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Research paper

Pulsatile developing channel flows in low Reynolds number regime

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Abstract

In this study, comprehensive numerical simulations were conducted to examine laminar pulsatile developing flows through flat channels. The developing velocity fields and the hydrodynamic entry length were explored for the Reynolds numbers from 20 to 200, and the low and intermediate non-dimensional pulsation frequency or the Womersley number ($1.08 \leq Wo \leq 8.86$). For all simulations, the pulsating amplification factor was considered from zero to one, ($0 \leq A \leq 1$), and to achieve more practical and relevant outcomes, time-dependent parabolic inlet velocity profiles were applied. The outcomes reveal that for the higher values of the pulsation frequency or the Womersley number ($6 \leq Wo \leq 8.66$), the maximum pulsatile entranced length during a cycle is close to the inlet length of the mean component of the flow. On the other hand, for the rest of the Womersley number range ($1.08 \leq Wo < 6$), and high amplification factor ($0.5 \leq A$), the value of the entrance length increases and is significantly different from the development length of the steady component. Moreover, the results demonstrate that the entry length correlates with the Womersley number through a power-law function, whilst it has linear correlations with the Reynolds number and the amplification factor. Further, using the result of the accomplished numerical study, a practical correlation of the entrance length is offered to be used in the design phase for any type of pulsatile flow through the flat channels.

1. Introduction

Due to their effect on extensive and diverse technologies, appliances, and systems, pulsating flows are a significant part of applied mechanics; including wave propagation and control in many engineering uses, in the design of industrial processes such as internal combustion engines, thermo-acoustic devices, gas turbines, etc. Furthermore, pulsatile pressure fields can be applied to enhance combustion efficiency and decline pollutant formation. Also, investigations of reciprocating flows can be utilized for the improvement of heat exchangers in Stirling motors and pulse-tube cryocoolers [1-6]. Generally, numerous functional problems, which include certain grades of unsteadiness, could be analyzed as the composition of the purely oscillatory and mean components. Moreover, pulsatile flow studies could be known as the building blocks for all unsteady flows, for instance, an oscillatory flow can be considered as a pulsating flow with zero mean components [2]. On the other hand, low Reynolds number pulsating flows are very usable in numerous mechanical and biomedical engineering fields such as duct flows, manifolds of engines, and blood flow in arteries and veins, etc. [7-10]

Due to the importance of pulsating flows in vastly diverse fields, pertinent subjects have been drawing much attention for decades. For the first time, Atabek and Chang [11] studied the development length of pulsatile flows in a circular duct with a periodic uniform inlet velocity profile, analytically. Krijger *et al.* [12] and He and Ku [13] numerically explored the pulsating flow through parallel plates and circular channels with uniform velocity conditions at the entry, respectively. Cho and Hyun [14] numerically analyzed the pulsating flow in circular ducts and declared that the mean flow fields in the whole entry region are practically unaffected by the oscillatory component.

Chan *et al.* [15] investigated the pulsating flow in pipes numerically, and unlike Cho and Hyun [14] reported that for different values of the oscillatory component the mean flow fields were found to be dissimilar.Ray *et al.* [16] presented numerical work to study the entry length of laminar pulsatile flows in circular ducts and suggested a useful formula for estimating the development length of such flows.

Using particle image velocimetry (PIV), Blythman *et al.* [17] experimentally investigated the instantaneous velocity profiles of pulsating flows in channels and presented some comparisons between the experimental outcomes and analytical solutions.Rydlewicz *et al.* [18] investigated the pulsating flow through the straight pipes to introduce a reasonable approach to diminish the pressure pulsation amplitude downstream.

More recently, Purdin and Ksenok [19] presented an analytical and numerical study for a low-amplitude pulsating flow in a flat channel.

