Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

Experimental study of frost formation on a fin-and-tube heat exchanger by natural convection

Mohammad Amini [a], *Ahmad R. Pishevar* [a], *Mahmood Yaghoubi* [b,*]

[a] *Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran*
[b] *School of Mechanical Engineering, Shiraz University, Shiraz, Fars 7134851154, Iran*

ARTICLE INFO

Article history:
Received 6 November 2013
Received in revised form
24 June 2014
Accepted 24 June 2014
Available online 5 July 2014

Keywords:
Natural convection
Frost formation
Finned tube
Environmental parameters

ABSTRACT

This paper presents an experimental study of frost growth on a fin-and-tube heat exchanger by natural convection. Experiments are carried out for refrigerant mean temperature of −10 °C, −15 °C and −20 °C, ambient temperatures between 20 °C and 30 °C and relative humidity varied from 50% to 70%. The results include changes of frost thickness and its impact on heat transfer rate under different environmental condition. Frost growth depends on time and location along the fin and tube heat exchanger. Frost thickness varies due to changes of air velocity, temperature and concentration boundary layers. The heat transfer rate and frost growth show strong dependence on refrigerant mean temperature, ambient air temperature and relative humidity. According to the measurements, some practical empirical correlations of frost growth and heat transfer are presented in terms of relevant dimensionless parameters.

Etude expérimentale de la formation de givre dans un échangeur de chaleur à tubes à ailettes grâce à la convection naturelle

Mots clés : Convection naturelle ; Formation de givre ; Tube à ailettes ; Paramètres environnementaux

1. Introduction

Using extended surfaces or fins is one of the most common ways to increase convection heat transfer. In refrigeration and air conditioning industries, to enhance heat transfer particularly in the evaporators, fin-and-tube heat exchangers are widely used. In cryogenic systems, frost formation on such heat exchangers is generally common. Frost takes place when moist air comes into contact with a cold surface whose temperature is below freezing temperature.

* *Corresponding author*. Tel.: +98 917 118 4335; fax: +98 711 230 1672.
E-mail addresses: m.amini@me.iut.ac.ir (M. Amini), apishe@cc.iut.ac.ir (A.R. Pishevar), yaghoubi@shirazu.ac.ir, yaghoubi.md@gmail.com (M. Yaghoubi).
http://dx.doi.org/10.1016/j.ijrefrig.2014.06.015
0140-7007/

Nomenclature

c_p	specific heat capacity (J kg^{-1} K^{-1})
d	fin spacing (m)
Fo	Fourier number based on ice properties
g	gravity acceleration (m s^{-2})
h	convection heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
l	height of test section (m)
$\dot{m}$	mass flow rate (kg s^{-1})
Nu_d	Nusselt number
P	pressure (Pa)
Q	heat transfer rate (W)
Ra	Rayleigh number
RH	relative humidity
t	time (s)
T	temperature (K)
x	distance from the top of fin (m)
x^*	dimensionless distance from the top of fin
X_i	the ith variable

Greek letters

α	thermal diffusivity (m^2 s^{-1})
β	volume expansion coefficient (K^{-1})
δ	frost thickness (mm)
δ_f^*	dimensionless frost thickness
δX_i	uncertainty in the variable X_i
$\delta X_{i,1}$	first-order uncertainty in X_i
$\delta X_{i,\text{fixed}}$	fixed uncertainty in X_i
$\delta X_{i,N}$	Nth-order uncertainty in X_i
Δ	difference
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

Subscripts

a	air
f	frost
l	lateral
m	mean
ref	refrigerant
u	up
v	water vapor

Superscript

*	dimensionless

Investigation of frost formation is complicated since heat and mass transfer are unsteady and nonlinear in porous layer with moving boundary. For this phemenon, numerous studies are performed for different geometries and for various thermal and hydrodynamic boundary conditions in forced convection regime. Na and Webb (2003) presented a theoretical analysis for nucleation process of frost formation on a cold surface. Na and Webb (2004) also investigated mass transfer on and within a frost layer. They concluded that some of the water vapor transferred from the air to the frost layer deposits on the frost surface and makes the frost layer thicker. The rest of water vapor penetrates into the frost layer and results in a denser frost layer. Yan et al. (2005) experimentally investigated the thermo fluid characteristics of frosted finned tube heat exchanger. The results of their investigation indicate that the amount of frost formation increases as air flow rate decreases. Lee and Ro (2005) presented a simple model for the growth of frost layer on a flat plate. They focused on diffusion and phase change inside the porous media.

Regarding free convection, Cremers and Mehra (1982) experimentally studied frost growth on a cooled vertical cylinder in free convection flow. Their investigation attempts to fill some gaps in understanding frost layer growth by presenting their observations of frost growth on a small diameter vertical cylinder in free convection. Fossa and Tanda (2002) experimentally investigated frost growth on a vertical plate in free convection. They reported that the largest values of frost thickness were generally found at the highest relative humidity. Tahavvor and Yaghoubi (2008) investigated the growth of frost and its properties with time by designing an artificial neural network. They (2009) also presented a mathematical model and predicted transition time and frost properties over a horizontal cylinder in the first stage of frost growth. They assumed that in the first stage, frost is formed as a column of ice on the surface and after the transition time, frost layer becomes a porous media. Tahavvor and Yaghoubi (2010) also investigated frost formation on a horizontal cylinder under natural convection experimentally and numerically for different ambient conditions. Fossa and Tanda (2010) experimentally investigated frost growth on the cooling surface which was placed in narrow vertical channels with different depth, open at the top and bottom in order to permit the natural circulation of ambient air. They reported an abrupt frost growth at the leading edge of the cooling surface that caused an obstruction to the beyond flow with consequent interruption of frost growth and sudden reduction in heat flux from air to the cooling plate. Mahdavi and Yaghoubi (2012) experimentally investigated frost formation over finned tube under natural convection. They observed almost no air passes between fins while there is a small distance between the fins. So frost forms only on the tip of the fins.

According to the above review, few studies of frost formation are reported based on free convection and the authors did not observe frost studies on fin and tube heat exchanger under natural convection. In industrial gas production units, this type of heat exchanger may be used as ambient vaporizer. Based on such applications, frost formation is studied on a fin-and-tube heat exchanger under natural convection and the influences of different environmental conditions are examined. In this investigation, it is tried to develop proper empirical correlations for heat transfer and frost growth as a function of Fourier number, Rayleigh number, dimensionless distance and relative humidity on a fin and tube heat exchanger under natural convection based on the experimental results. These correlations are very useful for engineers, scientists and designers who work on the control of defrost operations.

2. Experimental apparatus

Experiments are performed in a test room of 4 m × 4 m × 3 m as shown in Fig. 1. Some part of the room was designed for the