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Numerical simulation of frosting behavior and its effect on a direct-contact ambient air vaporizer

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ABSTRACT

Ambient air-based technology for liquefied natural gas vaporization is an ideal selection for reducing the average cost of terminals and maximizing operating efficiency. Thus, this study presents a numerical model to predict the frosting behavior and thermal performance of a direct-contact ambient air vaporizer. The empirical correlations for predicting some basic properties of the frost layer are used to establish the numerical model. The flow of cryogenic fluid in the vaporizer and the adverse effect of the frost layer are both considered in the model. Numerical results agree with the experimental data in the literature in a wide range of working conditions. The outlet temperature of the vaporizer initially surges because of the frost formation at the early stage. This surge decreases with time and ambient air temperature. The frost behavior on the vaporizer surface is not only related to surrounding conditions but also to the flow state of the fluid in the vaporizer. During operation, the lengths of the liquid-phase and two-phase sections increase, whereas that of the vapor-phase section decreases.

1. Introduction

With the continuous increase in energy demand and cost, reducing average cost and maximizing operating efficiency have become crucial objectives for liquefied natural gas (LNG) import terminals. Many vaporization operations at these terminals currently utilize submerged combustion vaporizers (SCVs), open rack vaporizers (ORVs), or other fired heaters to re-gasify LNG. In gas-fired systems, approximately 1.3%–1.6% of total LNG is used as fuel to heat and vaporize liquid natural gas. This operation not only reduces the amount of natural gas available for the market and increases average cost, but it also generates emissions that are detrimental to the environment, such as NO_x and CO. These emissions generally require special treatment systems. As for the ORVs, sea water may not meet the design requirements for seasonal reasons. The effluent, whose temperature is generally low, has a harmful impact on the neritic environment as well. Environmental pollution is a significant problem in China, and people pay increasing attention to the environment. The increased energy cost and environmental pressure prompt researchers to look to ambient air-based technologies for LNG vaporization. The use of low-grade heat from ambient air to re-gasify LNG lowers fuel consumption and operating cost. Moreover, ambient air vaporizers (AAVs) generate no emissions and they only generate ice and condensed water as effluents. These features render the overall terminal environment-friendly. Nonetheless, the vaporization capacity of AAVs changes dramatically due to the influence of frost layers deposited on the cold wall of vaporizers, as the porous frost layer composed of ice crystals and air pores has a low thermal conductivity. In addition to this, AAVs may also fail to meet the design requirement for seasonal or climate-related reasons. These challenges have limited the wide application of AAV in LNG terminals. Hence, the selection of a suitable vaporization system is significant because it directly influences the capital cost, operating cost, and environmental impact of terminals. Nonetheless, previous studies have rarely focused on the thermal performance of AAVs. Accurate numerical models must be established for AAV because these models affect the prediction of thermal performance and assist terminal developers in selecting appropriate vaporizers.

The main factors that affect the vaporization capacity of AAVs are frost growth and the deposition on the vaporizer wall. These factors are directly influenced by working conditions such as ambient temperature and humidity, and this influence complicates the problem considerably. Previous researchers have performed lots of outstanding research on frost formation. Some recent studies are summarized in Table 1, including information on geometry,

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Nomenclature

A	area [m^2]
Cp	specific heat [J/(kg K)]
D	mass diffusivity [m^2/s]
f	friction coefficient [−]
H	enthalpy [J/kg]
h_m	mass transfer coefficient [m/s^2]
h_{sv}	latent heat of sublimation [J/kg]
Kn	Knudsen number [-]
k	thermal conductivity [W/(m K)]
Le	Lewis number [−]
l	length [m]
m'	mass flux [kg/(m^{2}s)]
q	heat [W]
T	temperature [K]
t	time [s]
$\mathbf{u}$	velocity vector [m/s]
x	vapor quality [−]

Greek symbols

α	heat transfer coefficient [W/(m^2 K)]
ρ	density [kg/m^3]
δ	frost thickness [m]
ε	porosity [−]
φ	relative humidity
γ	thermal conductivity ratio
η	fin efficiency
λ	mean free path of gas molecules [m]
τ	tortuosity [−]

Subscripts

a	ambient air
$cond$	conductive
cro	cross section
dif	diffusive
eff	effective
fin	fin
fr	frost
fs	frost surface
i	ice
lat	latent heat
sen	sensible heat
v	water vapor

experimental temperature range, and humidity ratio.