Lobo and Chatterjee [20] explored several periodic and non-periodic flows in channels numerically. Amaratunga *et al.* [21] examined non-Newtonian oscillatory flows through circular ducts empirically. Using numerical simulations of unsteady flows, Shajari *et al.* [22] studied laminar oscillatory flows in flat microchannels and submitted a helpful formula to calculate the entry length of such flows.

Although in several different situations, assuming a uniform inlet velocity profile provides an acceptable approximation for the analysis of developing flow problems, for various reasons, the flow at the inlet of channels practically does not have a uniform velocity distribution [23-28].

Furthermore, the literature review demonstrated that, although many researchers have studied in the fields of steady and even oscillatory entrance flows [16, 22, 29], precise and extensive research of the entrance length of pulsating flows, with the low Reynolds and Womersley numbers, has not been accomplished so far.

Moreover, a general and practical correlation for predicting the entrance length of pulsating flows through channels is not already available in the literature.

In the current study, expansive numerical work was conducted to explore more details of pulsatile developing flows in flat channels with the consideration of the non-uniform inlet velocity distribution. Eventually, regarding the extracted data, a practical and helpful formula was delivered to calculate the required development length of pulsatile flows, which is particularly useful in the design phase of the wide range of micro- and macro-channel flows.

2. Problem statement

An isothermal and incompressible fluid with a pulsating parabolic velocity profile enters a two-dimensional rectangular channel of width D and length L, as depicted in Fig.1.

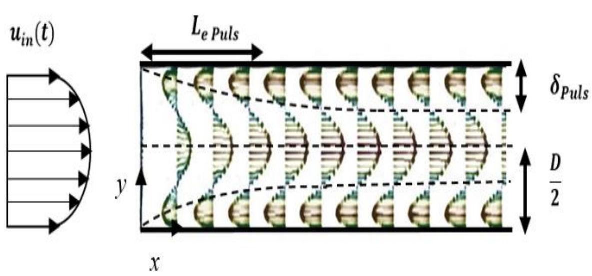

Fig. 1. Schematic of the considered problem.

Insomuch the velocity distribution consists of a periodic parabolic component superimposed on a steady parabolic component as:

$$u_{in} = U_0\left(1-\left(\frac{y-b}{b}\right)^2\right)\left(1+A\sin(2\pi f t)\right) \quad (1)$$

Whereas U_0 and b are constant values, and, f, t, and A are the pulsation frequency, time, and the amplification factor of pulsating flow, respectively.

As mentioned earlier, the pulsating flow is composed of the mean (steady) and oscillatory components, and A is the ratio of the amplitude of the oscillatory component to the mean component as:

$$u = u_s + u_{os}\sin(2\pi f t) = u_s\left(1+\frac{u_{os}}{u_s}\sin(2\pi f t)\right) = u_s\left(1+A\sin(2\pi f t)\right) \quad (2)$$

Owing to the conditions that could constantly happen upstream, in actual circumstances, the velocity profile at the inlet of a channel is not uniform [23, 24].

Thus, to provide much more advantageous outputs in the modeling process, the velocity in the inlet section was considered with parabolic distributions, delivered by Eq. (1).

It should be pointed out that the distance from the entry of the channel in which the flow evolves fully developed, and the velocity distribution gains its invariant final shape in every instant, is called the pulsating entrance length, ($L_{e\,Puls}$).

The governing equations, which consist of continuity and momentum equations, for the two- dimensional laminar flow with constant properties, are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \quad (3a)$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right), \quad (3b)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right). \quad (3c)$$

Whiles u and v, μ, and p are the velocity component along the x- and y-direction, the dynamic viscosity, and the effective pressure, respectively.

