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Flow resistance of low-frequency pulsatile turbulent flow in mini-channels

Nailiang Zhuang, Sichao Tan*, Hongsheng Yuan, Bonan Yang

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Heilongjiang 150001, PR China

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ABSTRACT

Plate-type nuclear reactor fuel is currently getting increasing attentions as it features excellent heat transfer ability and compact structure. To gain an insight into the influences of channel size and pulsatile parameters on flow resistance characteristics, steady and pulsatile turbulent experimental investigation were performed. Three channels with varying height were used. The covered ranges of time-averaged *Re* $Re_{ta} = (0.5–2) \times 10^4$, dimensionless frequency sqrtω' = 0.3–3.2, and pulsatile velocity amplitude $Av = 0.04–0.93$. A normalized parameter, friction factor ratio $C = \lambda_{ta}/\lambda_{ta}$, was proposed to denote the effects of flow fluctuation on time-averaged friction factor, where λ_{ta} and λ_{ta} are time-averaged and steady friction factor. The results show that in channel I (40×2 mm^2), the time-averaged friction factor is remarkably larger than the steady values in the ranges of 1.5<sqrtω'<3.2.. The friction factor ratio *C* increases with the increasing sqrtω' and *Av*, decreases with the increasing Re_{ta}. Further analysis indicated the friction factor ratio *C* is a function of dimensionless acceleration $\alpha^* = 4Av\sqrt{\omega'^2}/Re_{ta}$. As the channel height increasing, the time-averaged friction factor decreases gradually to the same values as that of steady flows in the present ranges of sqrtω'. Finally, correlations to predict time-averaged friction factor were proposed.

The effect of channel size is inferred to associate with the fractions of turbulent Stokes layer thickness to half-height of channels. In mini-channels, the turbulence Stokes layer is almost filled the entire flow area. As channel height increasing, the turbulence, which generated in near wall layer, cannot timely propagates into pipe core region before decaying-which cause the impact of superimposed unsteadiness fades rapidly. The effect of dimensionless frequency is interpreted as the response time of fluid to the rapid changes of pulsatile pressure gradient.

1. Introduction

Mini-channel has been widely used in the field of electronic, chemical and nuclear reactor engineering as its high heat transfer efficiency and compact structure (Piasecka and Hozejowska et al., 2004; Shen and Hibiki et al., 2012; Tan and Wang et al., 2013; Goulart and Wissink et al., 2016; Kim, 2016). Unsteady flows are common physical phenomena frequently encountered in such engineering applications as internal combustion engines, marine reactors, and other periodical processes in thermal systems. Although much effort has been put into the study of macroscale unsteady turbulent flow, the understanding of microscale turbulence under such conditions is far from complete.

There' re remarkably plenty of experimental (Richardson and Tyler, 1929; Schultz-Grunow, 1940; Karlsson and F, 1958; Brown and Margolis et al., 1969; Baird and Round et al., 1971; Gerrard, 1971; Mizushina and Maruyama et al., 1975; Melling and Whitelaw, 1976; Ohmi and Usui, 1976; Ohmi and Usui et al., 1976; Dean, 1978; Kirmse, 1979; Ohmi and Iguchi, 1980, 1981a, b; Ohmi and Iguchi et al., 1982; Hino and Kashiwayanagi et al., 1983; Ramaprian and Tu, 1983; Tu and Ramaprian, 1983; Winter and Nerem, 1984; Iguchi and Ohmi et al., 1985; Shemer and Wygnanski et al., 1985; Kurokawa and Morikawa, 1986; Mao and Hanratty, 1986; Iguchi and Ohmi et al., 1987; Kim and Moin et al., 1987; Brereton and Reynolds et al., 1990; Einav and Sokolov, 1993; Iguchi and Park et al., 1993; Tardu and Binder, 1993; Mao and Hanratty, 1994; Peng and Peterson et al., 1994; Tardu and Binder et al., 1994; Brereton and Mankbadi, 1995; Gibbings, 1996; Washington, 1997; Lodahl and Sumer et al., 1998; Zhao and Cheng, 1998; Gündoğdu and Çarpinlioğlu, 1999a, b; He and Jackson, 2000; Çarpinlioğlu and Gündoğdu, 2001; Özdinç Çarpinlioglu, 2003; Greenblatt and Moss, 2004; Morris and Forster, 2004; Vardy and Brown, 2004; Tardu and Costa, 2005; He and Ariyaratne et al., 2008; Pendyala and Jayanti et al., 2008; He and Jackson, 2009; Lovik and Abraham et al., 2009;

* Corresponding author.
E-mail addresses: zhuangnailiang@163.com (N. Zhuang), tansichao@hrbeu.edu.cn (S. Tan).

