Local and Integral Energy Based Evaluation for the Unsteady Friction Relevance in Transient Pipe Flows

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Abstract:

Unsteady friction and its modelling have been widely studied in transient pipe flows for its influences and modification effect on pressure waves. Such a feature is of great importance particularly in pipe systems where the extreme pressure values are due to the overlapping of pressure waves generated in different sections. This paper investigates the relevance of unsteady friction term by considering different models available in the literature. In particular, attention is focused on the following two commonly used one-dimensional (1D) models: the weighting function-based (WFB) model and the instantaneous acceleration-based (IAB) model. The investigation is executed through laboratory experiments and field tests as well as 1D/2D numerical simulations in simple pipeline systems. Realistic ranges of both initial (pre-transient) conditions and geometrical characteristics are considered. The data collected in experimental tests are first used to calibrate the unsteady friction models under investigation; and the validated models are then applied to identify their respective domains of applicability and the limitations.

The differences between models and data are measured using the local transient analysis (LTA) norm and the integral total energy (ITE) norm along the pipeline and the reasons for such discrepancies are explored in the paper. The practical implications of the use and improvements of different unsteady friction models for transient pipe flow simulations are discussed in the paper.

Keywords: Unsteady friction; transient pipe flows; WFB model; IAB model; local transient analysis; integral total energy

Introduction

The modelling of transients in pressurized pipe flows can be legitimately considered as an evergreen topic because of its constantly evolving nature and its crucial importance in the design and management of pipe networks. Thus in each epoch, according to the characteristics and operational needs of the related pipe systems, up-to-date analytical/numerical methods have been developed. In the case of friction simulation, the earliest computers evaluated the extreme transient pressures in long transmission mains by integrating the one-dimensional (1D) governing equations numerically within the Method of Characteristics (MOC) scheme. When modelling slow maneuvers, the quasi-steady state approach for determining the friction term in the momentum equation was proposed. Thereafter, when fast maneuvers became routine in the operation of pipe systems due to, as an example, the action of automatic control devices (Brunone and Morelli, 1989), the inadequacy of such a method for simulating the friction term was evident. The problems associated with the standard quasi-steady modelling of pipe friction form the driving force behind the research activity on unsteady friction.

In this context, the Zielke's solution (Zielke, 1968) for laminar transients is the first milestone towards a comprehensive analysis of unsteady friction in efficient 1D models. The analytical solution proposed by Zielke is based on the artificial separation of the total wall shear stress, τ_w, into two distinct components:

$$\tau_w = \tau_{ws} + \tau_{wu}, \qquad (1)$$

with τ_{ws} and τ_{wu} being the quasi-steady and unsteady components of τ_w, respectively. The Darcy-Weisbach equation has been commonly used to model the steady wall shear stress in pipe flows (Chaudhry, 1987). Moreover, Zielke's approach (1968) – where τ_{wu} is given by a weighted convolution of past accelerations – gives rise to the weighting function-based (WFB) models that are used to simulate turbulent unsteady friction. An alternative approach for turbulent unsteady friction evaluation is given by the instantaneous acceleration-based (IAB) models that have been proposed on the basis of laboratory tests.

As mentioned, the WFB models are an extension of Zielke solution originally for laminar flows to turbulent flows (Vardy and Brown, 1995; 2003; 2004). The key assumptions that have been made in the WFB models include: (1) fully developed flow; (2) negligible convective term; (3) incompressible momentum equation; (4) axisymmetric and stable velocity profile; and (5) quasi-steady and "frozen" viscosity during entire water hammer process. Many experimental, numerical, as well as analytical investigations (e.g., He and Jackson, 2000; Ghidaoui et al., 2002; Zhao and Ghidaoui, 2006; He et al., 2011; Duan et al., 2012) have indicated that assumptions (1) to (4) are valid for most transient flows in water pipelines, but the frozen turbulence hypothesis in (5) is valid only for a time duration of an order of the radial diffusion time scale. Once the longitudinal wave propagation time exceeds the radial diffusion time scale, the turbulence structures begin to change and thus the frozen hypothesis loses its validity. That is, the WFB models are expected to progressively lose its accuracy with the duration increase of the transient (Meniconi et al., 2014). This disadvantage was also pointed out by one of the original authors of the WFB model (Vardy et al., 2015). Due to the convolutional form of the WFB model, large data storage and memory space are required and the CPU computation time increases significantly with pipe system scales and complexities. As a result, these two disadvantages have limited the use of the WFB model to relatively small scale and simple pipeline systems (Duan et al., 2012). Several recursive approaches have been proposed in the literature to speed up simulations with compromises to their quality and accuracy (e.g., Trikka, 1975; Ghidaoui and Mansour, 2002; Adamkowski and Lewandowski, 2006; Vitkovsky et al., 2006; Szymkiewick and Mitosek, 2007, 2014; Vardy and Brown, 2007; Zarzycki et al., 2011).

On the other hand, the IAB model can be more suitable for practical applications for large scale and complex pipe systems compared to the WFB model due to its high computational efficiency without the convolutional computation. It was found that the implementation of the IAB unsteady friction model in 1D water hammer model does not significantly increase computation time compared to the situation of steady friction term only (Vitkovsky et al., 2000; Reddy et al., 2012). However, the IAB model – for which a thermodynamics framework is given in Axworthy et al. (2000) – was developed empirically based on various experimental tests and applications (Brunone et al., 1995; Brunone and Golia, 2008; Bergant et al., 2001). Particularly, two terms – local acceleration ($\partial V/\partial t$) and characteristic convection ($a \cdot \partial V/\partial x$) where V and a are flow velocity and wave speed respectively – together with an empirical coefficient (k_d) were assumed to represent the unsteady friction modification effect on the pressure waves. Thus the main disadvantage of applying this IAB model is the need of pre-calibration for the empirical coefficient, k_d, based on the available data in a specific system, which potentially increases the work load and uncertainties in practical applications. Although many researchers have investigated the determination and improvement of such k_d coefficient (Bergant and Simpson, 1994; Bughazen and Anderson, 1996; Pezzinga, 2000; Vardy and Brown, 1996; Reddy et al., 2012), so far there is not yet a general coefficient expression for the IAB model that is exactly valid and applicable for all practical cases. Moreover, many studies have implied that this k coefficient in the IAB model would be time and space dependent in transient pipe flow simulations (Vitkovsky et al. 2000; Brunone et al., 2004; Storli and Nielsen, 2011a, 2011b), which makes the calibration and application of this IAB model case-sensitive.

