International Journal of Heat and Mass Transfer 112 (2017) 850–861

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effect of initial cooling on heat and mass transfer at the cryogenic surface under natural convective condition

Sangho Choi [a,b], Sung Jin Kim [a,*]

[a] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Daejeon 305-701, Republic of Korea
[b] Department of Thermal & Aerodynamics, Korea Aerospace Research Institute, 115 Gwahangno, Daejeon 305-333, Republic of Korea

ARTICLE INFO

Article history:
Received 26 December 2016
Received in revised form 7 April 2017
Accepted 9 May 2017

Keywords:
Frost formation
Cryogenic surface
Heat and mass transfer
Effect of initial wall cooling
Natural convection

ABSTRACT

The effect of initial wall cooling from ambient temperature to cryogenic temperature on heat and mass transfer at the cryogenic surface under natural convection was experimentally and numerically investigated. The experimental study showed that the initial wall cooling had a strong effect on heat and mass transfer at the cryogenic surface. The frost under initial wall cooling grew considerably thicker than the case without initial wall cooling. The maximum heat flux under initial wall cooling was 40% of that without initial wall cooling, and the minimum heat flux under the initial wall cooling was 52% of that without initial wall cooling. In addition, a numerical model for the frost formation accounting for initial wall cooling was proposed. The proposed numerical model could explain the heat and mass transfer at the cryogenic surface during the cooling process as well as the filling and holdup process. In order to validate the proposed numerical model, experiments were performed under various ambient air temperature and relative humidity conditions: $10\,°C \le Ta \le 30\,°C$ and $30\% \le RH \le 90\%$. The maximum and minimum heat flux from the numerical model showed good agreement with experimental data within 10% and 25% error, respectively. The final frost thickness from the numerical model showed good agreement with experimental data within 13% error except for one case where mass transfer was reduced due to fog formation near the cryogenic surface. Therefore, the numerical model will be useful for estimating the heat flux in an uninsulated cryogenic system, such as a rocket oxygen tank.

1. Introduction

Frosting phenomenon on cold surface occurs in a variety of applications, such as refrigeration, aerodynamics, propellant loading in rockets, CO_2 reduction, and many others. Under atmospheric conditions, when the wall temperature drops below the dew point of air, water vapor in the air transfers to the wall and condenses at the surface because there is a pressure difference between the partial pressure of water vapor in the air and the saturation pressure at the wall temperature. If the wall temperature further decreases below the freezing point of water, deposition of water vapor into ice particles occurs. The thickness of the frost layer then starts to increase due to the growth and branching of the ice crystals.

Heat and mass transfer in uninsulated cryogenic systems has been extensively investigated because of their application in rocket propulsion system. The liquid oxygen tank used in rockets has no thermal insulation except in the case of the space shuttle as the frost formed on the cryogenic oxygen tank surface acts as a natural insulator. Because frost plays the role of an insulator, heat flux into the cryogenic oxygen tank is reduced considerably compared to that under no frost formation. Heat flux into the oxygen tank causes liquid oxygen to evaporate and to be stratified. Evaporation of liquid oxygen requires additional filling during ground operation, and stratification renders some portion of liquid oxygen unusable during flight. Therefore, accurate knowledge of heat and mass transfer at the cryogenic surface is important in optimizing the amount of oxygen loading in rockets.

In the early stages of rocket development many researchers investigated frost formation on uninsulated cryogenic surfaces. Ruccia and Mohr [1] experimentally studied frost formation on an oxygen-filled tank exposed to uncontrolled ambient air under natural convection and forced convection. They attempted to determine the applicability of certain existing heat transfer correlations at the cryogenic temperatures. However, these attempts were unsuccessful because the obscured heat flux measurement at the initial stage prevented them from verifying the calculated heat flux. Nevertheless, they found that the experimentally measured mass transfer rate was one-sixth lower than the theoretically expected results. Holten [2] experimentally studied heat and mass

* Corresponding author.
E-mail address: sungjinkim@kaist.ac.kr (S.J. Kim).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.033

