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An experimental study on ice formation around horizontal long tubes

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Abstract

The results of an experimental study are presented where the growth rate of ice on the outside of cooled copper tubes was studied. The tubes, which were immersed in water in an insulated vessel, were internally cooled by circulating glycol through them.

It was found that axial growth rate of ice is distinct at low values of the coolant Reynolds number and short freezing times. The slope of the ice thickness with axial distance showed moderate dependency on time but varied with coolant flow rate, and with Stanton and Biot numbers.

A key result from the experiments is the abrupt ice thickness enlargements on the surface of tube bends. This anomaly may be attributed to internal flow disturbances of the coolant, and creation of local eddies inside the bends that enhance growth of ice. The effect was evident for a low Reynolds number ($Re = 251.9$ and $Bi < 1$), and fades out for large Reynolds number flows.

Keywords: Thermal storage; Ice tank; Horizontal tube; Copper; Experiment; Growth; Ice

Etude expérimentale sur la formation de glace autour des tubes horizontaux d'une grande longueur

Mots clés : Accumulation thermique ; Bac à glace ; Tube horizontal ; Cuivre ; Expérimentation ; Croissance ; Glace

1. Introduction

Applications of energy storage systems are vast and becoming important in many processes ranging from storage of heat or coolness for buildings to thermal storage for satellites and particular shielding clothes [1]. Thermal energy storage (TES) is an uprising technology in the fields of air conditioning (A/C), refrigeration and power industry, where part of the load is stored during off peak period and then recharged whenever needed. Thermal energy is stored either as sensible heat where the amount of energy is controlled by the temperature level of a storing media or as latent heat. The use of solid—liquid phase change (isothermal process) allows for greater portion of energy to be stored and has attracted attention in recent years. For A/C of buildings, energy storage

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Nomenclature

A surface area (m^2)
C_p specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
C_s specific heat of solid phase ($J\,kg^{-1}\,K^{-1}$)
d diameter (m)
h heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k thermal conductivity ($W\,m^{-1}\,K^{-1}$)
M mass of ice
Nu Nusselt number
Q heat rate (W)
R tube radius (m)
Re Reynolds number (Vd_i/ν)
r_{ice} ice radius (m)
Ste Stefan number ($Ste = C_s(T - T_i)/\lambda$)
St Stanton number ($h/(\rho C_p)_c V$)
T temperature (K)
TR taper ratio (mm/m)
V coolant average velocity ($m\,s^{-1}$)
x distance (m)

Greek letters
δ ice thickness (mm)
ν kinematic viscosity ($m^2\,s^{-1}$)
λ latent heat (J/kg)
ρ density ($kg\,m^{-3}$)
τ time (s)

Subscripts
c coolant
i initial
s solid or surface
b bulk

systems are used for either load leveling (partial load storage) or full load storage [2,3]. Latent heat storage has important features where the size is small when compared to sensible heat storage, and usually cheap water can be used as the storage medium. In ice-storage systems ice is formed on the external surface of tube bundles during energy charging process. In the discharge mode, ice melts either through passing warm fluid inside the tubes (internal melt) or by direct contact with the ice exterior surface (external melt). A state of the art review on TES research was presented by Saito [4].

The problem of phase change, known as the Stefan problem, has received more attention recently because of developments of numerical solution methods and availability of high-speed computation algorithms. The literatures on phase change problem are abundant including analytical, numerical and approximate solution methods for both steady and transient conditions [5–7]. In addition, several experiments have been conducted to provide fundamental information on the freezing and melting process. Sinha and Gupta [8] reported the results of an experimental study of ice formation on the outer surface of a horizontal copper tube cooled by a flow of refrigerant at isothermal conditions. They developed a numerical model for the problem and the predicted results were in good agreements with the experimental measurements.

Sablani et al. [9] developed a correlation relating the time required for complete solidification of a phase change material (PCM) in an annular space to Biot number and the annulus geometry. Ismail and de Jesus [10] presented the results of a numerical parametric study on the solidification of a PCM around a cylinder carrying a heat-transfer fluid (HTF). The study showed the effects of the HTF entry temperature, initial PCM temperature and the thermal conductivity of the tube material on the evolution of solidification.

London and Seban [11] observed that freezing of substances around tubes may be considered as one-dimensional problem when the cooling medium has a constant temperature or for short tubes length. In general there is axial variation of the solid thickness along the tube because of the increase in the coolant temperature as it warms up along the length. This axial variation, which requires two-dimensional analysis was considered in the numerical solution of Sparrow and Hsu [12]. Shamsundar and Srinivasan [13,14] have developed an analytical solution for the problem and the results obtained were compared to the numerical solution of Sparrow and Hsu [12]. In the analysis they found out that, the temperature distribution in the radial direction is logarithmic, while the axial temperature variation is parabolic, for large Biot numbers ($Bi = hR/k_s$). Adding fins to the heat transfer surface would enhance the solidification process but the experiments of Sparrow et al. [15] showed that the presence of fins and bulk natural convection during phase change delays the solidification process. Zhang and Faghri [16] studied phase change in an annular space with finned internal surfaces. Ismail et al. [17] presented the results of a numerical and experimental investigation on solidification on the outer surface of a finned vertical cylinder. The time required for complete solidification of PCM in an annular space was found to be a function of geometrical parameters (number of fins, fins thickness, length of fins and the annular aspect ratio) in addition to the degree of superheat.

Most of the experimental investigations available in the literature were conducted for short length tubes ($x/R \leq 100$), which do not simulate the conditions in TES tanks and do not reflect the axial propagation of the freezing front. The objective of this study is to provide data on ice growth rate on relatively long tubes.

2. Experimental test facility

A schematic diagram of the test apparatus and test sections is shown in Fig. 1. The setup consists of a primary