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Heat Transfer Simulation of Evacuated Tube Collectors (ETC): An Application to a Prototype

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Abstract

Since fossil fuels shortages are predicted for the forthcoming generations, the use of renewable energy sources is playing a key role and is strongly recommended worldwide by national and international regulations. In this scenario, solar collectors for hot water preparation, space heating and cooling are becoming an increasingly interesting alternative, especially in the building sector because of population growth. Thus, the present paper is addressed to numerically investigate the thermal behaviour of a prototypal evacuated tube by solving the heat transfer differential equations using the Finite Element Method. This is to reproduce the heat transfer process occurring within the real system, helping the industry improve the prototype.

Keywords: simulation; heat transfer; solar collectors

1. Introduction

Solar energy is considered to be the most abundant renewable energy source and is available both in direct and indirect forms. Solar radiation represents the basis of all the natural phenomena and many human activities. It is worth noting that the total annual solar radiation falling on the Earth is more than 7500 times the world's total annual primary energy consumption and is even greater than all the estimated non-renewable energy sources. However, 80% of the present energy is still generated by fossil fuels, although they are finite resources and their combustion is harmful to the environment because of Greenhouse Gases (GHGs) and pollutants emissions which contribute to the global warming problem. Since fossil fuels shortages are predicted for the near future, the use and the research of alternative/Renewable Energy Sources (RES) for heating and cooling buildings or to produce electricity is strongly encouraged in many countries and by international and national regulations [Carlini *et al.*, 2012; Carlini *et al.*, 2013; Mosconi *et al.*, 2013; Sisinni *et al.*, 2013; Vecchione *et al.*, 2013; Villarini *et al.*, 2014]. In this scenario, solar thermal collectors are playing a growing and fundamental role, especially in the building sector where they are mainly used for hot water preparation space heating and cooling. This technology is relatively mature and cost competitive if compared with other energy sources [Carlini *et al.*, 2012; Carlini *et al.*, 2014; Carlini and Castellucci, 2011; Chang *et al.*, 2002; Dincer, 1998; Ibrahim *et al.*, 2014; Kalogirou and Papamarcou, 2000; Kalogirou, 2003; Micangeli *et al.*, 2013; Micangeli *et al.*, 2014; Kalogirou, 2004; Kreith and Kreider, 1978; Mathioulakis and Belessiotis, 2002; Weiss and Biermayr].

Basically, solar collectors consist of heat exchangers that convert the incoming solar radiation into heat, than transferring it to a fluid flowing within the collector itself [Borello *et al.*, 2012]. The circulating fluid is directly used as domestic hot water or in space conditioning equipment or is carried into a monitored thermal energy storage tank [Iannuzzo *et al.*, 2012]. Broadly speaking, two types of solar collectors can be distinguished, namely non concentrating or stationary and concentrating. While in the former the area for intercepting and absorbing solar radiation is the same surface, the latter usually has concave reflecting surfaces to intercept and focus the Sun's beam radiation to a smaller receiving area. In more detail, non concentrating solar collectors are classified according to their motion, i.e. stationary, single axis/double axes tracking, and the operating temperature [Kalogirou, 2004; Micangeli *et al.*, 2013].

Evacuated Tube Collectors (ETC) belong the first category and consist of a heat pipe inside a vacuum-sealed tube [Ricci *et al.*, 2015]. The copper pipe is attached to a black copper fin that fills the tube (absorber plate) and a metal tip is placed in the sealed pipe (condenser). The heat pipe contains a small amount of fluid which undergoes an evaporating/condensing cycle: solar heat evaporates the liquid and the vapour moves to the heat tank, where it condenses releasing its latent heat. Then, the condensed fluid returns back to the solar collector and the process is repeated [Kalogirou, 2004]. ETC combine the selective surface with an effective convection suppressor and the presence of the vacuum envelope reduces conduction and convection losses, thus reaching good performances at high temperature [Kalogirou, 2004].

The aim of the present paper is to investigate the thermal behaviour of a prototypal evacuated tube collector by means of steady state simulations in Comsol Multiphysics, thus involving the solution of heat transfer Partial Differential Equations (PDEs).