With the advantages and disadvantages of these two types of unsteady friction models evidenced in the literature, it is necessary to further evaluate systematically the unsteady friction relevance so as to understand more the situations of the need of these models for transient pipe flow simulations. At the same time, it is also essential to assess each type of model for their applicability domain and accuracy with regard to the importance and relevance situations of unsteady friction effect. To inspect and explain such problems, many researchers have put their efforts in this field, where most of them took the WFB model for investigation due to the relatively clear physical formulation and structure of this type of model, especially without empirical coefficient as in the IAB model. Kim (2011) has developed a combined model of merging the WFB and IAB models by introducing three coefficients for the simulation of laminar transient flows. Similarly as in original IAB model, the determination of these coefficients in this combined model is worthy of further investigations. Duan et al. (2012) investigated the importance of unsteady friction effect to the pressure envelope dissipation relative to the steady friction by using the analytical analysis, 2D numerical simulation and extensive experimental data. The WFB model was adopted in that study for the analytical analysis, and the results indicated that the relative importance of unsteady friction is actually dependent on a dimensionless parameter that describes the pipe scales and initial hydraulic conditions in the system. But the conclusion of that study relied mainly on the validity of the WFB model as well as on the local transient pressure response evaluation only, such that it may not be general to other models and all the cases of transient pipe systems. Thereafter, Meniconi et al. (2014) studied the validity of the WFB model for its "frozen" turbulent viscosity assumption, and a time-dependent (instantaneous) condition was proposed for improving the convolution term in the original WFB model. Clear improvements have been obtained in that study for reproducing the transient pressure envelope attenuation, especially for highly turbulent flows. Similar to previous studies, only the evaluation of local transient pressure responses has been focused on in that study, and the results and findings obtained are mainly limited to the localized section/region of the pipeline system, but may not be suitable or inapplicable to characterize the whole transient pipeline system where the wave reflections and change extents from the system boundaries are very different for different sections in the system. For clarity, the existing problem for transient behavior evaluation is stated in details in the following section.

To further understand the unsteady friction effect, it is worthwhile to investigate transient pipe flows from a more holistic perspective using global energy relations to evaluate the relevance and importance of unsteady friction models for transient flow simulations. In this paper, the differences between the IAB and WFB unsteady friction models are examined and explained from the perspectives of the local transient pressure response and global energy integration. The energy data obtained from these validated unsteady friction models as well as from a 2D turbulence model are used for the analysis. The considered transients are caused by fast maneuvers in comparison to the characteristic time of the pipeline; moreover, a realistic range of pipe scales (length and size) and initial hydraulic conditions from laboratory to field test systems are adopted in this study. Finally, discussion and suggestions on the relevance and improvement of unsteady friction model are provided.

Problem Statement

The local transient response (e.g., pressure) in the pipeline system has been widely used in the literature for the evaluation of transient models and simulation methods such as unsteady friction formulas and numerical discretization schemes. For example, the damping of transient pressure traces was reproduced by the unsteady friction model under investigation, with its difference from the benchmark results by simulation or measurement used for evaluating the accuracy of such model. This evaluation method could characterize the time-dependent evolution of transient responses so that the accuracy and influence of transient model and method could be assessed for the localized section focused in the system, but its result may not represent the global transient behaviors for the whole pipe system. In fact, the spatially dependent effect and difference of the transient behaviors have been observed numerically and experimentally in many previous studies. Specifically, by means of experimental tests it has evidenced that the unsteadiness of transient flow behaviors in the pipeline is strongly linked to the position of the section with respect to the boundaries (e.g., the maneuver valve and the supply tank) where the pressure waves are generated and reflected (Brunone and Berni, 2010). On this point, it is clear that the distance of the considered section from a transient source would determine the time interval between the successive wave fronts when the flow conditions are almost steady, and therefore, the role of unsteady friction due to such transient flow/velocity changes becomes very different (extent and frequency) in each section. The similar result was further confirmed in the numerical studies by

Storli and Nielsen (2011a, 2011b).

Furthermore, the wave reflections and superposition become increasingly complicated with the complexity of pipeline connections (junction boundaries) such as pipe networks (Chaudhry, 1987; Ghidaoui et al., 2005). Under this condition, the local transient trace envelopes are much more complex (e.g., non-monotonic and/or discontinuous change) than that in single pipeline system and meanwhile, their variation trends are very different at different measurement locations in the system (e.g., Karney and McInnis, 1990; Pothof and Karney, 2012). Particularly, Duan et al. (2011) have demonstrated from analytical analysis and numerical simulations that the spatial shifts of different forms of energy in the system may be induced by wave scattering effect due to complex wave reflections from complexities of pipe connections and internal conditions (e.g., corrosion and sediment). In this regard, the analysis based only on the local transient response may neglect (fully or partially) this spatially dependent transient behavior, so that its result is not suitable for evaluating the relevance and importance of unsteady friction for the whole transient pipeline system. In this paper, another evaluation method, based on the integral energy of the whole transient pipeline system proposed by Karney (1990), is investigated, which is described in the following section. With this proposed evaluation method, a comprehensive comparison of the two commonly used unsteady friction models (IAB and WFB models) and further understanding of the relevance of unsteady friction for transient flow modelling can then be obtained, which are within the scope of this study.

Models and Methods

The models and methods used for the investigation are presented briefly in this section.

