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Experimental investigation of void fraction variation in subcooled boiling flow under horizontal forced vibrations

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ABSTRACT

An experimental investigation of horizontal forced vibration effect on void fraction variation of subcooled boiling flow was carried out in this study. In order to simulate the fuel assembly subchannel of a boiling water reactor (BWR), an annular test section with inner and our diameters of 19.1 and 38.1 mm was utilized for subcooled boiling tests under atmospheric pressure. The annular test section was attached to an eccentric-cam vibrator, which was driven by a low-speed motor and can produce horizontal forced vibrations with frequency up to 20 Hz and maximum displacement of 22.2 mm. The inlet liquid velocity and subcooling were set as $v_{f,in} = 0.25–1.00$ m/s and $\Delta T_{Sub} = 5–20$ °C. Different heat fluxes of $q'' = 0.058–0.193$ MW/m^2 were loaded through the center heater rod, and the void fraction and fluid temperature were measured during the tests under stationary (no vibration) and vibration conditions. Test results show that in the subcooled boiling region, the void fraction and fluid temperature can vary under horizontal forced vibrations, and the variation trends were presented in N_{Zu}-N_{Sub} and $v_{f,in}$-$\langle\alpha\rangle$ plots. These variations can be explained by the potential changes of thermal boundary layers (TBL) and the heat transfer enhancement under vibrations. In addition, no significant change of void fraction and fluid temperature was found in or near the saturated boiling conditions under vibrations.

1. Introduction

Forced vibrations may cause certain effects on boiling and two-phase heat transfer systems, such as heat exchangers, boilers and nuclear reactors, etc. Some of them may affect the system performance/efficiency, whereas the others may be related to safety issues. For example in a boiling water reactor (BWR), if the void fraction is varied, the thermal neutron population and reactor power may be changed as well, which may result in scram events. In the past decades, several earthquakes have caused some unusual events for reactors, such as those in the BWR of Onagawa power plant in Tohoku, Japan, in 1993 [1,2] and the pressurized water reactors (PWR) of North Anna power station in Virginia, USA in 2011 [3] and so on, which were excited by the seismic forced vibrations of the M4.0 and M5.8 earthquakes, respectively. Besides, the M9.0 strong earthquake attacked the Fukushima Daiichi power plant (BWR) has attracted the people's attention to the potential effects of earthquake vibrations on reactor integrity, safety and fluid/flow phenomena. According to the official investigation reports, the forced vibrations by earthquakes may cause the changes of water space between fuel structures, oscillations of reactor core power and also the scram events. However, from the aspects of fluid flow and void-reactivity feedback in a nuclear reactor, if the void fraction distribution or the thermal boundary layer (TBL) in the cores were changed/affected due to forced vibrations, the moderator density and thermal neutron populations [4] may change and the core power may vary as well, and as a result the reactor core may scram. Hence, the potential effects of forced vibrations on a boiling and heat transfer system should be further investigated. In general, the earthquakes may cause forced vibrations with lower frequency (usually $f \leq 20$ Hz), and hence the low frequency forced vibrations are worthy to be examined.

Several researchers have carried out experimental investigations of vibration effects on boiling, two-phase flows and void fraction variations, and important literatures about low frequency vibrations have been briefly summarized in Table 1. Nangia and Chon [5] performed a pool boiling experiment with a vibration frequency of 20–115 Hz. They found that the heat transfer coefficient

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Nomenclature

a	acceleration [m/s^2]
A	area [m^2]
C_0	distribution parameter [–]
C_p	specific heat [kJ/kg]
D	diameter [m]
D_b	bubble diameter [m]
D_H	hydraulic diameter [m]
d	vibration displacement [mm]
f	frequency [Hz]
G^*	non-dimensional voltage [–]
g	gravitational acceleration [m/s^2], 1g = 9.8 m/s^2
h_{fg}	latent heat of vaporization [kJ/kg]
Δh_{sub}	subcooling enthalpy [kJ/kg]
$\langle j \rangle$	area-averaged superficial velocity or mixture volumetric flux [m/s]
$\langle j_f \rangle$	area-averaged superficial liquid velocity [m/s]
$\langle j_g \rangle$	area-averaged superficial gas velocity [m/s]
L_h	heated length [m]
m	mass flow rate [kg/s]
N_{Sub}	subcooling number [–]
N_{Zu}	Zuber number [–]
q''	heat flux [W/m^2]
S	slip ratio [–]
T	temperature [°C]
ΔT	temperature difference [°C]
v_f	area-averaged liquid velocity [m/s]
$v_{f,in}$	inlet liquid velocity [m/s]
v_g	area-averaged gas velocity [m/s]
$\langle\langle V_{gj} \rangle\rangle$	drift velocity [m/s]
x	quality [–]
z	axial length [m]