In addition, the considered boundary and initial conditions are as follows:

$$\text{At } x=0 \rightarrow u=U_0\left(1-\left(\frac{y-b}{b}\right)^2\right)\left(1+A\sin(2\pi f t)\right),\ v=0. \quad (4a)$$

$$\text{At } y=0, D \rightarrow u=v=0. \quad (4b)$$

$$\text{At } x=L \rightarrow \frac{\partial u}{\partial x}=0, v=0. \quad (4c)$$

$$\text{At } t=0 \rightarrow u=U_0\left(1-\left(\frac{y-b}{b}\right)^2\right),\ v=0. \quad (4d)$$

Moreover, the axial pressure gradient was regarded as:

$$-\frac{1}{\rho}\frac{\partial p}{\partial x}=p_0\left(1+A\cos(2\pi f t+\varphi)\right) \quad (5)$$

Insomuch, p_0 is a constant value and φ is the phase difference between $(\frac{\partial p}{\partial x})_{out}$ and u_{in} at any instant of time [16, 30].

3. Numerical simulations

As far as developing channel flows are concerned, the full Navier-Stokes equations are needed to achieve precise results for pulsating flows in the low Reynolds number regime [15].

In this work, finite volume pressure-based numerical modeling was conducted for all simulations [16, 31-34].

The grid and time-step independence investigations revealed that to achieve stable and consistent outputs, 80×200 control volumes for the spatial resolution were required.

Whereas, 360 time-steps per cycle for Wo < 2.17, and 180 time-steps per cycle for Wo > 2.17 were indispensable for temporal discretization.

As noted, the study was performed for Reynolds numbers ranging from 20 to 200, while the Womersley number was considered as 1.08, 2.17, 4.33, and 8.66, and the Amplification factor was assumed as 0 (steady flow), 0.25. 0.5, 0.75, and 1. The 90 selected values of Re were coupled with the considered values of Wo at each of the intended A values, separately. Finally, the 1800 sets of Re-Wo-A were utilized for numerical modeling and the needed database was created and employed to extract the expected formula.

3.1. Entrance length correlation

Concerning the design purposes in the field of pulsating channel flows, the maximum entrance length is the required and important factor during a cycle [16].
Therefore, in this work, according to the obtained numerical data, Eq. (13) is proposed to compute the maximum entry length in a cycle for the pulsating flows in flat channels, whilst Eq. (12) was offered for the entrance length of steady flows:

$$(L_e/D)_{st} = (0.3357 + 0.0044\ \mathrm{Re}^{1.6})^{0.7} \qquad (12)$$

$$(L_e/D)_{puls} = (L_e/D)_{st}\left[1+0.25\mathrm{A}+\left(\frac{0.75\mathrm{A}}{1+(\mathrm{Wo}^2/6.5\pi)^3}\right)\right] \qquad (13)$$

As noted, A is the amplification factor of pulsating flow, while Re and Wo are the Reynolds and the Womersley number, respectively.
It should be pointed out that the present correlation can be applied to obtain a conservative prediction of the entrance length for more complex pulsatile flows, for example triangular, trapezoidal, saw-tooth, or square-wave type.
Given that, the higher-order harmonics are expected to develop faster than the basic sinusoidal pulsatile flow [16], the maximum entrance length becomes shorter in such flows and can be estimated reliably using the proposed formula, Eq. (13).

3.2. Validation of the proposed correlation

To investigate the validation of the suggested formulas, Eq. (12-13), the evaluation of the effect of pulsation on the entrance length was carried out, and the ratio of entrance length with the presence of pulsation and without it was obtained for several cases. Finally, a comparison was made between the results and the available validated references (Table 1). In addition, some comparisons were made for steady flows that are delivered in Table 2.
Fortunately, the proposed correlations show satisfactory agreement with the valid references.