1D & 2D transient flow models

The continuity and momentum equations for 2D axisymmetric transient flows in pipelines are given as (Vardy and Hwang, 1991; Silva-Araya and Chaudhry, 1997; Pezzinga, 1999; Zhao and Ghidaoui, 2006; and Duan et al., 2012),

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial u}{\partial x}+\frac{a^2}{g}\frac{1}{r}\frac{\partial (rv)}{\partial r}=0\ , \tag{3}$$

$$\frac{\partial u}{\partial t}+g\frac{\partial H}{\partial x}=-\frac{1}{\rho r}\frac{\partial (r\tau)}{\partial r}\ , \tag{4}$$

where H = pressure head, u = longitudinal velocity, v = transverse velocity, a = wavespeed, t = time, x = spatial coordinate along pipeline, r = the distance from pipe axis, g = gravitational acceleration, ρ = fluid (water) density, and

$$\tau=\rho(\nu_k+\nu_t)\frac{\partial u}{\partial r}\ , \tag{5}$$

being the total shear stress, with ν_k and ν_t = kinematic viscosity and turbulent eddy viscosity, respectively.

The classic 1D model for transient pipe flows can be obtained by integrating above 2D model in Eqs. (3) & (4) throughout the pipe cross-sectional area, A, at each longitudinal location (x) and time (t), as (Duan et al. 2010),

$$\frac{gA}{a^2}\frac{\partial H}{\partial t}+\frac{\partial Q}{\partial x}=0\,, \tag{6}$$

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{\pi D}{\rho}\tau_w=0\,, \tag{7}$$

where Q = discharge, D = pipe internal diameter. The pipe wall shear stress τ_w is given by Eq. (1), with the unsteady component presented in the following section. Note that in this study, the 1D model of Eqs. (6) & (7) is used for the numerical simulations of transient pipe flows by different

1D unsteady friction models to be evaluated, while the 2D model of Eqs. (3) and (4) together with the 2D κ–ε turbulence model given below is adopted for generating detailed results as an evaluation benchmark of these 1D unsteady friction models. Furthermore, only the simple pipe systems of reservoir-pipe-valve and the pump (with check valve)-pipe-tank are studied in the paper, and therefore, the two pipe-end boundaries of tank/reservoir with constant head and valve/check valve with fixed/known flowrate, which has been widely used and implemented in the previous studies (e.g., Zhao and Ghidaoui 2006; Duan et al. 2010, 2012), are applied in the 1D and 2D models in the following study.

1D unsteady friction models

As illustrated in the former section, two different types of 1D unsteady friction models are studied in this paper, which can be expressed as follows:

(1) Weighting Function-Based (WFB) model (e.g., Zielke, 1968; Vardy and Brown, 1995):

$$\tau_{wu} = \frac{4\rho\nu_k}{DA}\int_0^t W(t-t')\frac{\partial Q(t')}{\partial t'}dt', \tag{8a}$$

where $W(t)$ = weighting function, and t' is a dummy time variable. The detailed expressions of weighting function $W(t)$ for laminar and turbulent flow cases have been provided in the classic references of Zielke (1968) and Vardy and Brown (1995, 2003), respectively.

(2) Instantaneous Acceleration-Based (IAB) model (e.g., Brunone et al., 1995; Bergant et al., 2001):

$$\tau_{wu} = \frac{k_d\rho D}{4A}\left(\frac{\partial Q}{\partial t} + sign(Q)\cdot a\left|\frac{\partial Q}{\partial x}\right|\right), \tag{8b}$$

in which $sign(Q)$ = +1 for $Q \geq 0$, or −1 when $Q < 0$; and other symbols are same as former definitions in this study.

Particularly, in the waterhammer literature (e.g., Daily, 1956; Vardy and Brown, 1995; Ghidaoui et al., 2002 and 2005; Duan et al., 2012), the transient flow process is usually divided into two different stages: one is the accelerating flow stage and the other is the decelerating flow process. With this division, the formation mechanism and evolution process of the unsteady friction for transient pipe flows can be better understood and studied separately (e.g., He and Jackson, 2000; Zhao and Ghidaoui, 2006; Ariyaratne et al., 2010; He et al., 2011; Vardy et al., 2015). Mathematically, the definitions of accelerating and decelerating flows can be expressed as,

$$sign(Q)\left|\frac{\partial Q}{\partial x}\right| : \begin{cases} >0 & \text{acceleration} \\ <0 & \text{deceleration} \end{cases}. \tag{9}$$

Furthermore, for the fair evaluation of the two unsteady friction models, the k_d coefficient in the IAB model Eq. (8b) is determined by the analytical expression developed in Vardy and Brown (1996), which is also based on the assumption of “frozen” and “two-layer” viscosity distribution as applied in the WFB model, as follows (Vitkovsky et al. 2000):

$$k_d = 5.44\mathbf{Re}^{0.5\log\left(14.3/\mathbf{Re}^{0.05}\right)}, \tag{10}$$

where $\mathbf{Re} = \boldsymbol{Q}_0 D/A\nu_k$ –) is the initial Reynolds number with the subscript 0 indicating the initial conditions. Therefore, a constant k_d value is suggested for the IAB model based on the initial flow condition (**Re**). Under the same assumption condition, the two unsteady friction models of IAB and WFB are to be compared and discussed for their different expression forms of representing the transient flow behaviors (i.e., historical convolution and instantaneous acceleration respectively) in the following study.