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Nomenclature

General symbols

a	channel height, m
Av	pulsatile velocity amplitude, $Av = \Delta U/U_{ta}$
b	channel width, m
C	friction factor ratio, $C = \lambda_{ta}/\lambda_{st}$
D	hydraulic diameter, m
f	pulsatile frequency, $f = 1/T$, Hz
g	gravity acceleration, m/s^2
L	length between pressure taps, m
P	pressure, Pa
R	pipe radius, m
Re	Reynolds number, $Re = UD/\nu$
S	turbulent Stokes number, $S = D(\omega/2\nu)^{0.5}$
t	time, s
T	pulsatile period, s
U	cross-section mean velocity, m/s
ΔP	pressure drop, Pa

Greek symbol

x	axial coordinate
λ	friction factor
φ	aspect ratio, $\varphi = a/b$
α	pulsatile acceleration, $\alpha = \partial U/\partial t$, m/s^2
$\alpha*$	Dimensionless acceleration, $\alpha^* = 4Av\sqrt{\omega'^2}/\mathrm{Re}_{ta}$
ν	kinetic viscosity, m^2/s
σ	uncertainty
ω	pulsatile frequency, $\omega = 2\pi/T$
sqrtω'	dimensionless frequency, sqrtω'$=R(\omega/\nu)^{0.5}$
δ	Stokes layer thickness, $\delta = (2\nu/\omega)^{0.5}$

Subscript

ta	time-averaged value
st	steady-state value

Zidouh and Labraga et al., 2009; Brunone and Berni, 2010; Di Liberto and Ciofalo, 2011; Su and Davidson et al., 2011; Wang and Huang et al., 2011; Çarpinlioğlu and Özahi, 2012; Manna and Vacca et al., 2012; Çarpinlioğlu and Özahi, 2013; Colonia and Romano, 2014; Özahi and Demir, 2014; Özahi and Çarpinlioğlu, 2015; Özahi and Çarpınlıoğlu, 2017) and numerical (Brown and Margolis et al., 1969; Kita and Adachi et al., 1980; Tu and Ramaprian, 1983; Kim and Moin et al., 1987; Scotti. and Piomelli, 2001; Scotti and Piomelli, 2002; Younis and Berger, 2004; Varghese and Frankel et al., 2007; He and Ariyaratne et al., 2008; Lovik and Abraham et al., 2009; Ariyaratne and He et al., 2010; Brunone and Berni, 2010; Di Liberto and Ciofalo, 2011; Manna and Vacca et al., 2012; Gorji and Seddighi et al., 2014; Manna and Vacca et al., 2015; Weng and Boij et al., 2016) studies on turbulent structures and frictional resistance characteristics of unsteady turbulence in macroscale pipe and duct flows. Among them, Brereton and Mankbadi (1995), Zhao and Cheng (1998), Gündoğdu and Çarpinlioğlu (1999a, b, 2001), Çarpinlioğlu, 2015) performed strict literature reviews of reciprocating flow and pulsatile flow. Researchers mainly focus on two hotspots, i.e., unsteady turbulent structure (including velocity profile, turbulent intensity, Reynolds-shear-stress, boundary layer structure, etc.) and frictional characteristics (or called wall-shear-stress).

