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Internal thermal coupling in direct-flow coaxial vacuum tube collectors

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Abstract

This investigation covers the impact of low flow rates on the efficiency of coaxial vacuum tube collectors. Measurements show an efficiency reduction of 10% if reducing the flow rate from 78 kg/m^2 h to 31 kg/m^2 h for a collector group with 60 parallel vacuum tubes with a coaxial flow conduit at one-sided connection. For a more profound understanding a model of the coaxial tube was developed which defines the main energy fluxes including the internal thermal coupling. The tube simulations show a non-linear temperature profile along the tube with the maximum temperature in the outer pipe. Due to heat transfer to the entering flow this maximum is not located at the fluid outlet. The non-linearity increases with decreasing flow rates. The experimentally determined flow distribution allows simulating the measured collector array. The simulation results confirm the efficiency decrease at low flow rates. The flow distribution has a further impact on efficiency reduction, but even at an ideal uniform flow, a considerable efficiency reduction at low flow rates is to be expected. As a consequence, low flow rates should be prevented for coaxial tube collectors, thus restricting the possible operation conditions. The effect of constructional modifications like diameter or material variations is presented. Finally the additional impact of a coaxial manifold design is discussed.

Keywords: Vacuum tube collector; Coaxial; Thermal coupling; Model; Temperature profile; Efficiency

1. Introduction

Metal-in-glass direct-flow vacuum tube collectors have a big market share in the solar sector. They are available with two different pipe designs. In the U-pipe configuration two pipes penetrate the vacuum envelope and are connected at the end with a 180°-bend (see Fig. 1a). The coaxial configuration has only one penetration using a pipe-in-pipe structure. Fig. 1b shows the coaxial design with the fluid entering the inner pipe. The indicated flow direction is a common suggestion of the manufacturers.

The coaxial design leads to a direct heat exchange between inlet and outlet flow like in a counter flow heat exchanger. If the pipe is heated from outside (here as solar heat coming from the absorber fin) this thermal coupling causes an internal heat flux from the outer to the inner pipe. That way the fluid in the outer pipe heats up the inner pipe fluid while the tube outlet temperature is reduced. The impact of the internal coupling on the temperature profile of coaxial pipes are well-known e.g., for borehole heat exchangers Loose (2006) and Sharqawy et al. (2009). But there is a lack of research about this effect in tubular solar collectors.

Kim et al. (2007) investigated all-glass vacuum tubes with a coaxial fluid conduit which have the space between inner glass tube and conduit filled with antifreeze. Kim et al. developed a one-dimensional numerical model considering the heat flux between inner and outer pipes. Han et al. (2008) expanded this model to a three dimensional one that allows the calculation of the temperature profile in the investigated tubes. The profile shows increasing temperatures in the inner and a maximum temperature inside the outer pipe. Lower mass flow rates increase the internal heat flux and thus making this profile more distinctive.

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Nomenclature

A	area (m^2)
α	absorptivity (–)
a_1	heat loss coefficient, independent of temperature (W/m^2 K)
a_2	heat loss coefficient, depending on temperature (W/m^2 K^2)
c_{eff}	collector heat capacity (J/kg K)
c_{p}	specific heat capacity (J/kg K)
ΔT	temperature difference (K)
ε	mass flow ratio (–)
η	efficiency (–)
η_0	conversion factor
$\dot{m}$	mass flow rate (kg/s)
κ	thermal conductivity (W/m K)
k	heat transfer coefficient (W/m^2 K)
k_θ	incident angle modifier
I	solar irradiance (W/m^2)
$\dot{Q}$	heat flux (W/m^2)
τ	transmissivity (–)
t	temperature (°C)
x	specific path length (m/m)

Subscripts

a	ambient
abs	absorber
ap	aperture
arith	arithmetic
b	beam
C	coupling
d	diffuse
e	exit
G	gain
i	inner
in	inlet
int	internal
L	loss
m	mean
o	outer
v	heat loss

Although effects on outlet temperature and efficiency are not discussed in the paper, the temperature profile suggests that they are influenced by the internal heat flux especially at low flow rates.

Regarding the impact of low mass flow rates on the solar collector efficiency there are a couple of investigations. Villar et al. (2009) report about a lower efficiency due to non-uniform flow and lower flow rates for a flat-plate collector with parallel tubes. The reduction of the conversion factor is 2% at 37 kg/m^2 h and non-uniform flow compared to uniform flow. Shah and Furbo (2006) investigated horizontal all-glass tubes connected to a vertical manifold with CFD simulations. The efficiency shows only small differences due to mass flow variations. However, investigations are missing about the influence of low flow rates on the efficiency of vacuum tubular collectors with coaxial pipes.

The aim of this work is to analyze the effect of the internal thermal coupling on the temperature profile and on the efficiency of a coaxial vacuum tube collector. For this purpose a model is developed which describes the main energy fluxes in the coaxial tube. In addition, measurements are carried out with a collector group consisting of two direct-flow collectors with 60 parallel connected tubes. A measured flow distribution allows to simulate each tube outlet temperature and the outlet temperature of the complete collector array, and thus to compare the model results to the measurements. Using the validated model a parameter study allows the examination of the collector with regard to flow rate and flow distribution, pipe dimension and material.

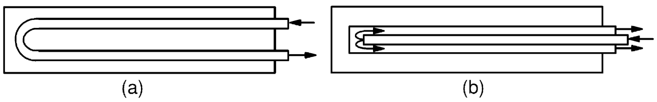

Fig. 1. Types of direct-flow vacuum tube collectors: (a) U-pipe configuration, (b) Coaxial configuration.

2. Theoretical model

A theoretical model was developed and programmed in Visual Basic to describe the temperature profile of a coaxial collector tube. Therefore the tube is divided into the outer circular ring and the inner pipe and further into elements in flow direction. Fig. 2 illustrates the collector tube divided into n elements with the main energy fluxes:

- $\tau\alpha \cdot I$: solar irradiance I after passing the tube glass and absorbed by the fin, which is implied by the product $\tau\alpha$.
- $\dot{Q}_{\mathrm{L}}$: heat losses from absorber to ambient.
- $\dot{Q}_{\mathrm{G}}$: heat gain from absorber to outer pipe.
- $\dot{Q}_{\mathrm{C}}$: coupling heat flux from outer to inner pipe.

The model is based on energy balances for absorber, inner and outer pipe in each element of the length x.

$$\text{Absorber}: \tau\alpha \cdot I = \dot{Q}_{\mathrm{G}} + \dot{Q}_{\mathrm{L}} \tag{1}$$

$$\text{Outer pipe}: \dot{m} \cdot c_{\mathrm{p}} \cdot \frac{dt}{dx} + \dot{Q}_{\mathrm{C}} = \dot{Q}_{\mathrm{G}} \tag{2}$$

$$\text{Inner pipe}: \dot{m} \cdot c_{\mathrm{p}} \cdot \frac{dt}{dx} = \dot{Q}_{\mathrm{C}} \tag{3}$$