2D κ–ε turbulence model

A formula is required for describing the turbulent shear stress in Eq. (5) to close the 2D transient model in Eqs. (3) & (4). In this study, the two-equation based 2D κ–ε turbulence model from Zhao and Ghidaoui (2006) is used. The mathematical form of the eddy viscosity in Eq. (5) is expressed as (Zhao and Ghidaoui, 2006; Duan et al., 2010, 2012),

$$\nu_t = C_\mu f_\mu \frac{\kappa^2}{\varepsilon} \ , \tag{11}$$

where C_μ, f_μ = coefficients; κ, ε = turbulent kinetic energy and dissipation rate respectively, and can be calculated by the following equations:

$$\frac{\partial \kappa}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu_k + \frac{\nu_t}{\sigma_\kappa}\right)\frac{\partial \kappa}{\partial r}\right] + \nu_t\left(\frac{\partial u}{\partial r}\right)^2 - \varepsilon \ , \tag{12}$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu_k + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right] + \nu_t C_{\varepsilon 1} f_1 \frac{\kappa}{\varepsilon}\left(\frac{\partial u}{\partial r}\right)^2 - C_{\varepsilon 2} f_2 \frac{\varepsilon^2}{\kappa} \ , \tag{13}$$

where: $f_w = 1.0 - \exp\left\{-\frac{\sqrt{R_y}}{2.30} + \left(\frac{\sqrt{R_y}}{2.30} - \frac{R_y}{8.89}\right)\left[1 - \exp\left(-\frac{R_y}{20}\right)\right]^3\right\}$; $R_y = \frac{y\sqrt{\kappa}}{\nu_k}$; $y = \frac{D}{2} - r$;

$$f_2 = f_w^2\left\{1.0 - 0.22\exp\left[-\left(\frac{R_t}{6}\right)^2\right]\right\}; \quad f_\mu = 0.4\frac{f_w}{\sqrt{R_t}} + \left(1 - 0.4\frac{f_w}{\sqrt{R_t}}\right)\left[1 - \exp\left(-\frac{R_y}{42.63}\right)\right]^3;$$

$$R_t = \frac{\kappa^2}{\nu_k \varepsilon}; \ C_\mu = 0.09; \ \sigma_\kappa = 1.0; \ \sigma_\varepsilon = 1.3; \ C_{\varepsilon 1} = 1.39; \ f_1 = 1.0; \ C_{\varepsilon 2} = 1.80.$$

Previous studies of Zhao and Ghidaoui (2006) and Duan et al. (2010, 2012) have successfully incorporated the 2D κ–ε turbulence model in the waterhammer system (Eqs. 3 & 4) and their results showed that this model can represent accurately the time-dependent turbulence dissipation effect during transient pipe flows. It is also important to note that the application of this 2D κ–ε model is very time consuming with high computational requirements. Therefore, in this study, it is applied only for the laboratory test system with relatively small pipe scales, with its result used as benchmark for the energy analysis to evaluate the two 1D models.

Unsteady friction evaluation by local transient analysis (LTA)

The above two types of unsteady friction models have been widely validated and evaluated for their accuracy and efficiency in the literature (e.g., Ghidaoui et al., 2005; and Adamkowski and Lewandowski, 2006; Duan et al. 2012). In this paper, the study of the differences in the magnitudes of transient pressure trace envelopes between the model result and experimental data at specific locations in the pipeline is referred to as local transient analysis (LTA) method. Mathematically, it is given as (Duan et al., 2012; Meniconi et al., 2014),

$$\gamma(m) = \frac{\Delta H_N(m) - \Delta H_T(m)}{\Delta H_T(m)}, \tag{14}$$

where γ = normalized difference of pressure head envelops between the numerical model result and measured data; ΔH = instantaneous transient pressure head relative to the initial steady state (or pre-transient) pressure head (i.e., subtracting the initial pressure head from instantaneous total pressure head); m = peak number of the pressure head trace; and subscripts N, T indicate the results from numerical model and experimental test, respectively.

Unsteady friction evaluation by integral total energy (ITE)

The LTA method has been widely adopted for evaluating unsteady friction models because of the convenience for obtaining the experimental data at a few key locations in the pipe system. However, the evaluation by this method is mainly valid for the trend and contribution of the unsteady friction dissipation for these specified locations, but may not be usable for the description of unsteady friction behaviors at other points in the system. For this purpose, in this study another method based on the energy analysis of the transient pipe flow system becomes useful, which is referred to as integral total energy (ITE) method. According to Karney (1990) and Duan et al. (2010), the energy relation for transient pipe flows can be expressed as,

$$\frac{dU}{dt}+\frac{dT}{dt}+D_f+W_E+W_P=0\,, \tag{15}$$

where $U = U(t)$ = the total internal energy in the system; $T = T(t)$ = the total kinetic energy in the system; $D_f = D_f(t) = D_{fs}(t) + D_{fu}(t)$ = the total rate of frictional dissipation, with $D_{fs}(t)$ and $D_{fu}(t)$ being the steady and unsteady components, respectively; $W_E = W_E(t)$ = the total rate of work from the ends of the pipeline; $W_P = W_P(t)$ = the total rate of work from the pipe-wall (e.g., visco-elastic deformation). Particularly, the frictional dissipation rate is written in the form of energy as,

$$D_f(t)=\frac{4}{D}\int_0^L \tau_w(x,t)Q(x,t)dx\,, \tag{16}$$

where L is the total length of the pipeline. The expressions for other terms in Eq. (15) can be referred to Karney (1990) and Duan et al. (2010). It is also noted that the ITE-based evaluation method requires both the spatial and temporal distribution of transient pressure head and flow which makes it impractical when one is using experimental measurement data. On this point in this study, the difference between the total friction dissipation rate (Eq. 16) from the unsteady friction models and the well-established 2D model simulation will be used for the model evaluation using the ITE method.

Experimental Setups and Tests

Two experimental test systems in Italy and New Zealand are used for the investigation, with the system schematics and system settings shown in Fig. 1 and Table 1. The experimental tests from Italy are conducted on a field test system, consisting of a constant diameter steel pipe with an upstream pump station with a check valve and discharging into a reservoir downstream. The transients were caused by the sudden failure of the pump station, followed by the fast closure of the check valve. The tests conducted in New Zealand are for a laboratory experimental test pipe system, which is composed of reservoir, pipeline and downstream valve. The transients were caused by the sudden closure of the valve. More details of these test system configurations can also be referred to the recent publications from the authors (Duan et al., 2013 and Meniconi et al., 2014). Three test cases are selected from extensive tests conducted in these two pipe systems by the authors and are shown in Table 1, with the initial Reynolds number, **Re** being in an order of 10^3, 10^4, and 10^5 respectively, covering a typical range of flow conditions in practical water supply pipelines.