4. Results and discussion

Figs. 2 and 3 present the velocity profiles changes along the axial direction, for Re = 100, Wo = 4.33, and A = 0.75, whereas parts (a), (b), (c) and (d) are associated with the several chosen phases ϕ=0, π/2, π, and 3π/2 respectively. As can be seen, velocity fields vary over the entrance region along the flow direction, and throughout the fully developed region, velocity profiles do not alter substantially along the channel length. Moreover, under the impact of pulsatory pressure fields, the shape and the development of velocity profiles are totally distinguished from steady-state circumstances. As can be seen in part (d), when the flow is decelerating, backflow is visible near the walls. The transformation of the velocity field is illustrated in Fig. 4, for Re = 150, Wo = 2.80 and A = 0.5, whilst parts (a), (b), (c), and (d) are associated with various chosen phases ϕ=0, π/2, π, and 3π/2, respectively.

Table 1. Validation results for the proposed correlation Eq. (13).

Author	Type of data	$L_{e\ puls}/L_{e\ st}$	
		Re=75 & Wo=3.07& A=0.75	Re =150 & Wo=4.34 & A=0.75
Present work	Numerical	1.70	1.51
Krijger *et al.* [12]	Numerical	1.60	1.27
Ray *et al.* [16]	Numerical	-	1.47

Table 2. Validation results for the proposed correlation Eq. (12).

Author	Type of data	Re=75	Re =150
Present work	Numerical	3.46	6.24
Durst *et al.* [26]	Numerical	-	6.73
Boger *et al.* [35]	Numerical	4.37	8.49

As can be seen, due to the reciprocating nature of the pulsating pressure gradient, the centerline velocity is not always in the identical phase to the velocity vectors close to the walls.

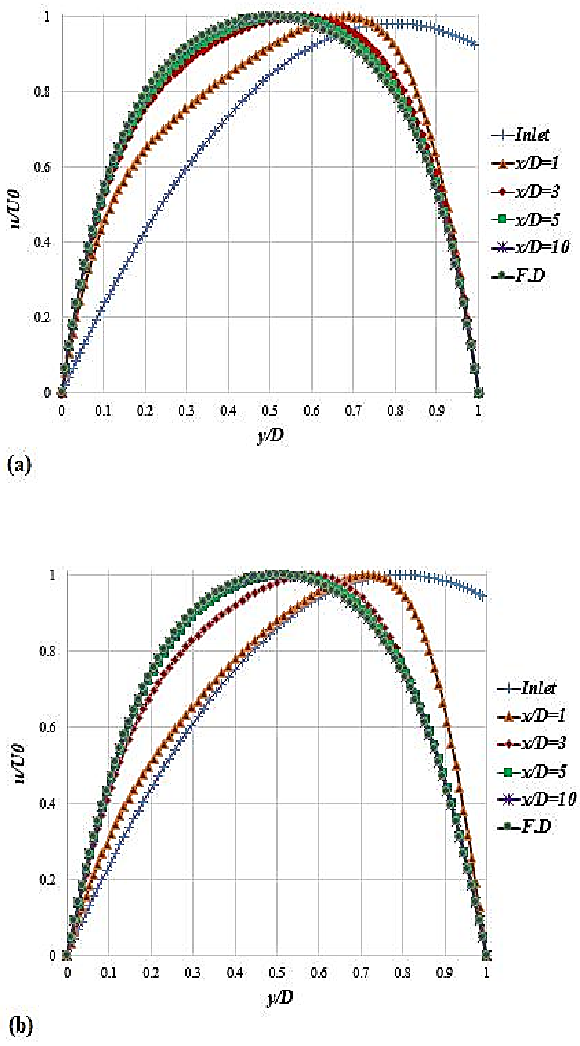

Fig. 2. Velocity distribution at different phases (a) 0, (b) $\pi/2$, for Re = 100, Wo = 4.33, and A = 0.75.

Fig. 4 (a and c) display that for some particular phases the velocity vectors near the walls stand in the opposite direction from the ones close to the centerline of the channel.

This occurs due to the high inertia in the core region, which increases the resistance of the flow field against the continuously imposed changes of the pulsatile pressure gradient and causes a phase difference.

Velocity contours along the channel length are displayed in Fig. 5, for Re = 50, Wo = 1.80, and A = 0.5. As can be seen, velocity profiles continuously change in the entry region to reach a constant shape and then remains unchanged.

