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Experimental and numerical study of thin ring and annular fin effects on improving the ice formation in ice-on-coil thermal storage systems

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HIGHLIGHTS

- Performances of thin rings and annular fins in the ice-on-coil system are compared.
- The superiority of using thin rings versus annular fins, is proved.
- Final size of the ice thickness on the ring, defines the optimum ring thickness.
- At a special distance size between annular fins, the maximum ice formation happens.

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ABSTRACT

Cooling load demand during the warmest hours of summer days leads to an increase in electrical energy request, intensifying the peak load. Thus, to reduce electrical energy consumption in peak hours, cold energy storage systems are used. One of the most common methods in this area is ice on coil energy storage that deals with the problem of heat transfer rate decreasing during charging. In this paper, performance of two heat transfer enhancement methods including usage of thin rings and annular fins around coils are compared. First, the thermal behavior of the system is simulated and the sensitivity analysis is performed. Then, design parameters for experimental set up are selected based on the results obtained from the sensitivity analysis. For the case of annular fins, results show that the optimum operating point is deduced when the distance between two adjacent fins becomes 50 mm. According to the numerical results, the experimental tests are designed. It is shown that ice formation in the cases of using annular fins and rings will be correspondingly 21% and 34% higher with respect to the bare tube. Besides, freezing will be sped up by 15% in the case of using finned and ringed tubes. Accordingly, diagonal thin rings have better performance with respect to annular fins. The reason is that the ice formation rate in the central region between the tubes is enhanced due to the presence of thin rings in this region.

1. Introduction

Cold thermal energy storage helps reserve cooling capacity overnight for later usage in peak periods. Applying this technology leads to more compact instruments, less energy consumption and lower maintenance and electrical costs of air conditioning systems [1–3]. Moreover, the coefficient of performance for hybrid system could increase and air conditioning quality will be improved in the humid climates because of the colder temperature of output air [4,5]. Although it has a significant importance in HVAC systems, there exists many challenges for using this technology. Several works have been performed to deal with them.

Some researches in the field of cold storage technology have concentrated on the optimization of the integrated system by selecting the appropriate strategies, optimizing the size and control methods. Sebzali and Rubini [6] investigated the effects of using chilled water storage unit in the common air conditioning system for Kuwait's climate. Results show that load leveling strategy gives the lowest life cycle cost compared to demand limiting and full storage strategies and it reduces the nominal chiller size up to 33 percent [7]. Yan et al. combined seasonal and short time cold energy storage systems [8]. They optimized component sizes and reduced system life-cycle costs by 40%. Chiu et al. [9] presented a multi-objective optimization on the system cost and cooling supply for various latent heat thermal energy storage (LHTES) configurations. They showed that an active free cooling LHTES system stores 75% of the required cooling energy at half the electricity consumption and at less than half of the conventional air

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Nomenclature

Abbreviation

HTF	heat transfer fluid
PCM	phase change material
TES	thermal energy storage

Symbols

A	area (m^2)
C	porosity constant
H	total enthalpy (J/K)
K	permeability
K_0	empirical constant in Kozeny-Carman equation
T	temperature (K)
U	velocity (m/s)
P	pressure (Pa)
L	latent heat of phase change (J/kg)
ΔH	latent heat
S	source term
S_x	x direction momentum source term
S_y	y direction momentum source term
h	sensible enthalpy
u	x direction velocity-vector component (m/s)
v	y direction velocity-vector component (m/s)
g	acceleration of gravity (m/s^2)
x, y	coordinate axes
t	time (s)
d	diameter (m)
k	thermal conductivity (W/m K)
c	specific heat (J/kg K)
q	small constant to avoid division by zero

Greek symbols

α	thermal diffusivity
β	liquid fraction
μ	viscosity (Pa s)
ρ	density (kg/m^3)
λ	thermal coefficient of expansion

Subscript

f	fluid
s	solid
l	liquid
ref	reference
w	water
i	ice
c	coil
b	buoyancy
h	enthalpy
x, y	coordinate axes

conditioning costs. Murphy et al. designed a controller that optimized electrical consumption cost in Ireland [10]. They used an ice storage component in the modeling in order to shift the electric demand to off-peak hour.

Component improvement of a cold storage technology is another interesting field of research. Various cold storage technologies have been designed including sensible, thermochemical and latent technologies. Thermochemical technology deals with several challenges not commercialized yet. LHTES requires less space and smaller temperature variation with respect to the sensible system. Therefore, LHTES is the most widely used technology. Among the LHTESs, the internal ice-on-coil systems are the most commonly used type of ice storage technology in the commercial applications [11]. One of the challenges in the ice on coil energy storage technology is the heat transfer rate reduction with the progress of charging process. Various solutions to tackle this challenge are followed.

The effect of geometry, arrangement of coils and properties of HTF with emphasis on heat transfer rate enhancement were also studied. Yang-Cheng and Chou [12] presented an enthalpy formulation based fixed grid approach to study the solidification around a number of staggered cylinders in a fixed volume. They modeled the effect of number of cylinders on the growth rate of ice layer. Buyruk et al. [13] calculated the effect of different geometries on the ice formation in a rectangular water-filled tank. The results show that the solid fraction for the aligned cylinders is smaller than the staggered ones. Ahmet et al. [14] studied the phase change phenomena around a horizontal tube in a cold thermal storage system and based on the experimental results, investigated the effects of different heat transfer fluid (HTF) inlet temperatures on the ice formation. Zheng et al. simulated thermal behavior of an ice on coil storage system [15]. The results show that larger pipe diameter improves the heat transfer rate, significantly. However, increasing thermal conductivity of tube has a minor effect on the heat resistance. Habeebullah [16] experimentally investigated the growth rate of ice on the cooled copper tubes. He found that axial growth rate of ice is different at low values of the coolant Reynolds number and small freezing times. Also, he found that ice on the bends is thicker, that is attributed to internal flow disturbances of the coolant, and creation of local eddies inside the bends. Kayansayan and Acar experimentally measured the temperature profile across the tube [17]. Results show that the dimensionless value of the total energy stored increases for increasing the Fourier and the Stefan numbers.

New concepts for increasing heat transfer rate in LHTES systems is recently introduced. Pointner and Steinmann proposed the phase change material flux (PCM-flux) concept for increasing the heat transfer rate inside a heat exchanger which included PCM packs moving across the heat transfer surface [18]. They experimentally demonstrated proof of concept. Yang et al. investigated the effect of using copper foam inside a shell and tube heat exchanger [19]. Comparison of the effect of flow rate and temperature of HTF on the charging rate shows that the effect of HTF temperature is more significant. Although these concepts have been technically proved, further research is needed for techno-economical improvements.

The extended surface for heat transfer rate is another method that was investigated. Zhang and Faghri [20] investigated the heat transfer improvement in the latent heat thermal energy storage system by using fins inside the tubes. The results show that adding internal fins accelerates heat transfer rate up to 15 percent when the thermal conductivity of the transfer fluid is low. Lacroix and Benmadda [21] studied the effect of finned vertical wall on the melting rate. Ismail and Lino [22] investigated the effects of the radial fin diameter and turbulence intensifiers on the improvement of the heat transfer rate around a horizontal tube that is immersed inside PCMs. Observations show that there is an optimum fin diameter for the time to complete solidification. The use of the turbulence intensifier results in high interface velocity and short time for completing solidification. However, this effect is less impressive than the effect of radial fins. Ismail et al. modeled the solidification time of PCM around an axial finned tube. They studied the effect of thickness, radius length and number of axial fins [23]. Moreover,