Cryogenics 84 (2017) 69–75

Contents lists available at ScienceDirect

Cryogenics

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

Research paper

Capacitance-based liquid holdup measurement of cryogenic two-phase flow in a nearly-horizontal tube

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ARTICLE INFO

Article history:
Received 17 November 2016
Received in revised form 20 April 2017
Accepted 21 April 2017
Available online 22 April 2017

Keywords:
Cryogenic
Two-phase flow
Liquid holdup
Capacitance measurement
Sensor

ABSTRACT

Liquid holdup measurement of cryogenic fluids is an area of considerable significance because of its inevitable occurrence in LNG transportation, rocket propellant delivery and superconducting equipment cooling, etc. To measure the liquid holdup of cryogenic two-phase flow, a capacitance sensor was carefully designed, which consists of a pair of optimized concave-electrode form with the electric circuit for the small capacitance detection. Four flow patterns were realized to evaluate the performance of the sensor in visualization experiments with liquid nitrogen and vaporous nitrogen. An image method was employed to calibrate the capacitance sensor, which led to a mathematical relationship between the capacitance and the liquid holdup. The results indicated that the obtained correlation between liquid holdup and capacitance satisfactorily coincided with the measured data.

1. Introduction

In gas-liquid flow, liquid holdup (h^*) is defined as $h^* = A_L/A$, where A is the cross-sectional area of the tube, and A_L is the area occupied by liquid. As one of the most important parameters related with pressure drop and flux measurement, determination of h^* is essential for classifying flow pattern and calculating mass transfer [1]. Cryogenic two-phase flow inevitably occurs in cryogenic heat exchangers, liquid natural gas (LNG) transfer lines and superconducting cooling facilities, etc. Nevertheless, it is still a big challenge to measure h^* of cryogenic fluids due to either the rigorous working conditions or the unfavorable physical properties compared to the conventional fluid pairs, such as water and air.

A number of holdup measurement techniques for ambient two-phase flow have been reported [2–4], including the quick-closing valve method [5], the electric impedance method [6,7], the capacitance method [8–10], the constant electric current method [11] and the nuclear magnetic resonance method [12]. Nevertheless, few publications reported about the above technologies applied to cryogenic conditions. One of the difficulties primarily comes from the easily evaporation of cryogenic fluids. Vacuum insulation is accordingly necessary to effectively decrease the heat leakage. Consequently, only Gamma-ray attenuation method [13], microwave method [14], radio frequency (RF) technique [15–17] and capacitance method [18] are reportedly feasible in a cryogenic environment. Among these methods, capacitive void fraction measurements are known as non-intrusion, quick response, low cost and simple form construction [19] for the liquid holdup measurement of refrigerants.

Capacitance-type sensors measure the liquid holdup based on different dielectric constants of the gas phase and liquid phase. The change of measured total capacitance reflects the volume fraction variation of the ratio of liquid to gas. Das and Pattanayak [20] developed a capacitor to identify flow regimes in cryogenic flows. The capacitor is connected to a multi-vibrator whose pulse width is modulated in response to the varied liquid holdup to detect the small capacitance changes. Unfortunately, they did not propose a correlation of capacitance-liquid holdup.

This work is devoted to measure the liquid holdup of cryogenic two-phase flow based on a developed capacitance sensor. Four typical flow patterns were realized in a nearly-horizontal tube to evaluate the performance of the sensor. The image method is employed to calibrate the sensor, and a calibration correlation is finally obtained with satisfactory accuracy.

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http://dx.doi.org/10.1016/j.cryogenics.2017.04.006

Nomenclature

A	cross-sectional area of inner tube (m^2)
A_L	area occupied by liquid (m^2)
B	Bond number
b	modified Bond number
C	capacitance (fF)
C_G	capacitance when filled with gas (fF)
C_L	capacitance when filled with liquid (fF)
C^*	normalized capacitance
D	inner diameter of inner tube (mm)
E	elliptic integral of the second kind
F	elliptic integral of the first kind
h	liquid film thickness (mm)
h^*	liquid holdup
L	length of electrode (mm)
P	pressure (Pa)
R	curvature radius (m^{-1})
t	thickness of the inner tubes (mm)
U	electric voltage (V)

Greek symbols

α	tube inclination (°)
β	electrode angle (°)
ε_0	absolute dielectric constant (F/m)
ε_r	relative dielectric constant
θ	contact angle (°)
κ_0	reference curvature at the center of the interface
ρ	density (kg/m^3)
σ	surface tension (N/m)