As it is commonly known, PDEs arise in many subject areas, such as fluid dynamics, electromagnetism, and in many physical, chemical and biological phenomena. Frequently, the related equations are so complicated that finding their solutions in closed form or by analytical means are impracticable or possible only for very simple geometries. Thus, one has to resort to seeking numerical approximations to the unknown analytical solution describing the real and complex object. These notes are devoted to a particular class of numerical techniques for the approximate solution of PDEs, that is the Finite Element Method (FEM) [Incropera *et al.*, 2007].

Comsol Multiphysics is a commercial software package which performs equation based modelling for different physical processes and applications, and consists of several modules concerning different branches. The Heat Transfer module helps the user in investigating the heat transfer mechanism, that is conduction, convection and thermal radiation, and a combination of them or in collaboration with other physics [Comsol Multiphysics User's Guide].

Nomenclature

C_p	specific heat at constant pressure ($J / kg \cdot K$)
e_b	blackbody hemispherical total emissive power
$\mathbf{F}$	body force vector (N/m^3)
G	irradiation or incoming radiative heat flux (W/m^2)
J	radiosity or total outgoing radiative flux (W/m^2)
$\mathbf{n}$	normal vector of the boundary
k	thermal conductivity ($W/ m \cdot K$)
p	pressure (Pa)
$\mathbf{q}$	conductive heat flux vector (W/m^2)
q_0	inward heat flux, normal to the boundary (W/m^2)
Q	heat source term (W)
Q_{vh}	viscous heating (W)
t	time (s)
T	absolute temperature (K)
T_0	temperature at a boundary (K)
$\mathbf{u}$	velocity field (m/s)
W_p	pressure work
ε	surface emissivity (dimensionless)
μ	dynamic viscosity (Pa x s)
ρ	density of the material (kg/m^3)
ρ_{refl}	surface reflectivity (dimensionless)

2. Material and methods

Broadly speaking, the simulating process in Comsol Multiphysics encompasses several steps, leading to build a specific model and following a logical sequence within a tree structure. First, the user is required to define the space dimension (1D, 2D, 2D axisymmetric or 3D) and the physic of the problem. Then, the study type –whose main items are stationary or time dependent analyses- has to be selected. Global definitions, such as parameters, variables or functions, may be assessed by the user in order to quickly draw the object or to specify other parameters within the simulation (e.g. heat source). The geometry is successfully built by importing files or by working with drawing operations within Comsol Multiphysics [Comsol Multiphysics User's Guide].

The Heat Transfer module comes stocked with an internal material database containing the material properties of a number of common fluids, gases and solids. This includes thermal conductivity, heat capacity and density. However, other material data can be imported or modified by the user. In order to solve the PDE describing the specific phenomenon, the mesh has to be created, choosing among different available options, namely from extra-fine to extra coarse meshes, leading to different and accurate solutions. The results and convergence plots of the problem can be visualised in the graphics window [Comsol Multiphysics User's Guide].

The heat transfer mechanism within the solar collector is due to conduction within the solid elements, convection and thermal radiation. The Conjugate Heat Transfer interface within Comsol Multiphysics' package describes heat transfer in solids and fluids and is tightly coupled with the fluid flow problem. In order to take into account the radiation contribute within the above mentioned physic, two different groups of modelling interfaces can be added, namely the Surface-to Surface Radiation and the Surface-to-Ambient Radiation [Comsol Multiphysics User's Guide].

2.1 Governing equations

The heat transfer due to conduction is governed by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q=\rho C_p\frac{\partial T}{\partial t} \quad (1)$$

or:

$$\nabla\cdot\left(k\nabla T\right)+Q=\rho\cdot C_p\frac{\partial T}{\partial t} \quad (2)$$

which is the general form of the heat diffusion equation in Cartesian coordinates. The latter provides the basic tool for heat conduction analysis, and describes an important physical condition, that is conservation energy. Its solution leads to determine the temperature distribution T(x, y, z) as a function of time. Hence, this equation states that at any point in the medium the net rate energy transfer due to conduction into a unit volume plus the volumetric rate of thermal energy generation must equal the rate of change of thermal energy stored within the volume.

