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Numerical analysis of the influence of wall vibration on heat transfer with liquid hydrogen boiling flow in a horizontal tube

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ABSTRACT

Tube vibration inevitably occurs on transfer lines of liquid hydrogen (LH2) and affects the heat transfer characteristic of LH2. In this study, a three-dimensional numerical method based on RPI boiling model and vibration model has been built to investigate the influence of tube vibration on boiling flow with LH2. The model has been partly verified by the experimental data from the literature and considered effective for liquid hydrogen boiling flow. The changes in the partition of heat flux were analyzed under certain conditions and the relative heat transfer coefficients under different amplitudes, frequencies and inlet velocities were compared. The numerical results indicate that the vibration can significantly enhance the convective heat flux while weaken the quenching heat flux and the evaporative heat flux. It illustrates that the changes of relative heat transfer coefficients are corresponding to the vibration velocity. In addition, the enhancement of heat transfer is more obvious when the Reynolds number of LH2 is relatively low.

Introduction

Liquid hydrogen (LH2) has been widely used as propellant in the aerospace industry and coolant in the cooling systems of superconductors. In the near future, hydrogen will be produced and transported in large quantities [1,2]. As one type of cryogenic fluids, LH2 owns the characteristics such as low boiling point and small latent heat, in comparison with ambient temperature fluids.

Boiling flow is a common phenomenon in fluid conveying systems and cooling systems. In boiling flow, the operation of pumps and on-off switch of valves will easily result in tube vibration which significantly affects the flow and heat transfer characteristics of LH2. A comprehensive understanding of LH2 boiling flow in a vibrating tube is of great importance to the reliable design and control of LH2 transportation system.

Several researches have been carried out in cryogenic fluid pool boiling and boiling flow with both experiments and

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Nomenclature

A	Amplitude (m)
A_b	Area of influence (m^2)
A_d	Projected area of a typical particle (m^2)
A_i	Interfacial area (m^2)
C_D	Drag force coefficient
C_l	Lift force coefficient
C_p	Specific heat capacity (J/kg K)
C_{TD}	Constant 1
D	Inner diameter of horizontal tube (m)
D_w	Bubble departure diameter (m)
f	Frequency (Hz)
f_d	Frequency of bubble departure (s^{-1})
F_D	Drag force (N)
$\vec{F}_{lift}$	Lift force (N)
$\vec{F}_{td,q}$	Turbulent dispersion force (N)
G	Gravitational acceleration (m/s^2)
h	Heat transfer coefficient (W/m^2 k)
h_0	Heat transfer coefficient without vibration (W/m^2 k)
h_{fv}	Latent heat of evaporation (W/kg)
h_{vib}	Heat transfer coefficient with vibration (W/m^2 k)
Ja_{sub}	Subcooled Jacob number
k	Turbulent kinetic energy (m^2/s^2)
K, C, n	Constant
L	Total length of horizontal tube (m)
Nu	Nusselt number
N_W	Nucleate site density (m^{-2})
Pr	Prandtl number
q	Heat flux (W/m^2)
Q_{pq}	Volumetric rate of energy transfer between phases (W)
Re	Reynolds number
t	Flow time (s)
T	Temperature (K)
t_d	Periodic time (s)
u	Velocity (m/s)
u_R	Relative velocity of primary and secondary phase(m/s)
x	Mass fraction of vapor phase
ΔT_{sub}	Subcooled temperature (K)

Subscripts

b	Bubble
C	Convective
E	Evaporative
f	Fluid
in	Inlet
l	Liquid
p	p^{th}phase
q	q^{th} phase
Q	Quenching
r	Relative
sub	Subcooling
sat	Saturation
v	Vapor
vib	Vibration
W	Wall

Greek symbols

α	Volume fraction
κ	Conductivity (W/m k)
λ	Diffusivity (m^2/s)
μ	Dynamic viscosity (N s/m^2)
ρ	Density (kg/m^3)

numerical simulations. Zhang et al. [3] performed the visualization experiments for LN2 nucleate pool boiling and evaluated the existing semi-empirical correlations for detachment frequency, bubble diameter and density of active sites. Wang et al. [4] analyzed the available hydrogen pool boiling experimental data and proposed several improved correlations for nucleate boiling, critical heat flux and minimum heat flux. Tatsumoto and Shirai et al. [5–7] conducted a series of experiments on liquid hydrogen boiling flow in a heated tube and concluded that the heat fluxes at the onset of nucleate boiling and the departure from nucleate boiling (DNB) were higher with higher flow velocity and greater subcooling in both horizontal and vertical tubes. Lee et al. [8] investigated local flow parameters including local void fraction and velocities under various conditions of mass flux, heat flux, and inlet subcooling in a vertical concentric annulus with a heated inner tube. The results showed that as the inlet subcooling or mass flux increased, the peak void fraction near the heated surface increased. In addition, the vapor velocity at lower inlet subcooling was larger than that at higher inlet subcooling. In respect of numerical researches, Li et al. [9] modified the two-fluid model by incorporating new closure correlations for boiling flow of liquid nitrogen and the results indicated that the lift force, the bubble diameter distribution and the active site density are important for accurate prediction. Jouhara et al. [10] used the volume of fluid (VOF) method and user defined functions (UDFs) in FLUENT to predict a boiling regime and two phase flow patterns with water and R134a in pool boiling. Kunkelmann [11] employed the VOF method of the OpenFOAM computational fluid dynamics (CFD) package to simulate boiling of HFE-7100 and the simulation results give a better understanding of transient heat transfer between the solid wall, the superheated liquid layer and the growing vapor bubble. Ho et al. [12] studied heat transfer characteristics of liquid hydrogen in a cryogenic storage tank with a heat pipe and an array of pump-nozzle units using the finite element method. The results indicated that the thermal performance of the system could be significantly improved by reducing the gap between the nozzle and the heat pipe. Ma et al. [13] numerically investigated the no-vent filling performance of liquid hydrogen tank under microgravity condition by embedding a pair of mass and heat transfer models into Fluent software. They suggested that sufficient precooling and reasonable inlet liquid subcooled degree are needed in order to guarantee the reliability and efficiency of the no-vent fill under microgravity.

To investigate vibration influence on the heat transfer characteristics, Kim et al. [14] studied the heat transfer enhancement induced by ultrasonic vibration in natural convection and pool boiling regimes. They discovered that the

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