Fig. 6 plots distributions of L_e/D versus Re for different Wo, whereas sections (a) and (b) correspond to A = 0.25 and 0.75, respectively.

It can be seen that L_e/D declines with the rise of the dimensionless pulsation frequency or the Womersley number.

This happens because, for the oscillatory component of the pulsatile flow, the wall effects solely require to disperse throughout the thickness of the pulsatile boundary layer, in contrast to the steady component of the flow, where the wall effects must be spread over the whole width of the channel to become fully developed.

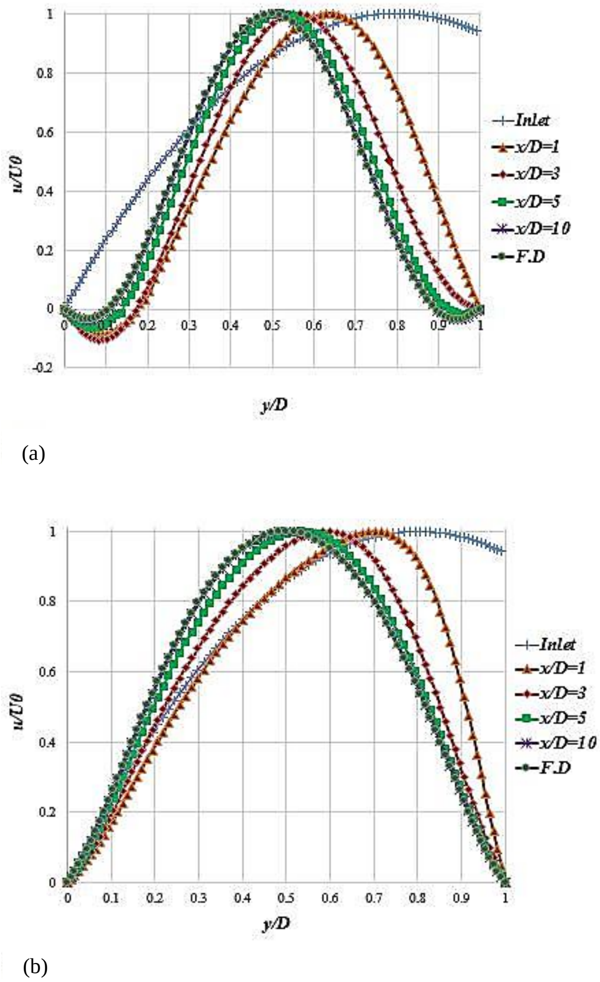

Fig. 3. Velocity distribution at different phases (a) π and (b) $3\pi/2$, for Re = 100, Wo = 4.33, and A = 0.75.

