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Measurement of boiling liquid levels by decomposition of sound waves in a waveguide

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ABSTRACT

Many industrial processes require knowledge of the level of hot bubbling liquid in a closed vessel. However, usually conventional instrumentation is unsuitable because of extremely high temperatures, and hot poisonous gases generated by the thermo-chemical processes of the boiling liquid. This paper proposes a novel method to detect such boiling liquid levels by monitoring the boiling/bubbling noise in the vessel using a waveguide. The principle of this method is that the axial modes of the air column and the liquid column in the closed vessel would change with change in liquid height. The sound pressure waves produced in the vessel due to bubbling and propagating along the vessel's axial direction can be captured by decomposition using two microphones in a waveguide co-axially attached to the vessel. These decomposed waves would show peaks at resonance frequencies corresponding to the vessel's axial modes, which would be used to calculate the liquid height. The proposed method was verified through extensive finite element simulations and experiments of boiling water over a wide range of conditions. The boiling water levels were correctly measured in each condition with an average accuracy of 98.8%. Thus, this waveguide system can continuously monitor boiling liquid levels based on the incident wave frequency and amplitude. Such a system has wide industrial applications, particularly in steel plants, where knowing the amount of molten steel during oxygen lancing faces many challenges.

1. Introduction

The phenomenon of nucleate pool boiling has numerous applications such as in power electronic and microelectronic cooling systems [1,2], in industrial boilers for power generation [3], chemical processing [4], steel making [5,6], research nuclear reactors [7–9]. Further, this phenomenon is extensively studied in nucleate pool boiling experiments to understand how bubbling phenomenon is affected by different parameters such as the liquid volume, the liquid microstructure, and type of heating surface [10,11]. In all these applications, the level or volume of the liquid is an important parameter that needs to be monitored continuously throughout the process. However, due to the hazardous conditions in and around vigorously boiling and bubbling liquids [6,9], currently there is no sensor that can monitor the boiling and bubbling liquid levels continuously throughout the boiling process.

For example, in steel plants, the process of basic oxygen steelmaking requires the knowledge of the accurate molten steel volume throughout the process [6,12,13]. However, continuous monitoring of the molten steel is difficult as oxygen lancing generates extremely high temperatures and poisonous gases in the vessel that render the conventional instrumentation unsuitable to measure the steel volume [6,12,13]. Similarly, in boiling water nuclear reactors, it is challenging to continuously monitor and detect the volumes of boiling water, and mass of steam produced. This is primarily because of the thermohydraulic and neutronic instabilities and large modal oscillations during the boiling stage [9]. Moreover, heavy mass flow of steam would damage any instrumentation placed near or attached to the reactor. In such systems, liquid volume is usually measured before starting the boiling process or, much later after the process has ended and the liquid has cooled down and the end product is already produced. However, the liquid volume changes throughout the process due to phase change during boiling, and/or due to reactions that produce liquid products in process plants. A measurement technique that can monitor the changing liquid levels throughout the boiling process without any sensor being attached to or near the boiling vessel would be very useful for such industrial and research applications.

Current techniques for measuring liquid levels are optical-fiber sensors [14,15], ultrasonic transducers [16], and capacitative sensors or electrodes [17,18], but these are not applicable to vigorous boiling liquids. Capacitive sensor-based methods require the sensor to be in contact with the liquid, and optical fiber-based

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methods require fiber tip to be in close proximity to the liquid. Thus, they are unsuitable in hazardous boiling conditions such as in process plants, nuclear reactors and steel making industry. Moreover, optical fiber tip placed closed to the liquid interface would be inaccurate in boiling conditions that lead to hot poisonous gases and fumes. Ultrasonic transducers use acoustic signal time of flight method [16], and sometimes the transmitter is mounted on long waveguides. This method can be more suitable in boiling liquid conditions. However, it needs an external driver and the measurement sensitivity in limited by the driver frequency.

This paper introduces a novel technique to detect boiling liquid levels continuously that does not require any sensor or transmitter to be placed near the vessel and does not require any external driver. The proposed technique measures the boiling liquid level by monitoring the bubbling noise through a waveguide connected to the vessel. The principle of this technique is that a change in the boiling liquid height in a closed vessel will change the length of the air column and the liquid column in the closed vessel, which in turn will change their axial normal modes. When the liquid is undergoing nucleate boiling the rigorous bubbling phenomenon will excite the liquid and air columns. The acoustic waves thus produced will show sharp resonance peaks at the axial modal frequencies of the vessel, which will be a function of the liquid level. These waves can be measured by wave decomposition using a waveguide attached coaxially to the vessel through an acoustically transparent film. Since, waveguides by construction have less sound attenuation and very low heat conduction per unit length, the sensors mounted at its other end would be protected from high temperature and fumes of boiling liquids. The resonance frequency of the decomposed incident wave spectra measured on the waveguide would be an indicator of the liquid height. To the best of our knowledge, this paper is the first ever application of wave decomposition theory into liquid level measurement. Other novelty of this paper is the use of nucleate bubbling as the source of acoustic excitation for resonance-based measurement. The following sections discuss the theory of this method and test it through finite element simulations and experiments.