<u>Fig. 1 is about here</u>

<u>Table 1 is about here</u>

The measured results near the transient sources (at the downstream valve end in laboratory test system in New Zealand, and the check valve location in field test system in Italy) are plotted as the black-solid line in Fig. 2, where the vertical coordinate represents the amplitude of the instantaneous transient pressure head (ΔH), and the axial coordinate is the dimensionless time, normalized by the wave travel time of the pipeline (L/a).

In the Italian test system, because of the crucial role played by boundary conditions in transient simulation, the actual time behaviour of the discharge at the pump, Q_P, and the duration of the pump stopping, i.e., response time T, were determined within an inverse transient analysis (ITA). The instant of time at which $Q_P = 0$ gives the value of T. In such a way, the actual inertia of the pumps has been taken into account properly. The detailed information has been given in Meniconi et al. (2012). According to the ITA results, in the current paper, when the 1D and 2D models were used for the numerical simulations, an approximate linear discharge curve (0 ~ T) has been applied. Since the calibrated T is relatively small compared to the characteristic wave period of this relatively long pipeline system (i.e., 4.17 km), it is very difficult to read the inertia effect of pumps with duration of T from both the experimental and numerical results in Fig. 2.

Based on Eq. (10), the k_d-efficient of the IAB model for each test case is calculated and listed in Table 1. More detailed comparison and analysis of measured data and numerical results is conducted in the next section.

Fig. 2 is about here

Numerical Simulation and Model Evaluation

The simulated pressure head traces are shown in Fig. 2 to compare with the measured data. The results from IAB and WFB models are distinguished by postfix "A" and "B" in the title of sub-figures for each case. Meanwhile, the results by quasi-steady friction modelling – numerical results by steady friction model – are also plotted in the figures. In the following analysis, the results and comparison of different models and data are performed by two methods – local transient analysis (LTA) method and integral total energy (ITE) method.

Result analysis by LTA method

The measured and calculated local transient pressure trances for all the test cases refer to Fig. 2; and from the result comparison it can be concluded that:

(1) The IAB model with instantaneous acceleration form could reproduce better the peak amplitudes (envelope) of transient pressure head than the WFB model with complete historical convolution form;

(2) The verified IAB model failed to simulate the oscillating phases/shapes of the signals especially for the flow decelerating process (e.g., the decreasing flow capacity as defined in Eq. (9) and an increasing slope of the pressure head as in Fig. 2);

(3) In the test no. NZ-1, the 2D κ–ε model could produce phase shapes that best match the experimental data compared to the two 1D unsteady friction models (NZ-1(A) and NZ-1(B) in Fig. 2).

The accuracy of each model for the prediction of the local transient pressure envelope can be analyzed based on the LTA method (Ghidaoui et al., 2005; Duan et al., 2012). For this analysis, the error of the amplitude prediction (γ) is calculated based on Eq. (14) and the results are shown in Fig. 3. It is clearly shown that the amplitude prediction error (γ) is progressively increasing with initial hydraulic condition (**Re**) for all 1D models (IAB and WFB as well as the steady friction models). Particularly, for the very high-**Re** flow case (IT-3(B)), the accuracy of the WFB model for predicting the transient pressure envelopes is similar to the quasi-steady friction model (Fig. 3), which indicates that the WFB model could not predict well the unsteady friction damping for highly turbulent flows. Meanwhile, the accuracy of IAB model is also decreasing with both **Re** and time which demonstrates again the limitation of assuming a constant k_d value (which is based on the initial condition only) for modelling the transient process as indicated in previous studies (e.g., Brunone et al., 2004; Storli and Nielsen, 2011a, 2011b). Notwithstanding this, the discrepancies are smaller compared to the WFB and steady friction models,

Fig. 3 is about here

Result analysis by ITE method

To further investigate the different performances of the IAB and WFB models, the ITE method based on Eq. (15) is applied. Based on Eq. (16), the numerical results of friction dissipation rates (steady and unsteady) for the three test cases are calculated and plotted in Fig. 4. The result comparison of Fig. 4 shows that the unsteady model prediction approaches the quasi-steady prediction for larger **Re** and pipe scales (*L*/*D*) and demonstrates that relative importance of unsteady friction is decreasing for large scale systems. This finding is consistent with the previous ones in the literature (Ramos et al. 2004; Duan et al., 2012; and Meniconi et al., 2014). Particularly, for each test case in Fig. 4, the steady component of the dissipation rate in the presence of either IAB or WFB models are very similar (almost constant), which means the inclusion of different unsteady friction models have little influence on the overall steady friction behaviors. With these observations in Fig. 4, it can be concluded the unsteady friction effect becomes less relevant and less important for practical and large scale pipe systems that usually have relative larger values of **Re** and *L*/*D*.

Furthermore, the result of Fig. 4 also reveals that the predicted unsteady dissipation rate by these two types of 1D unsteady friction models are very different from each other in both the amplitude and shape of the signal evolution process. To compare, the unsteady dissipation rates of all the three cases by the IAB and WFB models are plotted in Figs. 5(a) and 5(b) respectively. Particularly, the predicted amplitude of unsteady dissipation rate by the WFB model is almost twice of that by the IAB model for all the cases. However, the evolution of the dissipation and diffusion process (i.e., phase shape of the signals) for the WFB model consists of smoother transitions compared to the IAB model and is the reason for the different phase shapes observed in the local transient pressure head traces in Fig. 2. This result again implies the different effects of the expression forms of the transient behaviors (instantaneous acceleration or historical convolution), even though the key coefficients in these two 1D models are based on similar assumptions (e.g., "frozen" and "two-layer" viscosity).