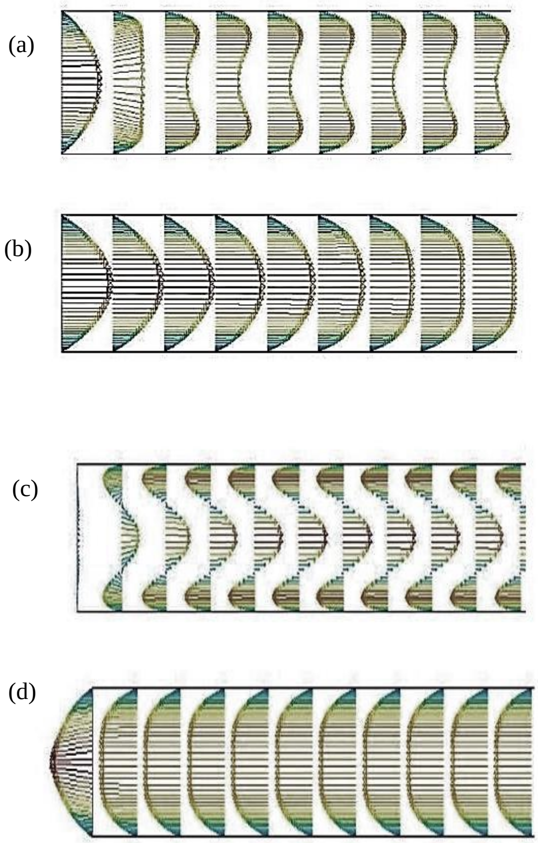

Fig. 4. Velocity profiles at different phases (a) 0, (b) $\pi/2$, (c) π and (d) $3\pi/2$, for Re = 150, Wo = 2.80, and A = 0.5.

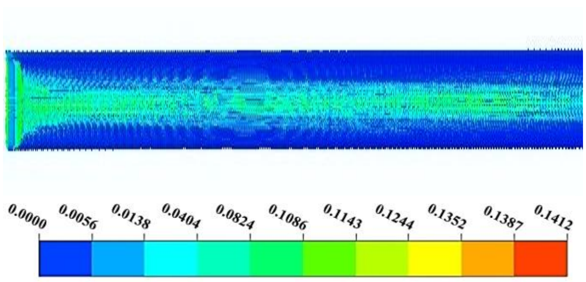

Fig. 5. Velocity contours along the channel length for Re = 50, Wo = 1.80, and A = 0.5.

In other words, for the high Womersley number flows, the effect of pulsation is felt principally in a thin layer near the walls [14]; and the oscillatory component of the pulsatile flow becomes fully developed at a short distance from the entry.

Therefore, it can be concluded that for the high values of the pulsation frequency or the Womersley number (e.g. Wo = 8.66), the maximum pulsating inlet length during a cycle, is close to the value of the development length of the mean component.

On the other hand, for the low Womersley number

(e.g. Wo = 1.08), and high amplification factor (Fig. 6(b)), the value of the entrance length increases and is significantly different from the value of the development length of the steady component. Furthermore, the slope of the rising of L_e/D versus Re reduces for the higher values of Wo. Fig. 7 illustrates the distribution of L_e/D versus Wo for different values of Re.

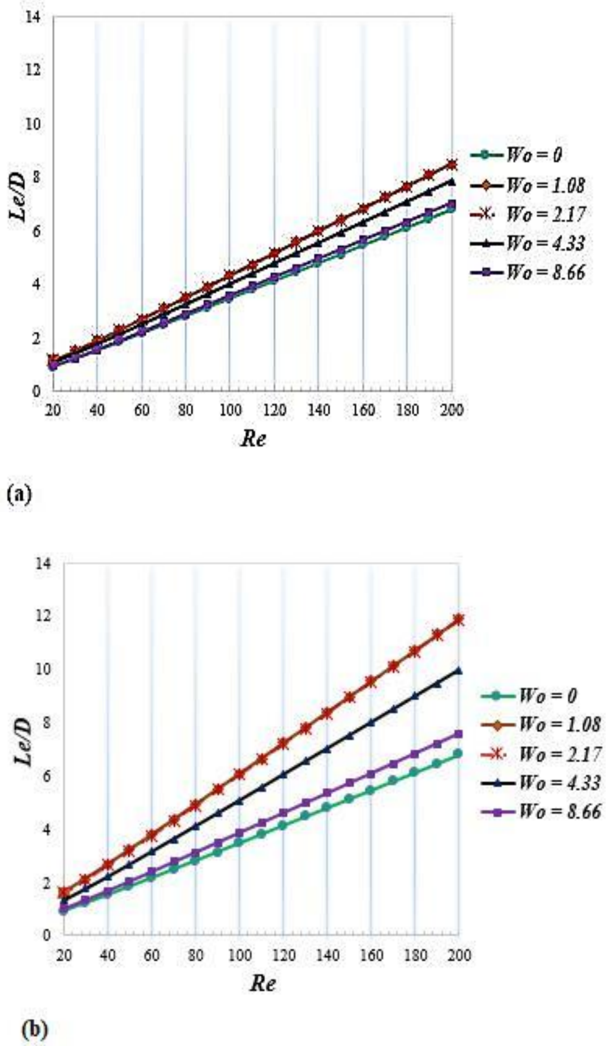

Fig. 6. L_e/D versus Re for various Wo, at A = (a) 0.25 and (b) 0.75.