Greek symbols

$\langle \alpha \rangle$	area-averaged void fraction [–]
β	density ratio [–]
$\langle \alpha^* \rangle$	non-dimensional void variation [–]
ρ	density [kg/m^3]
σ	surface tension [N/m]
ω	motor rotation speed [RPM]

Subscripts

2ϕ	two-phase
c	channel
f	liquid phase
fg	vaporization term
g	gas phase
gj	drift velocity term
H	hydraulic diameter term
in	input or inlet
m	measurement value
max	maximum value
NV	stationary (no vibration) condition
r	rod
Sub	subcooled property
V	vibration condition
wf	wall and fluid
z	z-location

Abbreviations

CHF	critical heat flux
(De.)	decrease of properties
DP	differential pressure
HV	horizontal vibration
NV	no vibration (stationary)
(In.)	increase of properties
ONB	onset of nucleate boiling
RMS	root mean square
TBL	thermal boundary layer
V	vibration
VV	vertical vibration
⟨ ⟩	area-averaged properties
⟨⟨ ⟩⟩	void-weighted area-averaged properties

Table 1
Existing experimental tests for vibration effects on boiling and two-phase flow [17–19,33].

Year	Researchers	Vib. f (Hz)	Fluids	Test condition[a]	Observations[b]
1967	Nangia and Chon	20–115	Water	Pool boiling, VV	h (In.) 200%, D_b (De.), bubble frequency (In.)
1990	Shioyama and Ohtomi	5–50	Freon-113	Flow boiling, VV	P and D_b fluctuations
1992	Skoczylas and Ubranski	0–12	Water	Thin-film boiling, VV	h (In.) 23.7–104.8%
1994	Nariai et al.	0–12.5	Water	Flow boiling, HV	α (De.) when f > 10 Hz
1996	Kawamura et al.	n/a	Water	Flow boiling, HV	D_b fluctuations
1998	Hibiki and Ishii	n/a	Air/water	Adiabatic flow	D_b, α, a_i variations
1999	Umekawa et al.	0.5–0.167	Water	Flow boiling	CHF (De.) 10–100%
2000	Osakabe et al.	∼10	Water	Enclosed boiling	Q (In.) 10.7%
2001	Abou-Ziyan et al.	0–4.33	Water, R134a	Enclosed boiling limit, VV	Boiling Q (In.): Water:5–20%, R134a: 250%
2002	Chou et al.	50	Water	Boiling, VV	Vapor (In.) 20–65%
2003	Chou et al.	10–60	Water	Boiling, VV	Vapor (In.) 15%
2004	Lee et al.	0–70		Flow boiling, HV	CHF (In.) 12.6%
2010	Chen et al.	0.5–4.5	Water	Flow boiling, HV	α (De.) at 4.5 Hz
2014	Chen et al.	0.75–6.5	Air/water	Adiabatic flow, HV	Flow regime change
2017	Chen et al.	0.75–20	Air/water	Adiabatic flow, HV	α changes in bubbly flow
2017	Present study	0.75–20	Water	Subcooled boiling, HV	α changes in subcooled region

[a] VV and HV represent vertical and horizontal vibrations, respectively.
[b] (In.) and (De.) represent increase and decrease of properties, respectively.

can be enhanced up to 200%, and bubble diameter and bubble emission rate can be affected. Shioyama and Ohtomi [6] carried out an subcooled flow boiling experiment with Freon-113 in a vertical heating tube with longitudinal vibrations at frequency of 5–50 Hz to measure pressure fluctuations and bubble sizes. Thermal boundary layer, bubble diameter and void fraction were found