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Research Paper

Experimental and numerical study of the freezing process of flat-plate solar collector

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HIGHLIGHTS

- A mathematical model for the freezing of flat-plate solar collector is present.
- A prototype experiment is conducted to validate the model.
- Factors influencing the antifreeze performance of the collector are investigated.
- The effect of employing TIM honeycomb on the flat-plate collector is studied.

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ABSTRACT

Flat-plate solar collector is vulnerable to the freezing-damage. But the study of the antifreeze performance of the flat-plate solar collector is rarely reported in the published literatures. This paper presents a model with high precision to simulate the cooling and freezing process of flat-plate solar collector exposed to cold ambient air and conducts a prototype experiment to validate the model. Based on the validated model, factors influencing the antifreeze performance of flat-plate solar collector are investigated. Besides, the antifreeze effect of introducing TIM transparent honeycomb (TIM: transparent insulation materials) in the flat-plate collector is studied numerically. Results show that narrowing the pipe space, increasing the pipe diameter or header diameter and reducing the emissivity of absorber and glass-cover are the effective ways of enhancing the antifreeze performance of flat-plate collector. Meanwhile, employing TIM transparent honeycomb can significantly improve the antifreeze performance of flat-plate collector and can put off the completely frozen time of the collector by 2.5 h.

1. Introduction

Flat-plate solar collector is the most common solar collector for solar water-heating and solar space heating which has been widely installed in residential and office buildings due to their reliable performance [1]. However, in cold areas, freezing is always one of the serious problems for the solar collecting system with flat-plate collectors, since flat-plate collector without an automatic drainage device for emptying usually experiences a cooling process in nights, resulting in the water frozen of the flat-plate solar collector. For most conventional flat-plate collector, There exists two types of heat loss during the work in daytime: top heat loss (across the airgap and glass-cover) and bottom heat loss (across the insulation layer and backboard) [2]. When in nights, the heat dissipates rapidly from the absorber to the ambient air and the sky dome due to the pretty low ambient air temperature and the sky equivalent temperature. Since most conventional flat-plate collector is low mass and has little heat storage capacity, the temperature of the absorber will drop rapidly to the freezing point of the water. When the freezing happens in a collector, the strain caused by the volumetric expansion of water can burst the pipes and cause the irreparable damage to the collector. Several researches have been conducted to study the freezing of the solar collector. In an earlier study, the University of Illinois performed a series of pipe freezing and bursting experiments [3]. This study included placing copper pipes filled with water in a commercial freezer and recording the water (or ice) temperature and internal pressure. The results of the study noted that the pipe bursting is due to the pressure building up in the region between two total ice blockages. No pressure building up occurs before the formation of both blockages, since freeze expansion is relieved by pushing water back into the mains inlet. In a recent study, Salasovich et al. [4] studied the freezing of the supply and return piping of the passive solar domestic hot

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Nomenclature

Symbols

A	cross-sectional area [m^2]
C	specific heat [J/(kg K)]
D	length of honeycomb cell [m]
E	current iteration results [K&J/kg]
E^*	previous iteration results [K&J/kg]
F	view factor
H	enthalpy [J/kg]
h	heat transfer coefficient [W/(K m^2)]
H_s^*	enthalpy of ice at freezing point [J/kg]
H_l^*	enthalpy of water at freezing point [J/kg]
J	effective radiation fluxes [W/m^2]
k_e	effective thermal conductivity of the honeycomb cell [W/(K m)]
L	height of honeycomb cell [m]
l	length [m]
M	mass per unit area [kg/m^2]
Nu	Nusselt number [dimensionless]
O	outside diameter [m]
Q	heat loss [W/m^2]
q	net heat flux density [W/m^2]
Ri	frozen water fraction [dimensionless]
Ra	Rayleigh number [dimensionless]
r	radial coordinate [m]
rc	rate of convergence [J/kg]
T	temperature [K]
T_0	freezing point of water [K]
t	time [s]
U	conduction heat transfer coefficient per unit length [W/(K m)]
U_{pg}	composite heat transfer coefficient across the honeycomb plate [W/(K m^2)]
V	volume [m^3]
v	velocity [m/s]
x	horizontal coordinate [m]
y	axial coordinate [m]
z	vertical coordinate [m]

Subscript

a	airgap (between absorber and glass-cover)
b	backboard
c	honeycomb cell
cv	convective
cd	conductive
ct	header
e	external environment
g	glass-cover
ic	ice
ins	insulation layer
jo	absorber-pipe joint
p	absorber plate
p'	bottom surface of the honeycomb cell
r	radiative
t	pipe
w	side walls of the honeycomb cell
wa	water

Greek symbols

γ	latent heat of water [J/kg]
δ	thickness [m]
ε	emissivity [dimensionless]
λ	thermal conductivity [W/(K m)]
ρ	density [kg/m^3]
σ	Stefan-Boltzman constant [5.6697×10^{-8} W/(K^4 m^2)]
φ	collector tilt angle [rad]

water systems (SDHWS). They presented a pipe-freeze model for the SDHWS and ran the simulation using 30 years of actual weather data. The results showed that increasing the pipe diameter and insulation thickness contributes to preventing pipe freeze. However, this study only focuses on the freezing of the supply and return pipe which are insulated with a heat insulation ring. In fact, the collector of the SDHWS is more vulnerable to freezing damage due to the radiation to the night sky.

In the past three decades, a large quantity of researches has been reported on the freeze protection of the solar collector. The conventional measures include using evacuated solar tubes in place of flat-plate collectors, adopting recirculation with antifreeze liquid, equipping with an automatic drainage device for emptying, and using reverse flow to reheat the collector in nights [5–9]. However, these approaches would either increase the cost or lower the thermal performance of the water-heating system with flat-plate collector. Hence, in order to find reliable and effective measures for the freeze protection, more attention is supposed to be paid to the cooling and freezing process of the solar collectors. However, studies of the antifreeze performance of the solar collector were rarely reported in the literatures due to the difficulty of the measurement of the freezing process in the pipes. With a new method of measuring the freezing state in the pipes, the freezing process of the flat-plate solar collector is researched by the authors in this paper.

Owing to the difficulty of experimentally studying the freezing issue of the solar collector, most previous studies focused on the numerical work. Beckman and Bradley [10] presented a freezing model for a single tube in a solar collector. The model is one-dimensional (cylindrical symmetry), and the heat transfer coefficients are all assumed constant (no variation with wind or temperature). The pipe is assumed to be long enough to accommodate a freezing or bursting event. Salasovich et al. [4] presented a pipe-freeze model that accounts for hot water draws for the SDHWS. In this model, the Beckman and Bradley model was refined for the draw case. However, the computational domain in this model was still confined to a single tube of a collector. The other components of the collector and variable weather conditions were not taken into account. Schollenberger et al. [11] experimentally characterized the conditions causing the freeze damage of the passive integral-collector-storage (ICS) solar collector and developed a model relating the freeze behavior to climatic conditions. In their study, Existing models for ICS thermal performance were modified to incorporate the freezing process, and have been validated with the experimental data. However, this model included too much simplification, and did not introduce elaborate phase change model to solve the freezing of the water in the collector. In their model, the whole collector was treated as one temperature node, and the transient lumped capacitance equation was adopted to solve cooling and freezing process of the collector. In the present work, a collector freezing model with enough complexity and accuracy was proposed, and the enthalpy model was introduced to solve the phase-changing heat transfer problem.

Since water-heating is mostly needed in winter when freezing condition is common, the operation of flat-plate solar collector under freezing conditions is inevitable. Thus, investigating the