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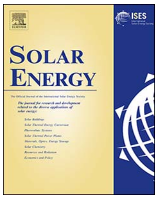

Numerical determination of the heat transfer coefficient for volumetric air receivers with wire meshes

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ABSTRACT

Volumetric receivers made of metallic plain-weave wire meshes are a promising technology that could lead to many different designs and configurations. This work deals with the numerical determination of the convective heat transfer coefficient between an air flow and stagger stacked plain-weave wire mesh screens that constitute the volumetric receivers. For that purpose, six geometries are studied with different geometrical characteristics, but with the constraint of finding pairs with similar porosities. The commercial code STAR-CCM+ was used for the detailed geometries for solving the microscopic equations. The numerical methodology, boundary conditions and main assumptions are presented. Based on a parametrical study over the velocity and wall temperature for each analyzed mesh, a correlation of the local volumetric convective heat transfer was found and depends on the Reynolds and Prandtl numbers. The different correlations were compared among them and with literature data showing similar trends and order of magnitudes. One of the correlations obtained was validated by using it in a homogeneous equivalent model assuming a local thermal non-equilibrium between the solid and fluid phases. The results were compared to the temperature profiles computed by a detailed simulation and show a very good agreement.

1. Introduction

The CRS using volumetric receiver technology is receiving a renovated interest because of its potential to increase the solar to electrical efficiency in solar power tower plants (Chen et al., 2016) and the associated advantages of the air receiver (such as availability of the fluid, no trace heating necessary, non-toxic, and 3–5 h of thermal storage) (Chen et al., 2017, 2015; Avila-Marin, 2011). This technology has the potential to increase the HTF temperature, reduce the thermal losses and, use high efficiency thermodynamic cycles (Romero et al., 2002). The research on volumetric receivers started in the early 80 s, with different materials and configurations. Ceramic materials can work at high temperatures but they have poor erosion resistance when used as foams (Ren et al., 2015), besides, the duration and effect of the foam failure strongly depends on the ligaments' microstructure (Rezaei et al., 2014). Metallic materials, work at lower temperatures than ceramics but offering the opportunity to test more configurations and geometries with a good mechanical performance (Hutter et al., 2011; Joo et al., 2011).

Since high efficiencies in the thermodynamic cycles are related to high HTF working temperatures, the most investigated option previously studied is the ceramic materials (Cagnoli et al., 2017; Mey-Cloutier et al., 2016; Wang et al., 2014; Zaversky et al., 2018), even though, the expected results with the different designs tested did not match the predicted nominal conditions (Avila-Marin, 2011).

Metallic materials have not received such interest, despite their advantages: the opportunity to easily work with different configurations and geometries, lightweight structures, lower working temperatures (< 800 °C) than ceramic materials that result in lower thermal losses, among others. In this framework, a recent study presents that it is not clear if ceramic materials are the best choice in terms of absorber efficiency and proposed volumetric structures made of dense metallic plain-weave wire mesh screens as an interesting candidate to reach absorber efficiencies exceeding 90% (Livshits et al., 2017).

Volumetric absorbers made with dense metallic wire mesh screens are characterized for being, generally, highly porous, with large specific

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Nomenclature

a	constant value (–)
A	surface area (m^2)
b	Reynolds constant value (–)
c	Prandlt constant value (–)
cf	compactness factor (–)
C	characteristic mesh constant (–)
d	diameter (m)
det	detailed (–)
d_h	hydraulic diameter (m)
F	Tong's correlation factor (–)
h	heat transfer coefficient (W/(m^2·K))
h_v	volumetric heat transfer coefficient (W/(m^3·K))
K_1	inertial permeability coefficient (m^2)
K_2	viscous permeability coefficient (m)
M	mesh size (1/m)
P	pressure (Pa)
Q	heat flux (W)
S_s	wire surface area (m^3)
T	temperature (K)
t	thickness (m)
V	volume (m^3)
w	distance between two wires (m)
Z	fluid direction (m)
Nu	Nusselt number (–)
Re	Reynolds number (–)
Re′	modified Reynolds number (–)
Pr	Prandtl number (–)
St	Stanton number (–)
a_v	specific surface area (1/m)
ρ	density (kg/m^3)
k	conductivity (W/(m·K))
c	heat capacity (J/(kg·K))
v	velocity (m/s)
v_D	Darcy velocity (m/s)
Ø	porosity (–)
$\bar{\bar{\tau}}$	viscous stress tensor (kg/(m·s^2))
μ	viscosity (Pa·s)