In the studies that use either a flat or vertical plate (No. 1–6), frost formation experiments are conducted carefully and frost properties are measured. Subsequently, empirical correlations are presented by researchers on the basis of various frosting parameters. For example, Hayashi et al. (1977) experimentally investigated the frost properties and suggested that the frost density is related to the surface temperature of frost. Hermes et al. (2009) compared the experimental data with previous correlation about frost density and found that the frost density can be predicted accurately if cold surface temperature was also accounted for in the correlation. Yang and Lee (2004) comprehensively investigated the effects of various environmental parameters on frost formation, including air temperature, air velocity, humidity, and cooling surface temperature. He proposed correlations for frost properties as functions of Reynolds number, Fourier number, humidity, and dimensionless temperature. Based on a simple model consisting of cylindrical frost columns surrounded by moist air, Şahin (2000) found that during the crystal growth period the thermal conductivity of frost layer was related to frost density and vapor diffusion which depended on the plate temperature, air temperature, and air humidity ratio. However, for the growth of frost, it is mainly affected by humidity ratio and cooling surface temperature (Lee and Ro, 2002), whereas air velocity and air temperature do not have appreciable effect on frost thickness (Kandula, 2011). Besides, the experiments conducted under varied humidity conditions revealed that the frost models developed for constant humidity can be applied directly to circumstances of varied humidity as well (Kandula, 2012).

In addition to these, some visualization results have also been obtained. For example, Hayashi et al. (1977) originally classified frost growth into three stages, namely, “crystal growth period”, “frost layer growth period” and “frost layer full growth period”. However, it's also important to notice that all previous experiments were conducted at a limited temperature and humidity range. The temperature of the cold wall is generally no less than −35 °C. For the AAVs, the inlet temperature of LNG can be as low as −159 °C, which has a large derivation with the experiments in literature.

The experiments conductors generally present numerical models for frosting in accordance with their experimental data. Le Gall et al. (1997) proposed a one-dimensional transient formulation to predict frost growth and densification. This model was based on water vapor diffusion, and the vapor on the frost surface was supposed to be saturated. However, according to the analysis proposed by Na and Webb (2004a), the saturation model over predicted the mass transfer rate in the frost layer. But the overpredictions can be compensated for by choosing empirical tortuosity factors to yield acceptable predictions. The super-saturation model (Na and Webb, 2004b) was later introduced into frosting models and it was found to be superior to analytical or numerical saturation models. Nevertheless, the model entails the numerical solutions of partial differential equations, which requires a reasonable computational effort (Hermes et al., 2009). On the basis

Table 1
Previous studies on frost formation.

No.	Geometry	Cold wall temperature (°C)	Humidity ratio (kg/kg)/Relative humidity (%)	Air temperature (°C)	Authors [reference]
1	Flat plate	−15	50 ~ 80	25	(Lee et al., 1997)
2	Vertical plate	−20 ~ −10	0.003 ~ 0.0055	5 ~ 20	(Lee and Ro, 2002)
3	Flat plate	−35 ~ −15	0.00322 ~ 0.00847	5 ~ 15	(Yang and Lee, 2004)
4	Flat plate	−30 ~ 0	40 ~ 90	−20 ~ 30	(Hermes et al., 2009)
5, 6	Flat plate	−17.8 ~ −9.5	54 ~ 81	22	(Kandula, 2011; Kandula, 2012)
7	Flat-plate finned tube	−15	70	5	(Yan et al., 2003)
8	Finned-tube heat exchanger	−33 ~ −30	61 ~ 70	8	(Yang et al., 2006)
9	Spirally coiled finned tube	−30 ~ −20	70 ~ 90	3 ~ 15	(Lee et al., 2013)