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ScienceDirect

Solar Energy 112 (2015) 154–162

SOLAR ENERGY

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Modelling of storage tanks with immersed heat exchangers

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Received 10 September 2014; received in revised form 25 November 2014; accepted 26 November 2014
Available online 18 December 2014

Communicated by: Associate Editor Luisa F. Cabeza

Abstract

A model of a storage tank with an immersed serpentine heat exchanger is described and validated against experimental data available from the literature. The tank is modelled one dimensionally using the multi-node approach corrected by an energy conservative reversion elimination algorithm to prevent inverse gradient solutions to occur. A one dimensional model in the flow direction is also used for the serpentine based on control volume techniques. The serpentine is discretized in equal sized control volumes and the energy equation is solved in each of them. The energy exchanged between the serpentine and the tank is then introduced as an internal heat source of the tank multi-node. With this model the behaviour of tanks with internal serpentines can be predicted minimising tuning parameters to be derived from previous experimental analysis of the tank. Additionally, by an appropriate formulation of the governing equations in the serpentine control volumes, it is possible to handle complex internal fluid phenomena as coupling of the tank within a thermosyphone cycle or two phase flow.

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Keywords: Storage tanks; Modelling; Serpentine; Immersed heat exchanger

1. Introduction

In most solar thermal systems some kind of heat exchanger is used to separate the thermal fluid circulating through the collector field from the thermal fluid inside the tank. For medium or small size systems, with a store volume below around 2000 l, the heat exchanger is normally integrated within the tank. Mantle tanks or storages with immersed heat exchangers are the two main devices used for this purpose.

Mantle tanks, also known as jacket or annular heat exchangers, are the simplest and cheapest means of obtaining high thermal effectiveness while promoting stratification. However, as discussed by Furbo (2003) and Shah (2000), the use of mantle tanks is limited to volumes below 800–1000 l, because above these volumes heat transfer area reduces considerably. In tanks with immersed heat exchangers this problem is overcome. Additionally, the tank to ambient heat loss coefficient is also reduced.

Three and two dimensional models for storage tanks can be used to investigate specific phenomena. For example, the thermal stratification of cylindrical horizontal tanks has recently been analysed by Savicki et al. (2011) and Yan and Davidson (2008) studied the transient heat transfer characteristics of immersed serpentine heat exchangers. From these studies, very detailed information can be obtained. However, the computational demand is high, and the model must be run by specialists. As a consequence, they are not suitable for long term studies under

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http://dx.doi.org/10.1016/j.solener.2014.11.032
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Nomenclature

A	area (m^2); algebraic coefficient in Eq. (8)
A_F	fitting coefficient in Eq. (16)
B	algebraic coefficient in Eq. (8)
C	fitting coefficient in Eq. (13)
C_F	fitting coefficient in Eq. (16)
C_N	fitting coefficient in Eq. (17)
CVs	control volumes
c_p	specific heat at constant pressure (J/kg K)
D	diameter (m)
Exp	experimental
Gr	Grashof number
Gz	Graetz number
h	heat transfer coefficient (W/m^2 K)
K	fitting coefficient in Eq. (13)
L	total serpentine length (m)
$LMTD$	logarithmic mean temperature difference (°C)
M	total number of control volumes used in the serpentine
$\dot{m}$	mass flow rate (kg/s)
N	total number of nodes used in the multi-node model
n_N	fitting coefficient in Eq. (17)
Num	numerical
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat (W)
Re	Reynolds number
S	surface (m^2)
T	temperature (°C)
UA	overall heat transfer coefficient (W/K)
V	volume (m^3)
β	volumetric coefficient of thermal expansion (1/K)
Δt	time increment (s)
δ	distance (m)
ϵ	heat exchanger effectiveness
κ	conductance (W/m^2 K)
Λ	equivalent conductivity coefficient (W/mK)
λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/s m)

Subscripts

ext	external
in	at inlet
ini	initial conditions
int	internal
m	control volume index in the serpentine model
n	node index in the tank multi-node model
out	at outlet

Superscripts

a	ambient
$acum$	accumulated heat
col	collector
F	forced convection
hx	heat exchanger
$load$	referred to heat load
$loss$	referred to heat loss
m	fitting coefficient in Eq. (13)
mix	mixing
N	natural (free) convection
n	fitting coefficient in Eq. (13)
o	value at the previous time step
tnk	tank
$wall$	referred to wall

operation conditions and cannot be used in market-oriented solar thermal systems engineering. Therefore, one-dimensional tank approaches are still normally used for long term studies as those recently presented by Campos Celador et al. (2011), Young-Deuk et al. (2012), Banister et al. (2014) or Shuhong et al. (2014), because they are able to offer an optimal compromise between accuracy and computational effort.

A widely used one-dimensional model for storage tanks is the multi-node model developed by Kleinbach et al. (1993). The tank is divided in different nodes from the bottom to the top, and the energy and mass conservation equations are solved at each of them over the time. This results into a one dimensional transient resolution of the tank.

An extension of the multi-node model was proposed by Newton et al. (1995) to include an immersed heat exchanger. This model assumes a constant heat transfer coefficient between the heat exchanger and storage fluid that must be introduced as an input value.

A multi-port store model able to include four immersed heat exchangers was developed by Drück (1994). The heat transfer coefficient must also be introduced by the user for specific conditions. Therefore, experimental data should be used to estimate this parameter, what is known as model tuning process. Time dependence of the heat transfer coefficient is then directly estimated by the model. This model is widespread in solar thermal system testing. However, the experimental data required for the tuning process is not always available for commercial stores.

Additionally, the multi-node model for storage tanks must also include a reversion elimination algorithm, see Mather et al. (2002). Basically, this algorithm forces that fluid temperatures of the different layers increase with

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