International Journal of Multiphase Flow 89 (2017) 150–162

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Updated results on hydrodynamic mass and damping estimations in tube bundles under two-phase crossflow

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ARTICLE INFO

Article history:
Received 26 January 2016
Revised 28 August 2016
Accepted 17 September 2016
Available online 11 November 2016

Keywords:
Cantilever-beam
Flow-induced vibration
Multiphase flow
Void fraction
Dynamic parameter

ABSTRACT

Flow-Induced Vibration (FIV) is the most critical dynamic issue in the design of shell-and-tube heat exchangers. This fluid-structure phenomenon may generate high amplitude vibration of tubes or structural parts, which leads to fretting wear between the tubes and supports, noise or even fatigue failure of internal components. The study of this phenomenon is more challenging if considered that two-phase crossflow exists in many shell-and-tube heat exchangers. In this framework, the analysis of the influence of void fraction and flow patterns on FIV is of particular interest. In fact, void fraction and flow patterns do affect the dynamic parameters involved in tube vibration and, hence, the current vibration mechanism. However, in spite of the importance of devices subjected to two-phase flow, FIV under these conditions have not been entirely understood. In this paper, the results of an extensive experimental campaign, aiming at validating the flow pattern maps found in open literature, are presented. For this purpose, a normal triangular (transversal pitch per diameter ratio of 1.26) tube bundle subjected to two-phase air - water vertical upward crossflow is used. Structural sensors are used to measure the tube dynamic responses and estimate parameters such as hydrodynamic mass and damping ratios, which are strongly dependent on flow conditions. Theoretical models and data previously published are compared with the present experimental results, showing good agreement.

1. Introduction

Shell-and-tube heat exchangers are one of the most commonly used heat exchanger type in industrial processes (Kanizawa and Ribatski, 2016a). These devices are also used as steam generators in pressurized water reactor nuclear power plants, which correspond to a critical operational condition since a mechanical failure implies in significant economical losses, unexpected shut downs, as well as critical radioactive accidents. According to Weaver et al. (2000), traditionally, the shell-and-tube heat exchangers presented thick tubes and supports walls, and the flow velocity was kept low. Thus, problems related to flow-induced vibration (FIV) were not of great concern, neither for the academy nor the industry. However, with the advent of more resistant materials and with more precise methods for the evaluation of the thermo-hydraulic parameters, the tubes and supports wall thickness have reduced, as well as flow velocity have increased to improve the heat transfer performance. In that way, problems related to FIV became more relevant, which is reflected in the recurrent report of heat exchanger failures related to this phenomenon and several publications available since the 70s. Nowadays, FIV is the most important dynamic issue at the design stage of a heat exchanger.

Pettigrew and Taylor (2003) indicated that for such heat exchangers, the forces generated by the axial component of the flow velocity are negligible, while the transversal component is critical for FIV. Based on the review presented by Taylor and Pettigrew (2001), as well as in the literature in general, it is accepted that the most important FIV mechanisms during single-phase flow are: (i) fluidelastic instability, (ii) vortex shedding, (iii) random excitation and (iv) acoustic resonance. According to Noghrehkar et al. (1999) and Green and Hetsroni (1995), almost half of shell-and-tube heat exchangers in the industry operate under two-phase flow condition in the shell side, which correspond

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.09.022
0301-9322/

to a more critical condition for FIV. Moreover, as suggested in literature (Pettigrew and Taylor, 2004), one should consider that non-continuous flow patterns, as intermittent and churn, should be avoided since these flow patterns are critical for FIV.

Due to the preponderance of components subjected to two-phase flows, the database of experimental studies on FIV is constantly updated with new-findings and improved design criteria for heat exchangers (Mitra et al., 2009). Nonetheless, the number of research and publication about FIV under two-phase flows is reduced (Pettigrew et al., 2001), which is not surprising, since not even single-phase FIV, a simpler topic, is not yet fully understood.

Vibration during two-phase flow depends on flow patterns, i.e., gas and liquid phase distributions, which in turn depend on void fraction and mass flux. In general, the related literature point out that flow pattern is a complex issue to face, since it affects the dynamic parameters of the system, e.g. damping and hydrodynamic mass, the excitation forces, and therefore the tube vibration response. The fact that mechanical behavior can be strongly affected by the flow conditions is also an indication that structural sensing can be used to monitor such conditions. However, accurate models describing the dynamic parameters variations against, e.g., void fraction and flow pattern, are needed in order to allow the proper correlation between flow conditions and structural behavior. In that sense, it is important to notice that, as mentioned in Taylor and Pettigrew (2001), the available thermohydraulic models fail to completely explain the behavior of dynamic parameters, rendering this as a field of interest for new studies and more general models, that could account for the deviations related to flow pattern transitions.