Fig. 4 is about here

Fig. 5 is about here

Based on the former definitions in Eq. (8) and Eq. (9), the decelerating and accelerating transient flow stages can be demonstrated in principle by the decreasing and increasing intervals respectively of the friction dissipation rates as shown in Figs. 4 and 5. From this perspective, the comparative results in Figs. 4 and 5 show that the two 1D unsteady friction models could result in the negative dissipation rates during the transient deceleration stage, which can never be shown in the steady friction model results. Therefore, during a complete wave period, the total dissipation due to unsteady friction would depend on an integrated effect of both the positive and negative parts of the dissipation rates with regard to wave propagation progress. Meanwhile, as stated in the Section 2, the spatially dependent effect of transient flow and unsteady friction behaviors has been observed and confirmed in previous studies (e.g., Brunone et al., 2004; Storli and Nielsen, 2011a and 2011b). Consequently, a comprehensive comparison based on the total energy analysis for the whole transient system is necessary to further quantify and understand the difference of these two 1D unsteady friction models, which is discussed in the next section.

Energy Analysis and Result Discussion

As indicated in the former problem statement of this study, it is necessary and important to analyze the global transient behaviors by the two 1D unsteady friction models for the whole transient process of the pipe system, in order to understand more details on the difference of these two models and the relevance of the unsteady friction modelling. For this purpose, the energy results based on the ITE evaluation method of Eq. (15) are calculated and shown in Figs. 6 and 7. Note that for convenience, the energy results of Figs. 6 and 7 are normalized by the initial total energy in the test system.

Fig. 6 is about here

Fig. 7 is about here

Overall, the results of Figs. 6 and 7 show more significant energy dissipation by the WFB model than that by the IAB model for all the test cases. Meanwhile, combining the energy evolution results of Figs. 6 and 7 together with the previous analysis of Fig. 5 indicates that:

(1) the instantaneous flow characteristics such as the local acceleration term implemented in the IAB model can mainly affect the amplitude damping of the transient responses by immediate and fast (sharp) change of the unsteady friction effect (unsteady shear stress) (e.g., the sharpen shape of the signals in Fig. 5);

(2) the historical flow behaviors as included in the convolution term in the WFB model, which was described as a “memory” effect in Boltzmann kinetic theory by Chen et al. (2004),

have great influences to the total energy dissipation during the wave propagation process by the gradual and continuous increase of unsteady shear stress for the wave dispersion (e.g., the smoothing shape of the signals in Fig. 5).

To examine this energy variation trend and difference of the two 1D unsteady friction models, the test case NZ-1 is taken for example and the 2D κ–ε model results are used for comparative analysis and shown in Fig. 8. Compared to the 2D κ–ε model results in Fig. 8, both the IAB and WFB models have underestimated the energy dissipation trend after the initial wave period (e.g., 1st wave period of $4L/a$ in Fig. 8).

<u>Fig. 8 is about here</u>

To further explain, the time-domain and frequency-domain results of the unsteady wall shear stress at the mid-length location of the pipeline produced by different unsteady friction models relative to the result by steady friction model are shown in Figs. 9(a) and 9(b) respectively. The time-domain result comparison of Fig. 9(a) indicates that both 1D models could not reproduce the variation of both the magnitude and shape of the unsteady wall shear stress during the transient process. Specifically, it is shown that: (i) the IAB model overestimates the peak amplitude of unsteady wall shear stress for the accelerating flows, and meanwhile underestimates that for the decelerating flow process during each wave period; (ii) the WFB model overestimates the peak amplitude of the unsteady wall shear tress for both the accelerating and decelerating flows, but underestimates the sustaining duration of the generated unsteady wall shear stress in each transient stage. In other words, the WFB model provides over-fast dissipation rate of the formed unsteady wall shear stress due to its "frozen" viscosity distribution assumption used for the whole historical transient process and its continuous influence to the instantaneous (current) wave behaviors. Therefore, according to plots in Fig. 2, the IAB predicted better in the amplitude attenuation, but worse in the phase shape evolution than the WFB model.

Fig. 9 is about here

On the other hand, the frequency domain results of Fig. 9(b) imply clearly the frequency dependence of unsteady friction effect (unsteady wall shear stress) during transient process. This result is consistent with the findings in many previous studies (e.g., Zielke 1968; Vardy and Brown 1995, 2003, 2004). Moreover, compared to the 2D model result in Fig. 9(b), it is shown that these two 1D models have underestimated the unsteady wall shear stress in the low frequency domain (e.g., $\omega/(a/4L) < 10$ in this test case, with $a/4L$ being the fundamental frequency of the pipe system), but overestimated that effect in the relatively high frequency domain (e.g., $\omega/(a/4L) > 10$ in this test case). As indicated similarly in the former time domain results of Fig. 9(a), the difference between the 1D models and 2D model in Fig. 9(b) demonstrates again the inaccuracy of the "frozen" viscosity assumption (WFB model) and the inadequacy of the instantaneous flow influence only (IAB model) for the relatively long-time transients (e.g., large-scale pipeline with relatively low wave frequency). With this understanding, it is necessary in the future work to develop appropriate 1D unsteady friction model that can represent accurately such frequency dependent effect in both low and high frequency domains for transient turbulent flows.

Suggestion and Implication for Model Improvement

Based on the results and analysis above, possible improvements of current 1D unsteady friction formulation and modelling could be made by combining the advantages of both the IAB and WFB models with the indicative information from the 2D model. Particularly, the inclusion of temporal and spatial "memory" effects, such as time- and space-dependent terms of flow condition and system configuration influences (e.g., **Re**, L/D), may be helpful to improve the simulation results of both the amplitude attenuation and the phase shape evolution of the transient responses. In fact, preliminary effort has been taken in recent studies such as Meniconi et al. (2014) and Vardy et al. (2015) to inspect the first aspect in terms of time-dependent flow condition influences to the unsteady friction effect, while the investigation of the second aspect with considering the spatially dependent unsteady friction effect and the combination of both aspects need more future work in this field.