2. Theory

The present model for boiling liquid height detection is based on the prerequisite that at the time of measurement the liquid is at the stage of nucleate boiling and there is significant bubbling within the liquid. This bubbling or boiling is equivalent to a random noise that excites the liquid and gas columns within the vessel over a wide range of frequencies that at least cover the first acoustic axial mode of the vessel. The theoretical development of this method is discussed in details below:

2.1. Resonance frequencies of a vessel containing hot bubbling liquid

Although the proposed method is applicable to any vessel shape, for sake of demonstration a cylindrical vessel is chosen. A cylindrical closed vessel of length 'L' and radius 'a' is a right cylindrical rigid walled duct. The pressure P in a right cylindrical duct can be represented as a superposition of three standing waves Z, R and Θ in the axial direction (z), radial direction (r), and circumferential direction (θ) respectively, and is given by the following set of equations [19]:

$$P(r,\theta,z) = R\Theta Z;\ Z = \cos k_{zl}z;\ \Theta = \cos(m\theta + \gamma_{lmn});$$
$$R = J_m(k_{mn}r);\ l,m,n = 0,1,2,\ldots \quad (1)$$

where, J and γ are Bessel functions of the first and second kind respectively. A cylindrical duct has (l,m,n) resonant modes corresponding to the axial, radial, and circumferential directions. For the cylindrical duct with both ends closed, the boundary conditions are velocity nodes or pressure antinodes at the rigid ends of the cylinder. This gives the following set of equations for normal axial modes of the cylinder and the corresponding natural axial modal frequencies, f_{zl}.

$$\sin k_{zl}z = 0;\ \text{at } z = 0, L \ \Rightarrow\ f_{zl} = \frac{c}{2L} \times l \quad (2)$$

Similarly, functions R and Θ have pressure antinodes at walls of the cylinder (at r = a), which gives the following set of equations for the natural frequencies of the cross-sectional modes, f_{mn}:

$$k_{mn}a = j'_{mn} \ \Rightarrow\ f_{mn} = j'_{mn} \times \frac{c}{2\pi a};\ j'_{mn} = 0, 1.84, 3.05, 3.83, \ldots \quad (3)$$

Here, j'_{mn} is the nth extremum of the mth Bessel function of the first kind.

For a cylindrical duct with top end open and bottom end closed, the cross-sectional modes remain the same as given in Eq. (3). However, for axial modes the boundary conditions are pressure antinode (velocity node) at bottom end and pressure node (velocity antinode) at top end of the cylinder. Thus, the natural axial modal frequencies, f_{zl} are given by the following equation:

$$\cos k_{zl}L = 0;\ \Rightarrow\ f_{zl} = \frac{c}{4L} \times (2l + 1) \quad (4)$$

Fig. 1 shows a cylindrical vessel containing boiling liquid. Let c_L and c_G be the speed of sound in the liquid and the gas media of the vessel respectively, and ρ_L and ρ_G be their specific densities. At the stage of nucleate boiling, the hot boiling liquid and the vapors above the liquid in a rigid closed vessel after attaining thermal equilibrium will be at the liquid's saturation temperature. Therefore, for the presented problem, c_G and c_L are the speed of sound for the gas and liquid column at the liquid's saturation temperature.

A closed cylindrical vessel when empty or completely filled with hot liquid is acoustically equivalent to a rigid-walled both end closed right cylindrical duct with speed of sound as c_G and c_L respectively. When the vessel is partially filled, the vessel's liquid column is acoustically equivalent to a rigid-walled one end open and one end closed cylindrical duct with speed of sound as c_L. Now, considering that $\rho_L >> \rho_G$, the vessel's gas column (above the liquid) is acoustically equivalent to a rigid-walled both end closed cylindrical duct with speed of sound as c_G. From Fig. 1 and Eq. (2), when the vessel is empty then the first axial modal frequency is $c_G/(2\,L)$, and when the vessel is completely filled with the liquid then the first axial modal frequency is $c_L/(2\,L)$. However, when the vessel is partially filled with the liquid to a height h, then referring to Fig. 1 the first axial modal frequency of the gas column is $c_G/(2(L-h))$ (from Eq. (2)), and of the liquid column is $c_L/(4\,h)$ (from Eq. (4)). In this case, since $c_G < c_L$, the vessel's first axial mode is due to the gas column until the liquid length increases to a value given by Eq. (5).

$$\frac{c_L}{4h} \leqslant \frac{c_G}{2(L-h)} \ \Rightarrow\ h \geqslant \frac{c_L}{2c_G + c_L}L \quad (5)$$

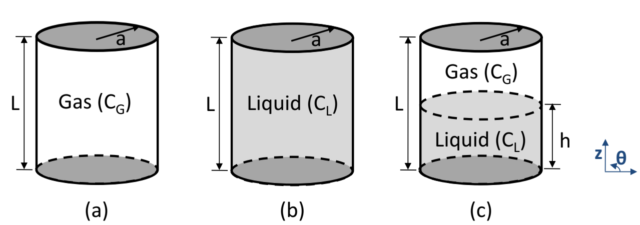

Fig. 1. Analogy of a closed cylindrical vessel as a duct.