For a steady-state problem, the temperature does not change with time and the first term disappears, that is the amount of energy storage does not vary and hence Eq. 2 reduces to the following form:

$$\nabla \cdot \left(k\nabla T \right) + Q = 0 \tag{3}$$

The foregoing equations emerge from Fourier's law, which may be considered as the cornerstone of conduction heat transfer: it is not derived from first principles and is a vector expression indicating that the heat flux is normal to an isotherm and in the direction of decreasing temperature.
In order to determine the temperature distribution in a medium, the heat equation must be appropriately solved. Such a solution depends on the physical conditions existing at the boundaries of the medium and on conditions existing in the medium at some initial time if the problem is time dependent. The heat equation accepts two basic types of boundary conditions: specified temperature and specified heat flux. The first condition is a constraint type –which is commonly known as Dirichlet condition- and corresponds to a situation for which the boundary surface is maintained at a fixed temperature:

$$T = T_0 \; on \; \partial\Omega \tag{4}$$

The specified heat flux conditions defines the inward heat flux by the following expression:

$$-\vec{n} \cdot \vec{q} = q_0 \tag{5}$$

The heat transfer in fluids is given by:

$$\rho \cdot \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = \nabla \cdot \left[-p\vec{I} + \mu\left(\nabla \vec{u} + \left(\nabla \vec{u} \right)^T \right) - \frac{2}{3}\mu\left(\nabla \cdot \vec{u} \right)\vec{I} \right] + \vec{F} \tag{6}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0 \tag{7}$$

$$\rho C_p \cdot \vec{u} \nabla T = \nabla \cdot \left(k\nabla T \right) + Q + Q_{vh} + W_p \tag{8}$$

which represent the general expression of the momentum, the continuity and the heat equation for a fluid respectively. When the node Fluid is added within the Comsol model, the volume force, all the terms related to the heat sources and pressure work are neglected [Comsol Multiphysics User's Guide; Incropera *et al*, 2007].
The radiation may interact with convective and conductive heat transfer and its contribute may be taken into account by adding two boundary conditions: Surface-to-Surface Radiation and the External Radiation Source. With regard to the first condition, the concept of irradiation G and radiosity J needs to be further investigated. The irradiation G at a point can be written as the sum of the mutual

irradiation coming from other boundaries in the model G_m, the irradiation from the external radiation sources G_{ext}, and the ambient radiation G_{amb}[Incropera *et al.*, 2007; Comsol Multiphysics User's Guide]:

$$G = G_m + G_{ext} + G_{amb} \tag{9}$$

The radiosity J is the sum of the reflected irradiation and the emitted radiation. For diffuse-grey surface, it is defined as:

$$J = \rho_{refl} G + \varepsilon e_b(T) \tag{10}$$

2.2 Description of the prototype

The innovative prototype differs from standard ETC since a third integrated pipe is included in the system, thus ensuring parallel connection of multiple modules. More precisely, the collector consists of 18 borosilicate double air-casing vacuum tubes, whose diameter is equal to 58 mm. The tubes are fixed within an anodized aluminium frame and are crossed by direct and diffused solar radiation, which is then captured in the absorber. The latter is made of aluminium and transfers heat to the copper U tube within the pipes. The collector technical specifications are given in table 1 [Ricci *et al*., 2015]:

Parameters	**Value**
Length x width x height	2002 x 1712 x 120 mm
Gross area	3,427 m^2
Aperture area	1,8 m^2
Absorber area	1,46 m^2
Weight	86,5 kg
Fluid content	3,09 l
Maximum pressure	1000 kPa
Flow range	0,8 l/(min x m^2)
Absorption coefficient	< 94,5 ± 2 %
Transfer coefficient of the glass	< 91,5 ± 1 %

Table 1: Prototype specifications [Ricci *et al*., 2015].

