Annals of Nuclear Energy 120 (2018) 630–641

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Effects of low-*Re* pulsatile flow on friction characteristics in bare square array rod bundles

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ARTICLE INFO

Article history:
Received 7 March 2018
Received in revised form 15 June 2018
Accepted 17 June 2018

Keywords:
Pulsatile flow
Rod bundle
Flow resistance
Dimensionless acceleration

ABSTRACT

Interest in unsteady flow in floating systems has increased in recent times. This paper presents the results of the experimental investigation on the resistance characteristics of pulsating flow through square array bare rod bundles with $P/D = 1.326$ and $W/D = 1.268$ conducted in the range of time-averaged Reynold's number $\mathrm{Re}_{ta} = 1\text{–}7 \times 10^3$ and dimensionless acceleration (α) of 0.001–0.013. Pulsatile flow affects the time-averaged friction factor because it changes the velocity field close to the wall. The dimensionless frequency parameter ($\sqrt{\omega'}$) relates the frequency to the viscous effects while the dimensionless acceleration (α) is the product of the velocity amplitude (A_u), diameter (D) of the channel and the frequency (ω) normalized by the mean velocity (U_m). Ratios (C_λ) of the time-averaged friction factor (λ_p) in pulsatile flow to the friction factor (λ_s) in a steady flow and (C_p) of their average pressure drops were used to compare the two flows. C_λ and C_p increase with an increase in A_u, $\sqrt{\omega'}$ and α; but decreases with increase in Re_{ta}. The dynamics of the extra turbulence generated as a result of pulsation was also analyzed in the subchannels.

1. Introduction

Unsteady flow is a common phenomenon in floating reactors and other periodical processes in thermal systems. Such flows can be oscillatory or pulsatile in nature. Pulsatile flow is a time-dependent periodic flow superimposed over a mean steady flow. Low frequency ($f < 1$ Hz) unsteady flow often occur in the reactor core and other thermodynamic devices while under transient conditions (Tan et al., 2013). Pioneering research into pulsatile flow in pipes date back some decades. Some of those earlier researchers were motivated by its application in biological systems (Womersley, 1955). There is a sizeable number of recent experimental and theoretical studies on pulsatile flow in pipes and rectangular channels (Brunone et al., 2000; He and Jackson, 2009; Iguchi et al., 1993; Kurokawa and Morikawa, 1986; Spiga, 1994; Morris and Forster, 2004; Sedat and Costa, 2005; Shemer et al., 1985) to site a few, while a comprehensive list can be found in (Zhuang et al., 2017). A thorough review of the status of theoretical and experimental work in pulsatile flow up to the year 2000 was carried out by (Carpinlioglu and Gundogbu, 2001; Gundogbu and Carpinlioglu, 1999a,b).

Pulsatile flow, like steady flow, may be in the laminar, transitional or turbulent regime. It is laminar when the flow remains undisturbed throughout the flow cycle. The transitional or conditionally turbulent flow is when the transition process is sensitive to the strong acceleration and deceleration while fully turbulent flow is characterized by high-frequency fluctuations throughout the flow cycle. The regime change occurs at a critical Reynolds number. There are also critical values of dimensionless frequency $\sqrt{\omega'}(= R\sqrt{\omega/v})$ at which pulsatile flow nature radically change (Carpinlioglu & Gundogbu, 2001) and are classified accordingly into quasi-steady ($\sqrt{\omega'} < 1.32$), intermediate ($1.32 < \sqrt{\omega'} < 28$) and inertia dominant ($\sqrt{\omega'} > 28$) (Ohmi and Iguchi, 1980a,b). Researchers have proposed correlations for the Critical Reynold's number at which the first turbulence burst is expected in oscillatory flow as a function of $\sqrt{\omega'}$ for channels. There is also a classification in terms of mean velocity amplitude A_u $(= \Delta U_m/U_{m,ta})$, a flow of $0.05 \le A_u \le 2.00$ is considered of low amplitude while $A_u > 2.00$ is of a high amplitude. The shortcoming in using a critical Re_{ta} is that it is affected by both $\sqrt{\omega'}$ and A_u while the later categorization based on them ($\sqrt{\omega'}$ and A_u) also could be inadequate because it does not incorporate information of the shear stress dynamics that occur between the boundary layer and the mean flow that is necessary of the numerical simulation of pulsatile flow.

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https://doi.org/10.1016/j.anucene.2018.06.033
0306-4549/