In terms of practical implications to the use and development of unsteady friction models the obtained results may be summarized as follows:

(1) the inclusion of unsteady friction or turbulence models becomes significant and necessary for the transient flow simulations for relatively small scale pipe systems or equivalent small scale pipe systems such as pipe networks with relatively high frequency wave behaviors.

(2) for the extreme pressure strength based design of practical transient pipe systems, the use of IAB model is more preferable to the WFB model, since the IAB model would be more accurate to simulate the maximum and minimum envelopes of transient responses;

(3) for the integrated flowing process based device design of transient pipe systems, such as valve/pump operation, protection equipment (e.g., surge-tank, air-chamber, etc.), the use of WFB model is preferable because it can provide more reliable transient evolution process such as the accumulated amount of total energy and mass in certain wave period and duration.

Summary and Conclusions

This paper investigates the relevance and importance of unsteady friction effect and its modelling for transient pipe flows. The two commonly used 1D unsteady friction models – the instantaneous acceleration based (IAB) model and the weighting function based (WFB) model – have been investigated in this study. Laboratory experiments and field tests as well as extensive 1D and 2D numerical simulations are performed for this investigation with covering a realistic range of both the flow conditions (**Re**) and system scales (L/D). The unsteady friction relevance and models are evaluated systematically by the methods of local transient analysis (LTA) and the integrated total energy (ITE).

The analysis result from the LTA method shows that the importance of unsteady friction effect to the transient envelope attenuation is decreasing with initial flow conditions (**Re**) and pipe scales (L/D), while that from the ITE method reveals that the relevance of unsteady friction to the system energy dissipation is highly dependent on the unsteady friction model used. On the first hand, the results by the LTA indicate that the IAB model, which includes the instantaneous flow characteristics only, could predict better the transient envelope attenuation than transient evolution phase shape; while the WFB model, which implements the historical flow behavior influences, could have a better compromise between the predictions of both the transient amplitude and phase. On the other hand, the results by the ITE imply that both the IAB and WFB models could not predict accurately the total energy relations (amplitude and phase) during transient process. Particularly, both the 1D unsteady friction models can underestimate the unsteady friction effect in the low frequency domain, and may overestimate that effect in the relatively high frequency domain, so that both models would become problematic as they are used for simulating a long-duration transient pipe flow.

The results and findings of this study may provide potential ways for developing and improving further the 1D unsteady friction models, which is necessary and important for both fundamental researches and engineering applications in the future work.

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Table 1 System settings for experimental tests

Test no.	System information	L (m)	D (mm)	a (m/s)	$\mathbf{Re_0}$	Analytical k value	Transient generation
NZ-1	Reservoir-pipe-valve	41.6	72.4	1180	3,130	0.0051	Fast closure of end-valve
IT-2	Pump-check valve-pipe-reservoir	4170	260	1210	27,734	0.0115	Pump failure and fast closure of check valve
IT-3					136,139	0.0067	

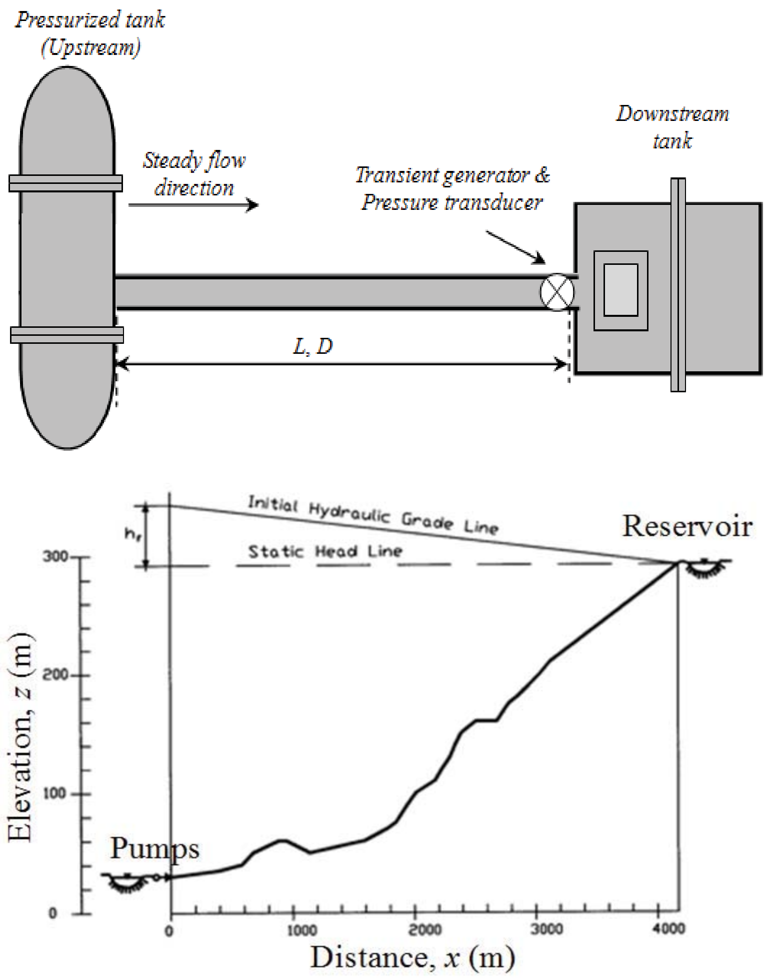

Fig. 1: (a) Sketch of laboratory experimental test pipeline system in the University of Canterbury, New Zealand; (b) Longitudinal section of the pump rising pipeline system in Recanati, Italy