Regarding the vibration mechanisms, Khushnood et al. (2012) pointed out that the same excitation mechanisms of single-phase flow are present during two-phase flow, and that the occurrence of a specific vibration excitation mechanism depends on the operational conditions. According to Pettigrew et al. (1991), fluideslastic instability and turbulence excitation are the most important mechanisms in tube bundles during two-phase crossflow, while periodic shedding and acoustic resonance are unlikely to occur, nonetheless, Feenstra et al. (2000) reported the occurrence of FIV excited by periodic shedding for very low void fraction values. Fluidelastic instability (FEI) have been extensively studied since it is the most dangerous excitation mechanism, it may lead to a tube bundle collapse within reduced working hours. Nowadays, engineers have several design guidelines to avoid this phenomenon, among others, the Connors' - Blevins instability model is widely used. This model allows the estimation of the threshold of instability in terms of flow velocity and the dynamic parameters of the tube. Nonetheless, it is noteworthy that towards the end of the 1970s solid experimental evidence began to be gathered against the Connors' - Blevins semi-analytical model, as it was found that fluidelastic instabilities take place even if the pattern of intercylinder displacements was not the one required by the Connors' theory (Païdoussis, 1983). Despite this aspect, the model is still widely adopted due to the fact that it is easy to implement and also because the model's parameters have been experimentally adjusted to give conservative estimates. It must be pointed out that, despite the available design criteria, the FEI nature has not yet been fully understood, which currently opens room for research in this field (Sawadogo and Mureithi, 2014).

In order to study some of the missing details on FIV characteristics, a test bench has been constructed. The present manuscript presents an experimental study on the FIV by two-phase flow on a flexible tube embedded in a transverse flow tube bundle. The remainder of this document is organized as such: the next sections present a short review of dynamic parameters such as resonance frequency, hydrodynamic mass and damping ratio under two-phase flow. Next, a description of the test bench and flow patterns that can be reproduced with it are presented. Finally, updated experimental results are discussed and compared with the open literature in terms of mass flux, void fraction and flow patterns.

2. Review of dynamic parameters influenced by two-phase flow

The dynamic response of a vibrating tube in a heat exchanger (as well as for any mechanical system) depends on its inertia, stiffness and energy dissipaters (damping), which are referred to as the dynamic parameters. The system's damping and inertia measured during two-phase flow are quite different from that measured in air or water single-phase flows. Furthermore, these parameters are known to depend on fluid properties as well as on the component geometry and adjacent boundaries, whether rigid or elastic (Khushnood et al., 2012). In the subsections below, hydrodynamic mass and damping ratio are defined according to the literature. Also, the mathematical models to estimate these parameters are reviewed.

2.1. Hydrodynamic mass

Hydrodynamic mass (sometimes called as added mass or virtual mass) is defined as the equivalent mass of external fluid vibrating with the structure (Pettigrew and Taylor, 1994), in this case a tube. It increases the apparent inertia of the vibrating body, but the stiffness remains the same, hence modifying the tube's dynamic behavior. Carlucci and Brown (1983) studied hydrodynamic mass of a single cylinder in axial two-phase flow simulated by air-water mixtures. They deduced experimentally the hydrodynamic mass per unit length of the cylinders, m_h, in terms of the resonance frequency of the cylinder in two-phase mixture, f, as follows:

$$m_h = m_t\left[\left(\frac{f_g}{f}\right)^2 - 1\right], \tag{1}$$

where m_t is the mass of the tube alone per unit length and f_g is the resonance frequency of the tube in air. Since m_t and f are constant, one can understand the variation of m_h in terms of the variation of f depending on the flow characteristics.

On the other hand, the hydrodynamic mass of a tube vibrating in a tube bundle can also be predicted by using the theoretical model presented in Rogers et al. (1984) for liquid flow:

$$m_h = \left(\frac{\rho\pi d^2}{4}\right)\left[\frac{(D_e/d)^2+1}{(D_e/d)^2-1}\right], \tag{2}$$

where d is the tube diameter, the term (D_e/d) represents the effect of confinement for a tube inside a triangular tube bundle, which is formulated by:

$$\frac{D_e}{d} = \left(0.96 + 0.5\frac{P}{d}\right)\frac{P}{d}, \tag{3}$$

in which P is the transverse pitch of the tube bundle, and the density, ρ, must be assumed equal to the homogeneous density of the mixture, ρ_H, at superficial void fraction α, also referred as area averaged void fraction, rendering:

$$\rho_H = \rho_l(1-\alpha) + \rho_g\alpha \tag{4}$$

As it can be noticed from Eq. (2), the hydrodynamic mass depends directly on void fraction since the other terms are constant for a given test section. Thus, if m_h is strongly dependent on void fraction, then the hydrodynamic mass might be also affected by flow patterns, which implies that flow patterns must be considered in the analysis of experimental data concerning hydrodynamic mass.

According to the information found in literature, the models proposed by Carlucci and Brown (1983) and Rogers et al. (1984) are