Subscripts

f	fluid
l	local
m	mass-average
s	solid
tot	total
x	X direction
y	Y direction

surface area and with a highly tortuous and winding flow path. This porous media has been used in different applications including refrigeration, food processing, heat pipes, thermal insulation, thermal storage, fuel cells, regenerators and volumetric air receivers (Costa et al., 2014; Cheng et al., 2013). When deployed in CRS with volumetric receivers, they can serve as lightweight structures that enhance the heat transfer. The knowledge and the characterization of the heat exchanges between the porous matrix and the fluid circulating through is a parameter of great importance because it couples the temperature between the fluid and solid phases (Vafai, 2015) and its study would define the interest of newer configurations such as the ones studied in this paper.

There is little published work in the literature for either experimental or numerical determination of the convective heat transfer between dense wire mesh, where the screens are touching with no space, and the circulating fluid.

Tong and London (1957) reported an extensive measurement study about the friction factor and heat transfer coefficient (HTC) for inline plain weave laminates and staggered cross-rod matrices in a wide range of Reynolds numbers.

Hellmuth and Matthews (1997) experimentally studied the HTC for parallel wire mesh screens placed some distance apart, what it is called sparse wire mesh arrangement, for consideration as a solar volumetric absorber.

Avila-Marin et al. (2017) numerically studied, for the first time, the convective HTC for dense wire mesh with two types of arrangement. The work focused on just one mesh type, and the correlations were implemented in a porous absorber model developed in Computational Fluid Dynamic (CFD). The results were compared with some experimental results, showing a good agreement.

Livshits et al. (2017) studied and compared the convective HTC for ceramic honeycomb and ceramic foams numerically and for dense wire mesh and sparse wire mesh experimentally. This study concludes that both ceramic honeycomb and some types of foams produce lower convection leading to lower absorber efficiency. On the other hand, they identified the dense wire mesh structure as a possible solution for solar volumetric absorber to reach or exceed the expected 90% thermal efficiency at an air outlet temperature of 1000 °C.

As a result of the lack of information available in the literature about the convective HTC with dense wire mesh arrangements, the main goals of this paper are: First, the numerical analysis of the HTC between the air flow and six detailed staggered stacked plain-weave wire mesh screens and, second, to produce correlations of the HTC for six mesh screens selected. Those meshes present different geometrical characteristics, but with the constraint of finding pairs with similar porosities, in order to analyze the effect of the specific surface area of different mesh with similar porosities. The results are then validated in a homogeneous equivalent model (HEM) compared to the results of 3D CFD simulations and compared with literature data.

2. Geometric characteristics of plain-weave wire mesh screens

The plain-weave wire mesh screen is the most commonly used weave type (Zhao et al., 2013). Two geometrical parameters that describe the mesh are the wire diameter, *d* and the mesh size or the mesh count, *M*. Fig. 1 shows plan and edge views of a section of screen. Serpentine wire filament have diameter, *d* and corresponding mesh size, *M*. The wire filament pitch is $M^{-1} = w + d$. In absence of crimping, the screen has thickness $t = d_x + d_y$.

The plain-weave wire mesh screens arrangement is an important design parameter for volumetric absorbers. The literature shows two main arrangements of stacked plain-weave screens (Zhao et al., 2013), the inline arrangement, Fig. 2(a), where successive wire mesh screens are aligned and the stagger arrangement, Fig. 2(b), where successive wire mesh screens are offset in two directions by $0.5 \cdot M^{-1}$. The inline pattern has lower pressure drop, HTC and higher porosity, thus less frontal thermal losses when used as a volumetric absorber, compared to the staggered pattern that has the opposite behavior (Avila-Marin et al., 2017).

An accurate estimation of key porous parameters undoubtedly helps to understand the heat transfer mechanisms inside those porous structures. The following section presents data related to the volumetric porosity, the specific surface area, and the mesh hydraulic diameter for both types of arrangements for the plain-weave wire mesh screens.