Abbreviations

LN_2	saturated liquid nitrogen
VN_2	saturated vaporous nitrogen
i	phase

2. Capacitance sensor design

It is reported that the concave electrode configuration has higher sensitivity when compared with the plank form and double-helix form [21]. Therefore, a pair of concave electrodes, made of copper, is chosen and placed on the outer wall, as shown in Fig. 1. Electrode angle (β) and electrode length (L) in the longitudinal direction, which have great effects on the sensitivity, should be optimized. Finite element simulations with the commercial code, COMSOL, are carried out to optimize the L and β values. The electrical potential, field distribution and capacitance between the electrodes are calculated based on Eqs. (13).

$$\nabla \cdot [\varepsilon_0 \varepsilon_r(x,y,z)\vec{E}(x,y,z)] = 0 \quad (1)$$

$$\vec{E}(x,y,z) = -\nabla[\varphi(x,y,z)] \quad (2)$$

$$C = \frac{1}{U}\oiint_S \varepsilon_0 \varepsilon_r(x,y,z)\vec{E}(x,y,z) \cdot d\vec{A} \quad (3)$$

where U is the electric voltage between the electrodes, and $\varphi(x,y,z)$ is the electric potential with the boundary condition of U. ε_0 is the absolute dielectric constant in vacuum, which equals to 8.8542×10^{-12} F/m. The dielectric constants used in the simulations were $\varepsilon_r = 1.44$ for the liquid nitrogen (LN_2) [22], $\varepsilon_r = 1$ for the gas and $\varepsilon_r = 2$ for the tube. The tube diameter and thickness are set as 34 mm and 1.5 mm, respectively. The electrode angle and the electrode length are adjusted to investigate their effects on electrical field distribution and resulting capacitance values.

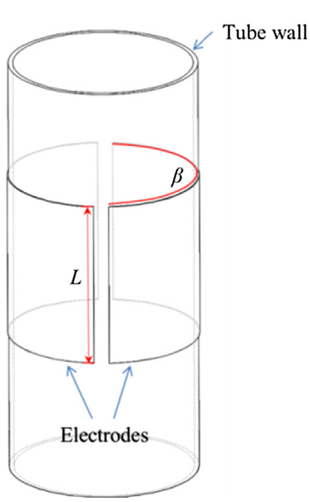

Fig. 1. Configuration of capacitance sensor with external concave electrodes.

Fig. 2(a) illustrates that the sensitivity of the capacitance sensor increases as L increases, especially when h^* is in the range of 0–0.1 and 0.9–1. C_G is the capacitance when the tube is completely filled with gas. Nevertheless, a large L value inevitably leads to the severe spatial filtering effect, and then possibly induces the failure of tracking local flow characteristics. Canière [9] concluded that L equal to D has a negligible effect on the wave frequency response under different flow patterns. As a compromise, the L value of 20 mm is finally chosen in our studies. Fig. 2(b) indicates that the large value of β can also improve the sensitivity of the capacitance sensor. Canière et al. [23] came to a similar conclusion through finite element analysis that β should be as high as constructively possible, and they set the value of β as 160°. Finally, the electrode angle is designed as 170° in consideration of the installation errors. To limit the influence of stray capacitances, an active shielded electrode made of aluminum was used to closely surround the two sensor electrodes.

The dielectric constants of all gases are approximately equal to 1. In contrast, unlike water having a dielectric constant one order of magnitude greater than a gas, the dielectric constants of cryogenic liquids are often just slightly larger than its vapor value, as shown in Table 1. Consequently, the change of measured capacitance caused by the volume fraction variance of cryogenic liquids is very small, which is in the order of fF. A high-precision circuit for the capacitance sensor is necessarily in need. In this work, a 24-bit sigma-delta capacitance-to-digital converter (AD7745 by ADI Corp.) was adopted to digitize the measured capacitance. The converter features inherent high resolution (24-bit no missing codes, up to 21-bit effective resolution), high linearity (±0.01%), and high resolution (4 aF). The excitation frequency is 32 kHz and the update rate is adjustable from 10 Hz to 90 Hz. The signal to noise ratio is about 46 dB at the update of 50 Hz. The configuration and the circuit of the capacitance sensor are illustrated in Fig. 3.