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ScienceDirect

Solar Energy 125 (2016) 398–414

SOLAR ENERGY

www.elsevier.com/locate/solener

Modeling of an ice storage buried in the ground for solar heating applications. Validations with one year of monitored data from a pilot plant

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Received 17 September 2015; received in revised form 27 November 2015; accepted 12 December 2015
Available online 11 January 2016

Communicated by: Associate Editor Cabeza Luisa F.

Abstract

A mathematical model for an ice storage buried in the ground is presented and validated with experimental results of one full operation year of a pilot plant with a 75 m^3 ice storage. The ice storage was designed with heat exchangers that can be de-iced and it was developed for heating applications using a combined solar thermal and heat pump system. Because of the inherent coupling between the ice storage and the ground, a ground model was developed and coupled with the ice storage for the validation.

The ice storage model is based on a transient one dimensional energy equation derived along the height of the storage with equally distributed control volumes. The ground is solved with a transient heat conduction equation with a heat source term from the ice storage. The physical ground domain is discretized in an axial-symmetrical mesh concentrated in high density gradient regions close to the ice storage. The models are solved in sequence until global convergence is achieved.

The model was found to be in good agreement in terms of ice storage temperature and energy exchanged by the heat exchangers. Extracted energy from the storage was very well predicted. However, differences were found in the energy delivered by the wall heat exchangers. Ground temperatures were found to be well predicted below and above the storage, but not at the sides of the storage were over-predicted values, partially due to the simplifications assumed in this region, were observed.

Keywords: Ice storage; Ground; Modeling; Solar heating

The interest in combining solar collectors with a heat pump for residential heating applications has grown in the last decade. A system that combines an ice storage, solar thermal collectors and a heat pump for heating applications is commonly know as solar-ice system. In the literature several papers address these types of systems from a theoretical perspective using simulations, e.g. Trinkl et al. (2009), Tamasauskas et al. (2012), Winteler et al. (2014), Carbonell et al. (2014) and from a practical point of view in field installations, e.g. Loose and Drück (2012) and Philippen et al. (2014). A detailed review of ice storage systems currently offered on the Swiss market is provided in Minder et al. (2014), where the analyzed systems are distinguished by the ice storage capacity (from several hours up to several weeks) when used as single source for the heat pump.

The expression "ice storage" is used as a common name for a thermal storage that uses the phase change enthalpy of water from liquid to solid as a part of its storage

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http://dx.doi.org/10.1016/j.solener.2015.12.009

Nomenclature

A	area (m^2)
C	fitting coefficient in Eq. (8)
c_p	specific heat at constant pressure (J/kg K)
D	diameter (m)
F_P	efficiency of the heat exchanger
F_{FR}	removal factor
F_{PP}	flow factor
h_f	water specific enthalpy of fusion (J/kg)
r	radius coordinate (m)
U	global heat transfer coefficient (W/m^2 K)
M	mass of water (kg)
M_{ice}	mass of ice (kg)
$\dot{m}$	mass flow rate (kg/s)
n	fitting coefficient in Eq. (8)
N_{cv}	number of control volumes
Nu	Nusselt number
$\dot{q}$	heat (W/m^3)
$\dot{q}_{sol}$	solar radiation on horizontal surface (W/m^2)
$\dot{q}_v$	heat source (W/m^3)
$\dot{Q}$	heat (W)
$\dot{Q}_+$	positive component of the heat (W)
$\dot{Q}_-$	negative component of the heat (W)
Ra	Rayleigh number
t	time
T	water temperature (°C)
T_f	brine temperature (°C)
T_g	ground temperature (°C)
V	volume (m^3)
V_r	ratio of ice volume
y	axial coordinate (m)
δ	distance (s)
Δt	time increment (s)
$\Delta\delta$	distance increment (s)
α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)

Subscripts

a	accumulated heat
av	averaged
ex	exchange
ext	external or surroundings
E	east nodal value
f	fluid (brine)
fr	freeze
g	ground
hx	heat exchanger
i	index of coordinate r
in	inlet or internal conditions
j	index of coordinate y
$loss$	referred to heat loss
N	north nodal value
o	outlet conditions
p	plate
P	nodal value
s	surface
sol	solar
sk	sink
S	south nodal value
hx	heat exchanger
W	west nodal value

Superscripts

o	value at previous time step
m	melting

capacity. By freezing water, a high amount of heat can be extracted: freezing of 1 kg of water releases the same amount of heat as the cooling of 1 kg of water from 79.5 °C to 0 °C. The high specific storage capacity due to the use of the latent heat of the storage water is an important characteristic of ice storages. Usually, heat is extracted from ice storages with a heat pump. As an illustrative example, the hydraulic scheme with main components of a possible solar-ice heating system is shown schematically in Fig. 1. The heat is extracted via heat exchangers that are immersed into the storage water. As the heat transfer fluid has to be cooled below 0 °C, a mixture of water with antifreeze flows through the heat exchangers. If during the heat extraction, the surface temperature of the heat exchanger drops below the freezing point of water, ice can be formed on the heat exchangers. By this process of building up ice, the latent heat of the storage water is extracted. Besides the latent heat, also the sensible heat of the storage water can be used.

Ice storages have been used for many decades in the cooling industry and for air-conditioning of buildings ASHRAE (2007). These storages are mostly optimized for the provision of high cooling power with the aim to reduce chiller power needs and electricity cost by shaving the cooling peak load. Different requirements apply when ice storages are used in heating systems for buildings (which may also include a function for cooling the building). Here it is of high importance that the storage has a low cost, is simply mounted, and needs minimal maintenance. In contrast to cooling applications, the reduction of the size of the heat pump and the electricity savings in peak demand periods are not relevant.