To the studies of frictional resistance characteristics, Brown and Margolis et al. (1969) classified pulsatile flows into three regions, i.e., low, intermediate, and high frequency regions, with respect to the relationship between dimensionless frequency (sqrtω') and time-averaged Re (Re_{ta}) ($\omega R^2/\upsilon \simeq 0.025\mathrm{Re}$). Schultz-Grunow (1940), Streeter and Wylie (1967), Brown and Margolis et al. (1969) and Baird and Round et al. (1971) provided their experimental results that the low frequency region, pulsatile turbulent friction factor can be predicted from steady flow friction factor formula. Later, Ohmi and Iguchi et al. (1980) classified pulsatile turbulence flow pattern into three regions with respect to dimensionless frequency (sqrtω'), i.e., quasi-steady (1.32<sqrtω'), intermediate (1.32<sqrtω' <28), and inertia dominant ones (28<sqrtω'). They declared that pulsatile velocity amplitude Av has no effect on flow patterns (Ohmi and Iguchi et al., 1980). As the observation of Ohmi and Iguchi et al. (1980), the transient friction factor $\lambda(t)$ and time-averaged friction factor λ_{ta} of pulsatile turbulent flow are equal to those of steady flows in quasi-steady regime. In the intermediate and inertia dominant regimes, transient friction factor $\lambda(t)$ is smaller than λ_{st} and $\lambda(t)$ is larger than λ_{st} in the first part of decelerating zone of pulsatile period and it is smaller than λ_{st} in the rest of decelerating zone (Ohmi and Iguchi, 1981a). Further, Ohmi and Iguchi (1980, 1981a) proposed that in the intermediate region (in their paper (Ohmi and Iguchi, 1981a), sqrtω' =22), the time-averaged friction factor λ_{ta} increases monotonically with the increasing in both $\omega'/\mathrm{Re}_{ta}^{3/4}$ and Av. Ramaprian and Tu (1983), Tu and Ramaprian (1983) conducted pulsatile turbulent experiments with two types of conditions, i.e., $\mathrm{Re}_{ta} = 5\times10^4$, $f = 0.5$ Hz, $Av = 0.65$ (in intermediate region) and $\mathrm{Re}_{ta} = 5\times10^4$, $f = 3.6$ Hz, $Av = 0.15$ (in inertia dominant region). They confirmed that quasi-steady turbulence model such as Prandtl-energy model can't be used in intermediate region and fails to capture the details of shear-stress variation over the whole pulsatile period. Mao and Hanratty (1994) focused on the influence of large-amplitude on turbulent frictional characteristics ($\mathrm{Re}_{ta} = 9700$, $T = 2$ s, 2.45 s, 3.46 s and $\mathrm{Re}_{ta} = 19{,}200$, $T = 2$ s, 1.5 s, 1 s with $Av = 1.04$–1.08) and observed the transient wall drag decreases by 10–15% when Re_{ta} increases from 9700 to 19,200, with flow reversal appear over an appreciable part of pulsatile period. They inferred this phenomenon is associated with the decrease in turbulence time scales with increasing Re_{ta}. The turbulence flow does not respond as rapidly to sudden changes of pressure drop. Tardu and Binder et al. (1994) performed their measurements detailed turbulent statistics in a macroscale rectangular channel (flow area $100 \times 1000mm^2$) and shown that the wall shear stress is only slight affected by the imposed oscillations (just increasing by most 16%) under condition of $\mathrm{Re}_{ta} = 8500$, $Av = 0.1$–0.7, and $T = 4$–132 s. Shuy (1996) and later the recommends of (Washington, 1997) found that in accelerating and decelerating turbulent pipe flows, the wall shear stress during the accelerating flows in less than steady flows and during decelerating flows wall shear stress is greater than that of steady flows. They proposed their explanation that the response to the change of pressure gradient in core region of pipe is greatly more rapid than that in near wall region. As a result, changes in the velocity field of fluid adjacent to the pipe wall lag behind flow rate changes in the core by a period proportional to $R(\Delta U \times \mu)$. Thus, the shear stresses along the pipe walls always represent an earlier core flow regime. Zidouh and Labraga et al. (2009) measured the wall shear stress and found for higher decelerations, the unsteady wall shear stress is consistently higher than quasi-steady values. Later, Greenblatt and Moss (1999), He and Jackson (2000), Greenblatt and Moss (2004), He and Ariyaratne et al. (2008), He and Jackson (2009) reported their observations that under rapid change of imposed pressure gradient or at high pulsatile frequency, the mean-flow effects were confined to the near wall region and in the pipe core region the turbulence fluctuations were effectively frozen. However, the wall shear stress or frictional characteristics were not reported. As the statement of literature review (Gündoğdu and Çarpinlioğlu, 1999a; Çarpinlioğlu and Gündoğdu, 2001), there's less study on the influence of pulsatile velocity amplitude in the intermediate and inertia dominant regimes. Conclusions can be drawn that especially in intermediate and inertia dominant regions