International Journal of Heat and Mass Transfer 93 (2016) 441–463

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Assessment of existing two phase heat transfer coefficient and critical heat flux correlations for cryogenic flow boiling in pipe quenching experiments

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ARTICLE INFO

Article history:
Received 24 May 2015
Received in revised form 8 September 2015
Accepted 9 September 2015

Keywords:
Liquid hydrogen
Liquid nitrogen
Quenching
Critical heat flux
Nucleate boiling
Film boiling
SINDA/FLUINT

ABSTRACT

To enable efficient design and analysis of cryogenic propellant transfer systems, high accuracy models are required for predicting two phase flow boiling and heat transfer at reduced temperatures. The penalty for poor models translates into higher margin, safety factor, and ultimately cost in design. Recently, there has been a drive towards developing universal correlations to cover a broad range of fluids, tube diameters, and thermodynamic conditions for predicting heat flux and pressure drop. These correlations do not, however, cover cryogenic fluids like liquid hydrogen. Therefore the purpose of this paper is to apply popular two phase heat transfer correlations used in commercial codes against available flow boiling data for cryogenic fluids. Specifically, quenching test data for critical heat flux and two phase heat transfer coefficient are compared against the correlations. Results show that existing correlations over-predict heat transfer by as much as 20,000% and that significant model improvements are warranted.

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1. Introduction

1.1. Role of cryogenic fluids in modern world

Cryogenic fluids, which are substances that exist as liquids at extremely low temperatures, are employed in a wide variety of applications throughout industry. Liquid nitrogen (LN_2) is used to fast freeze food [1], to preserve tissues and blood [2], and to kill unhealthy tissues in cryosurgery [3]. Liquid oxygen (LOX) is used in the medical industry, life support systems, and fuel cells [4]. In the space industry, liquid helium (LHe) is used to chill down Earth-orbiting telescopes and satellites [5,6]. Liquid hydrogen (LH_2) is used to chill down superconducting magnets [7,8] and as rocket fuel to prechill [9] and ignite high performance engines such as the Shuttle [10]. Perhaps the most prolific use of cryogenic fluids is in the proposed fuel depots [11,12]. A depot is defined as an Earth-orbiting propellant storage vessel that will be used to store LOX and LH_2 in Low Earth Orbit (LEO) indefinitely to refuel spacecraft [13]. This technology will enable long duration human and robotic missions beyond LEO because a higher percentage of spacecraft mass can be used for payload or for larger engines, and the vehicle can achieve higher velocities once outside the gravity well of Earth.

Before cryogenic liquid can flow, the transfer line and associated hardware must be chilled down or "quenched" to temperatures below the fluid saturation temperature. The most direct, repeatable, and reliable method to remove heat is to use the cryogen itself to quench the transfer system. Due to the ultra-low normal boiling point of cryogens, phase change, complex flow patterns, two-phase flow boiling, and heat transfer are inevitable during the chilldown process.

1.2. Importance of accurate cryogenic flow boiling predictive tools

Experimental and numerical studies on two-phase flow have been carried out for nearly a century. Hundreds of carefully controlled experiments have been performed, resulting in a large database that covers multiple fluids, flow geometries, heat input, and fluid quality. As a result, numerous empirical correlations have been proposed to model two-phase heat transfer coefficient (HTC), pressure drop, and heat flux.

The complexity of two-phase flow features that occur during childown makes it difficult to provide correlations that are valid

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.09.028
0017-9310/Published by Elsevier Ltd.

Nomenclature

A	area [m^2]
Bo	boiling number
c_P	specific heat [J/kg K]
d	diameter [m]
F	two phase multiplier
F_{ij}	view factor
Fr	Froude number
G	mass flux [kg/m^2 s]
g	gravity [m/s^2]
h	heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat [J/kg]
h_i	enthalpy [J/kg]
I	current [A]
k	thermal conductivity [W/m K]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
MAE	mean absolute error
MW	molecular weight
N	number of data points
P	pressure
P_F	wetted perimeter [m]
P_H	heated perimeter [m]
Pr	Prandtl number
Q	heat [W]
q''	heat flux [W/m^2]
r	radius [m]
Re	Reynolds number
S_N	nucleate boiling suppression factor
T	temperature [K]
t	time [s]
U	uncertainty
V	voltage [V]
v	velocity [m/s]
We	Weber number
X_{tt}	Martinelli parameter
Y	mass fraction
z	distance along pipe [m]

Greek

α	thermal diffusivity [m^2/s]
γ	surface tension [N/m]
ΔT_e	temperature difference between wall and fluid saturation [K]
ΔP_{sat}	saturation pressure difference based on wall and fluid [Pa]
ε	emissivity
μ	viscosity [kg/m s]
ρ	density [kg/m^3]
σ	Stefan–Boltzmann constant [W/m^2 K^4]
x	quality
x_e	equilibrium quality
ψ	two phase constant

Subscripts

b	boiling
cb	convection boiling
C	critical
CHF	critical heat flux
d	based on diameter
exp	experimental
f	fluid
FB	film boiling
g	gas
gascond	gas conduction
HT	heated tube
i	inner
L	based on length
l, lo	liquid only
lv	liquid/vapor
mic	macro-convective
mic	micro-convective
mix	mixture
NB	nucleate boiling
o	outer
R	reduced
rad	radiation
S	surface
sat	saturated
solidcond	solid conduction
spl	single phase liquid
TB	transition boiling
tp	two phase
v	vapor
w	wall

over a wide range of conditions. Typically, separate heat transfer correlations must be used for modeling different boiling regimes and different flow patterns. For example, the Chen [14] correlation is valid for modeling the nucleate boiling (NB) regime over a wide range of fluids:

$$h_{\rm NB} = h_{mic}S_N + h_{mac}F \tag{1}$$

where h_{mac} is the "macro-convective" HTC and h_{mic} is the "micro-convective" HTC based on bubble nucleation growth rate where S_N is the NB suppression factor that accounts for differences between measured superheat and superheat from surface cavities caused by the presence of the thermal boundary layer, and F is the two-phase multiplier. Both constants are fit to experimental data:

$$S_N = \frac{1}{1 + 0.00000253{\rm Re}_{tp}^{1.17}F^{1.4625}} \tag{2}$$

where the two-phase Re number is defined as:

$${\rm Re}_{tp} = \frac{Gd_i}{\mu_l}(1 - x_e) \tag{3}$$

$$F = \left(\frac{1}{X_{tt}} + 0.213\right)^{0.736} \tag{4}$$

where the Martinelli parameter is used:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \tag{5}$$

The two HTCs are defined as:

$$h_{mic} = 0.00122\frac{k_l^{0.79}c_{p,l}^{0.45}\rho_l^{0.49}\Delta T_e^{0.24}\Delta P_{sat}^{0.75}}{\gamma_{lv}^{0.5}\mu_l^{0.29}h_{fg}^{0.24}\rho_v^{0.24}} \tag{6}$$

$$h_{mac} = 0.023{\rm Re}_{tp}^{0.8}{\rm Pr}_l^{0.4}\left(\frac{k_l}{d_i}\right) \tag{7}$$