single-pass flat solar collector. Computer code was developed to estimate the mean temperatures in the collector. The volume air flow, the length of the collector, and the space between the absorber and the lower plate all affect the thermal performance of the solar air collector. A numerical comparison between