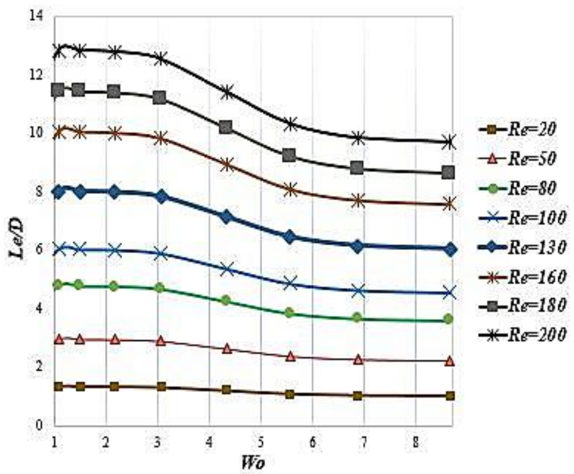

Fig. 7. L_e/D versus Wo for various Re, at A = 0.5.

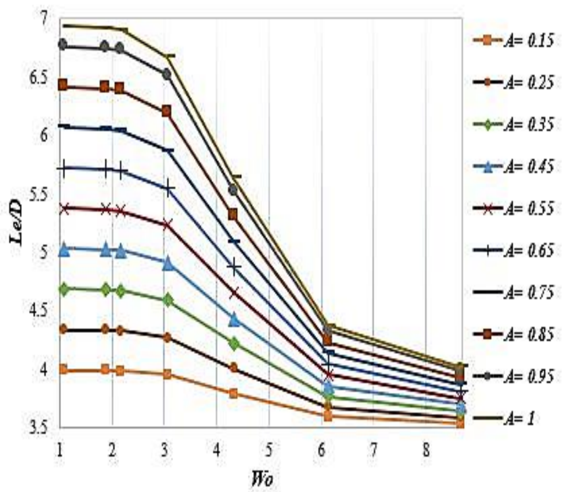

Fig. 8. L_e/D versus Wo for various A, at Re = 100.

Furthermore, the results establish that the entrance length correlates with the Womersley number through a power-law function, whilst it has linear correlations with the Reynolds number (Fig. 6).
As can be seen, the entrance length diminishes with the growth of Wo, whereas it rises when Re increases.
In other words, the results show that the development length changes with the pulsation frequency are not very significant in the range of high Womersley numbers ($6 \leq$ Wo).
Fig. 8 represents the distributions of L_e/D versus Wo for the different values of A (Eq. (13)). The results reveal that L_e/D rises with A, while declines with Wo. Moreover, the results demonstrate that for the lower range of the amplification factor (i.e., $A \leq 0.45$), the entrance length remains constant roughly with Wo for the higher values of the Womersley number (i.e., Wo ≥ 6).

5. Conclusions

In this study, in order to establish a simple and useful correlation to estimate the entrance length of any type of pulsatile flow through plane channels, the time-dependent Navier-Stokes equations have been investigated numerically. All the simulations were conducted for low Reynolds number laminar flows, whilst, the pulsation frequency varied from the low to the intermediate values ($1.08 \leq$ Wo < 8.86). The results show that for the Womersley number ranging Wo < 6 and high amplification factor ($0.5 \leq A$), the entrance length is significantly different from the development length of the steady component. Furthermore, the results indicate that the development length correlates with the Womersley number through a power-law function, whiles it has linear correlations with the Reynolds number and the amplification factor.

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