2.3 Geometry, modelling parameters and meshing phase

The simulation in Comsol Multiphysics is carried out for a piece volume of the prototypal solar collector (figure 1), whose material thermal properties are reported in table 2. The simulation in steady-state conditions is developed for a 10 cm long-cylinder, representing a small portion of the entire system: this is to reduce the computational solving time, still ensuring a correct description and good understanding of the heat transfer occurring within the solar collector. The surface emissivity of the aluminium fin is assumed equal to 6.5 %, according to the technical sheet. In order to properly solve the differential equation describing the phenomenon, the boundary conditions shown in table 3 are adopted.

With specific regard to the boundary conditions, it is worth noting that T_{alu_fin} was measured by placing two thermocouples on the inner surface of the solar collector.

The simulation is carried out for a portion of cylinder which is assumed to be placed in middle of one single tube: T_{in} and T_{out} are the temperature values at the beginning and end of the inlet and outgoing pipe respectively (table 3). The mesh consists of tetrahedral elements and fine size-dimensions are chosen to discretise the system (table 4, figure 3).

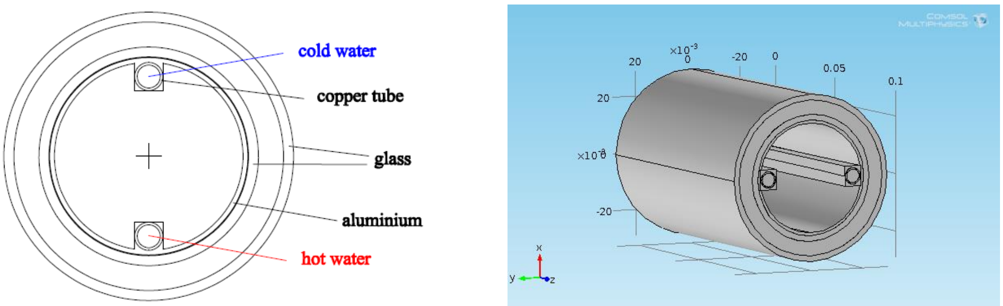

Figure 1: Geometry of the system.

Material	**k**	**ρ**	**Cp**
Air	f(T)	f(T)	f(T)
Aluminium	160	2700	900
Copper	400	8700	385
Glass	1,1	220	480
Water	f(T)	f(T)	f(T)

Table 2: Thermal properties of the material in the solar collector.

. Boundary conditions	**Value**
Initial values	25 °C
T_{alu_fin}	170 °C
T_{in}	40 °C
T_{out}	46 °C

Table 3: Boundary conditions for solving the differential equations within the control volume

Domain elements	77223
Boundary elements	29841
Edge elements	3314

Table 1: Mesh elements.

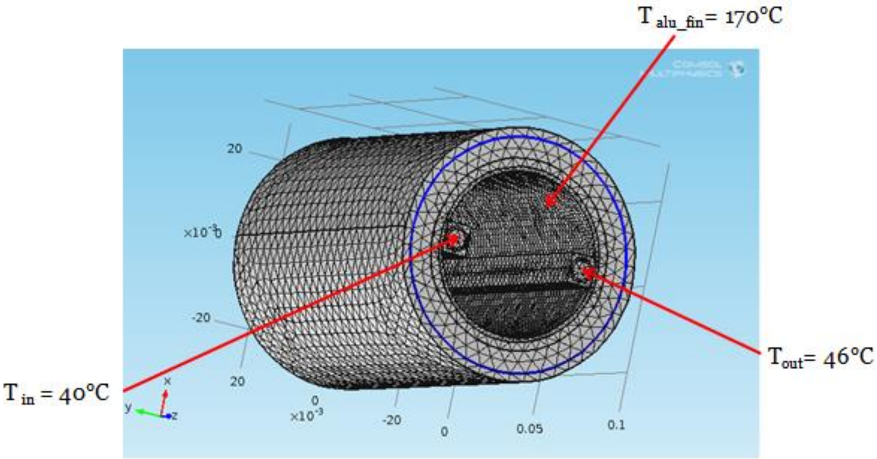

Figure 2: Boundary conditions of the problem and fine-size mesh for the investigated model.

