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Modeling of an ice storage based on a de-icing concept for solar heating applications

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Abstract

The development and validation of a mathematical model of an ice storage tank with heat exchangers that can be de-iced is presented. The ice storage tank model is developed for a solar-ice system, i.e. a system that combines solar thermal collectors with a heat pump to provide space heating and domestic hot water.

The model is based on the one dimensional resolution of the energy conservation equation of a fluid submitted to a phase change, and it is able to consider the detachment of the ice plates from the heat exchangers. The ice growing layer is calculated using the analytical solution of a flat plate configuration with a quasi steady state approximation.

Experiments were conducted with a laboratory scale ice storage of 1 m^3. Several operating modes were investigated in order to validate the model under different conditions of interest. The model predicted successfully most of the operating modes for the main variables such as heat exchanger outlet temperature and heat transfer, as well as mass of ice produced and melted.

Keywords: Ice storage; Modeling; Solar and heat pumps; Solar-ice

1. Introduction

The heating energy demand of the domestic and industrial sectors covers around 50% of the total energy demand in Europe (European Technology Platform on Renewable Heating and Cooling, 2011). The increase of efficiency of heating and cooling systems for these sectors is therefore of great importance. Combining solar collectors with a heat pump for heating and domestic hot water preparation is becoming a popular option in order to achieve systems with high ratio of heat delivered over electricity consumption, i.e. a high Seasonal Performance Factor (SPF). A systematic classification of solar and heat pump systems was proposed in Frank et al. (2010) and an updated review of these systems is provided in Hadorn (2015). From all the solar and heat pump concepts used in heating applications, those that use an ice storage are sometimes referred as solar-ice systems. The ice storage is used in this application as a heat source for the heat pump and it is loaded by the solar field, which can also be used as a direct heat source for the heat pump. Explanations of different solar-ice systems can be found elsewhere (Trinkl et al., 2009; Winteler et al., 2014; Carbonell et al., 2014a). A solar-ice system can be seen as an alternative to ground source heat pump systems when for example, regulations forbid to drill boreholes.

The advantages of using ice storages in heating applications are: (i) they can be installed in the basement of the building to have a good access to the storage and also

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Nomenclature

A	area (m^2)
C	fitting coefficient in Eq. (13)
c_p	specific heat at constant pressure (J/kg K)
f_l	liquid fraction
F_P	efficiency of the heat exchanger
F_{FR}	removal factor
F_{PP}	flow factor
h	specific enthalpy (J/kg)
h_f	specific enthalpy of fusion (J/kg)
U	global heat transfer coefficient (W/m^2 K)
M	total mass (kg)
M_{ice}	mass of ice (kg)
$\dot{m}$	mass flow rate (kg/s)
n	fitting coefficient in Eq. (13)
Nu	Nusselt number
$\dot{q}$	heat per unit volume (W/m^3)
$\dot{q}_v$	heat source per unit volume (W/m^3)
$\dot{Q}$	heat (W)
Ra	Rayleigh number
t	time (s)
T	temperature (°C) (without subscript refers to water)
$\vec{v}$	velocity vector (m/s)
V	volume (m^3)
V_r	ratio of total ice volume (%)
$V_{r,float}$	ratio of floating ice volume (%)
y	vertical coordinate (m)
Δt	time increment (s)
$\Delta\delta$	distance increment (m)
α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)

Subscripts

a	accumulated heat
av	averaged
c	conduction
ext	external or surroundings
f	fluid (brine)
$float$	floating
fr	freeze
in	inlet or internal conditions
j	index of coordinate y
$loss$	referred to heat loss
o	outlet conditions
p	plate
r	ratio
ref	reference
s	surface
sk	sink
hx	heat exchanger

Superscripts

o	value at previous time step
m	melting

useful when there is no ground space available; (ii) they have higher energy storage density compared to sensible storages; (iii) they can be used as additional sensible storages to store surplus solar heat, especially in summer and at high temperatures.

Ice storage concepts are generally classified as a function of the mechanism used to produce the ice. The description of different ice systems for cooling applications can be found in Mehling and Cabeza (2008). The main ice production concepts used nowadays are: (i) ice on heat exchanger, typically referred as ice-on-coil; (ii) ice slurries and (iii) module type. From the module type, the most common system is macroencapsulation of ice, also known as ice balls. The most widely employed method for cooling applications is ice on heat exchanger (ice-on-hx). Ice-on-hx is also the most widespread concept in solar-ice applications. In fact, to the author's knowledge, there is not a single system on the market using ice slurries or ice balls for solar heating applications and only one research work has been found using ice slurries (Tamasauskas et al., 2012). Some authors have tried to use a material different from water for this application (see e.g. Qi et al. (2008)). Nevertheless, the price of water, its availability, non-toxicity and high latent heat of fusion makes its use for this application the most favorable option.

Among the ice-on-hx solutions, several heat exchanger concepts are used. The ice storage system employed here is based on immersed steel flat plate heat exchangers with a de-icing concept. The de-icing is possible by means of solar heat from the solar collectors or with heat from the lower part of the combi-store, which is charged solely with solar energy. When the heat pump extracts heat from the ice storage with brine temperatures below 0 °C, ice is formed on the surface of the immersed heat exchangers in the ice storage tank. Growing ice layers on the heat exchanger decrease the overall heat transfer coefficient from the ice forming layer to the brine in the heat exchanger. This results in lower brine temperatures, and thus in a lower heat pump performance. A strategy to prevent the effect of a decreasing overall heat transfer coefficient in a flat plate heat exchanger is to remove the ice layers periodically. The ice layers are de-iced when the heat pump is switched off before reaching too low brine temperatures by melting the ice that is in contact with the heat exchanger. Thereupon the ice layers separate from the heat exchangers due to buoyancy forces and accumulate at the