Nomenclature

General symbols		T	Period (s)
t	Time (s)	U_m	Cross-sectional mean velocity (m/s)
C_λ	Coefficient λ_p/λ_s	ℓ_s'	Stokes-Reynolds number
D_e	Equivalent diameter (m)	A'	Cross-sectional flow area (m^2)
g	Acceleration of gravity (m/s^2)	P'	Wetted perimeter (m)
τ_w	Wall shear stress	A_p	Pressure amplitude
Re_{ta}	Time-averaged Reynolds number	C_p	Coefficient $\overline{\Delta P_p}/\Delta P_s$
λ_p	Time-averaged friction factor in pulsatile flow	*Greek*	*symbols*
λ_s	Friction factor in steady flow	ω	Angular frequency, $(2\pi/T)$
μ	Dynamic viscosity($kg/m.s$)	α	Dimensionless acceleration
$\sqrt{\omega'}$	Dimensionless frequency	ρ	Density
$T*$	Scaled delay time	λ	Friction factor
L	Distance between two pressure taps (m)	δ	Stoke's layer thickness
Q	Volumetric flow rate (m^3/h)	σ	Uncertainty
D	Diameter (m)		
P/D	Pitch/Diameter	*Subs*	
$\overline{\Delta P}$	Pressure difference (Pa)	ta	Time-averaged
A_u	Amplitude ($\Delta U_m/U_{m,ta}$)	in	Instantaneous
v	Kinetic viscosity (m^2/s)	s	steady
Re	Reynolds number	p	pulsatile
ρ	Density	–	mean

The non-slip condition at the wall necessitates the generation of additional shear stress in the boundary layer that propagates through the flow in response to the periodic mass flow transients in pulsatile flow. The stress response to pulsation in laminar flow attenuates with the Stoke layer thickness $\delta(=\sqrt{2v/\omega})$ base on which the velocity profile in response to pulsation is divided into the attenuating and the fully attenuated parts (Nebauer and Blackburn, 2009). High-frequency pulsation results in thinner Stoke layer thickness and a greater decay of the shear stress such that when $\delta \approx 5$ wall unit, the shear wave is restricted to the viscous sub-layer (He and Jackson, 2009). At a reduced frequency, the shear waves are able to propagate beyond the boundary and interact with the turbulence field of the mean flow. The measure of how far shear waves penetrate into the mean flow is scaled in terms of dimensionless parameters such as the turbulent penetration depth or Stokes-Reynolds number $\ell_s'(=u_\tau\sqrt{2/v\omega})$. The rate of the wave propagation is only a function of the frictional velocity ($\approx 0.8u_\tau$) and the time $T^*(=Tu_\tau/R)$ for the shear wave to travel across the flow is given by the ratio of the radius to the velocity of the wave(He and Jackson, 2009). Based on these parameters, pulsatile flow can also be categorized as intermediate and quasi-steady, however, none of them addresses the influence of the mean velocity amplitude of the fluctuation.

The pressure drop in rod bundle rises an approximately 10% above circular pipes but is independent of the number of rods (Rehme, 1972). The empirical correlation is based on the regime, bundle type and *P/D* ratio (Cheng and Todreas, 1986). Induced fluctuation in steady flow increases the average flow resistance contrary to theoretical understanding (Carpinlioglu and Gundogbu, 2001). Donovan et al. (1994) reported effects of oscillatory amplitude and frequency on fluid resistance for laminar flow in rigid pipes contrary to the analytical results that concluded that oscillations will not affect the average resistance.

Friction factor in rod bundle is an important design criterion. Researchers have often focused on the extra resistance generated by appendages to the bundle (Tamai, et al. 2006), (Wakasugi and Kakehi, 2016) during steady flow. (Zhuang et al. 2017) compared flow resistance in steady and pulsatile flows in mini-channels. They found that the ratio of the Stokes layer thickness to the channel dimensions is a key factor in the extent that pulsation affects the frictional characteristics. The classification of channels into conventional-, mini- and micro-channels is based on dimensions (Kandlikar, 2002). Subchannel friction factor and mixing parameters have also interested researchers because of the development of a subchannel code (Cheng and Todreas, 1986). However, extending the investigation of pulsatile flow to the subchannels of rod bundle is rare. Currently, there are safety concerns with the increasing interest to deploy floating nuclear reactors into ocean conditions making this study rather apt. Therefore, this paper focuses on comparison of steady and pulsatile flow in rod bundles to explore the response of flow to changing pulsatile parameters in terms of the frictional pressure drops and frictional factors.

2. Materials and method

2.1. Flow loop

The schematic diagram of the loop is presented below (Fig. 1). It consists of a vertical test-section, electromagnetic flow meter, centrifugal pump, differential pressure meter and a water tank large enough to keep the loop thermally isolated. Distilled water was circulated as the working fluid because of its purity and absence of air

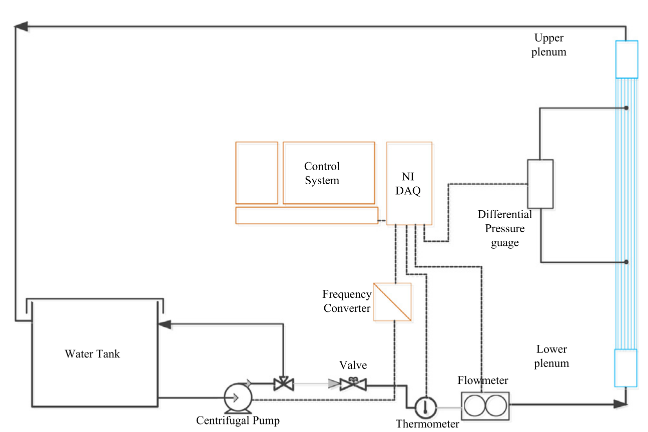

Fig. 1. Schematic diagram of the experimental loop.