3. Results and conclusion

The results generated by the steady state simulation in Comsol Multiphysics are given in figure 4, in terms of surface temperature on a vertical section and on the whole volume of the problem. The postprocessing clearly shows the fundamental role played by the copper layer where the highest temperature occurs, and confirms the limited heat losses due to convection and conduction in the vacuum envelope, thus leading to good performances of the collector in terms of conversion efficiency (figure 4).

The number of iterations and related error are given in figure 5: it can be seen that the convergence of the problem is reached after 8 iterations performed in 25 s.

Although it may be difficult to represent in detail some of the phenomena occurring in real systems, the present simulation carefully describes the heat transfer processes in a prototypal evacuated tube. Moreover, it is demonstrated to be a powerful tool for process design since offering a number of advantages, such as the possibility of changing geometrical parameters and physical properties. This helps the industry to model and create a system to a high degree of accuracy, thus improving the prototype step by step, depending on the crucial elements emerging from the simulation itself. As a consequence, computer modelling of thermal systems may provide thorough understanding of system operation and component interactions and temperature variations of the system. Furthermore, it is possible to estimate the amount of energy delivery from the system and the design variable changes by using the same weather conditions.

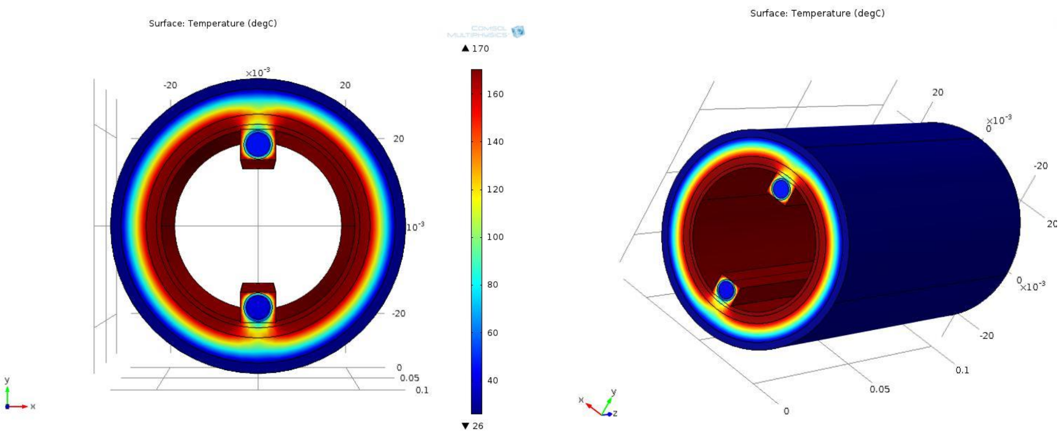

Figure 3: Surface temperature in degC for steady state conditions (xy vertical section on the left, on the whole control volume on the right).

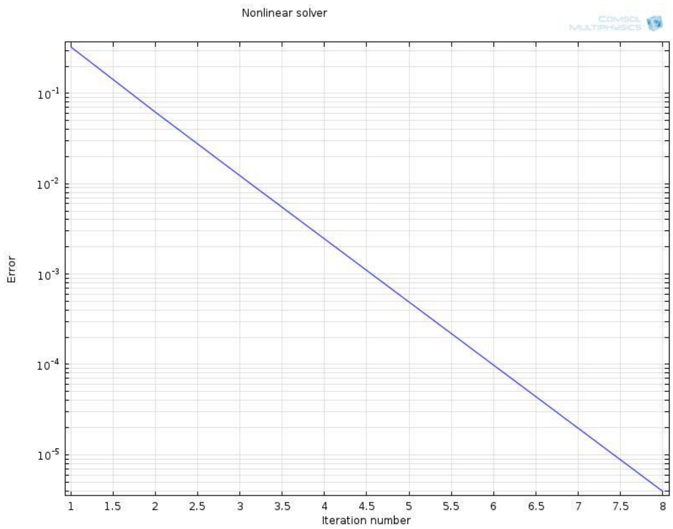

Figure 4: Error and number of iterations in the convergence plot.

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