Nomenclature

B	porosity
c_p	specific heat capacity at constant pressure (J/kg·K)
Gr	Grashof number
h	convective heat transfer coefficient (W/m^2·K)
h_m	mass transfer coefficient (m/s)
H	latent heat (J/kg)
k	thermal conductivity (W/m·K)
Le	Lewis number
$\dot{m}''$	mass flux (kg/m^2·s)
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux (W/m^2)
R	gas constant (J/kg·K)
Ra	Rayleigh number
Re	Reynolds number
RH	relative humidity (%)
t	time (s)
T	temperature (K)
w	absolute humidity (kg/kg$_{da}$)
x	spatial coordinate (m)

Greek symbols

α	dimensionless wall temperature
δ	frost thickness (m)
ϵ	emissivity
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant
$\emptyset$	view factor

Subscript

a	air
cond	conduction
conv	convection
cool	cooling
cryo	cryogenic condition
d	diffusion
da	dry air
D	diameter
f	frost
i	ice
ini	initial condition
l	liquid
L	length
lat	latent
LOX	liquid oxygen
m	mass transfer
rad	radiation
ref	reference temperature
s	solid
SS	stainless steel
sat	saturation
th	thickness
tp	triple point of water
v	vapor
wall	wall condition

transfer in an oxygen-filled tank exposed to humidity-controlled air under natural convection. He found that heat flux was the maximum at the moment of exposure to ambient air and decreased rapidly, and then approached a minimum as time passed. Furthermore, he found that the effective heat transfer modes were convection and radiation at cryogenic temperatures and phase change heat transfer had a minimal effect. Barron and Han [3] studied heat and mass transfer in a nitrogen-filled tank in a temperature and humidity controlled chamber. They found that heat transfer was in good agreement with the theoretical expectation, but mass transfer was much lower than the theoretical prediction. They explained that mass transfer was reduced because water droplets or ice particles in the boundary layer blocked diffusion of the water vapor. Shah [4] experimentally and numerically investigated frost formation on a liquid nitrogen cooled surface under forced convection. He proposed a simple theoretical model and the experimental results showed good agreement with the proposed model. He found that the density distribution within the frost layer was nearly uniform. Brian et al. [5] experimentally studied frost formation on a liquid nitrogen cooled plate from a humid air stream. They suggested an empirical correlation for the frost thermal conductivity with average frost density and temperature. Biguria and Wenzel [6] conducted an experiment to obtain the thermal conductivity and density of frost. They used Freon as the coolant which was cooled by liquid nitrogen. They suggested complex correlations for the frost thermal conductivity and density as a function of the wall temperature, humidity, air velocity, time, and flow regime.

Recently, Kim et al. [7] numerically investigated frost formation on a cryogenic oxidizer tank wall for a liquid-propulsion rocket. They numerically analyzed the effects of parameters and stated that wind speed, air temperature, and relative humidity had significant effects on heat and mass transfer. However, their results were based on a numerical analysis and were not validated. Liu et al. [8] experimentally studied frost formation on a liquid nitrogen cooled surface under various conditions. They found that oxygen-rich water droplets were formed on a cryogenic surface, and they measured the frost layer thickness at various wall temperatures, air temperatures, and relative humidity conditions.

All the previous researchers experimentally or numerically studied frost formation under a constant cryogenic temperature, although the main application, namely, rocket prelaunch operations, is not a constant temperature process. In the rocket prelaunch operations, the oxygen tank should be initially cooled from the ambient temperature to the cryogenic temperature before a constant cryogenic temperature is reached during the filling and holdup process, as shown in Fig. 1. During the initial wall cooling, which usually takes approximately 60 min, frost starts to form on the wall and a considerable amount of frost is accumulated on the wall by the time the wall temperature reaches the cryogenic

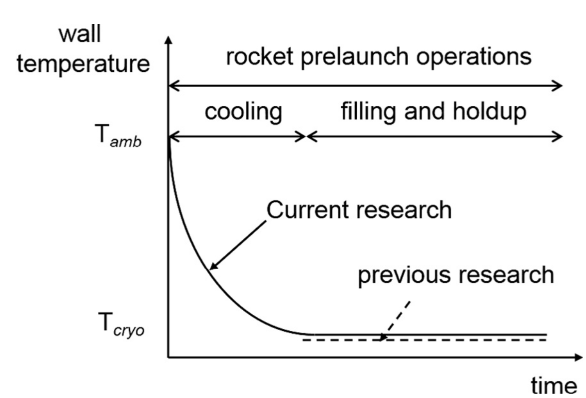

Fig. 1. Wall temperature variations with and without initial wall cooling.