Figure2

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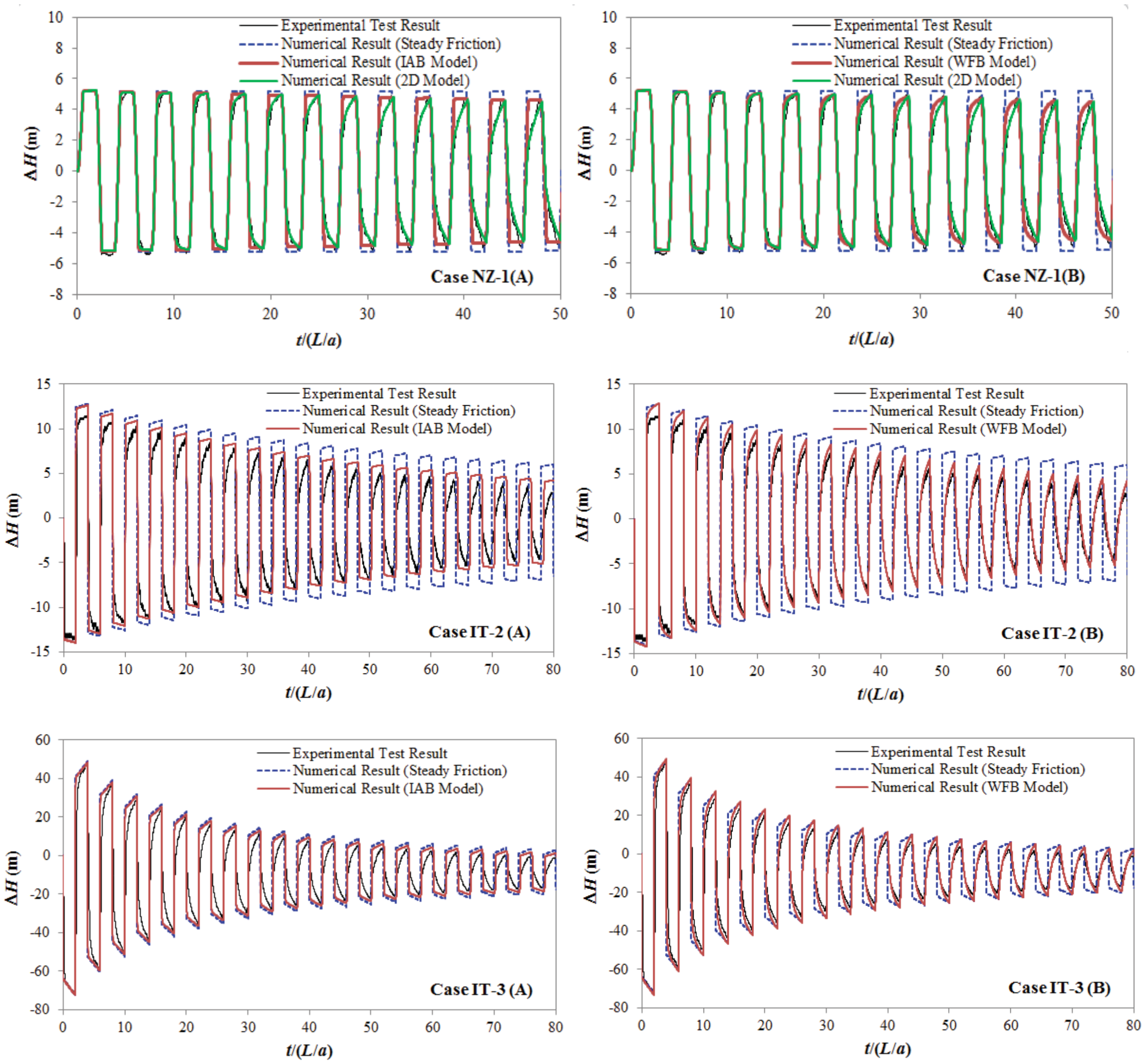

Fig. 2: Results of pressure head traces by experimental tests and different numerical models

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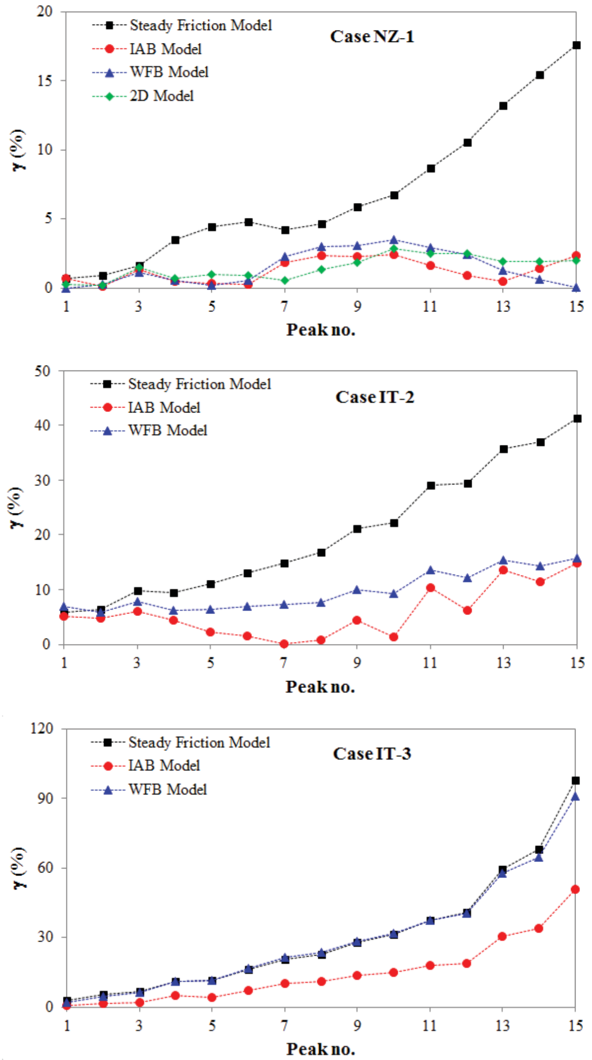

Fig. 3: LTA method: modelling errors (γ) of pressure envelope attenuation by different models

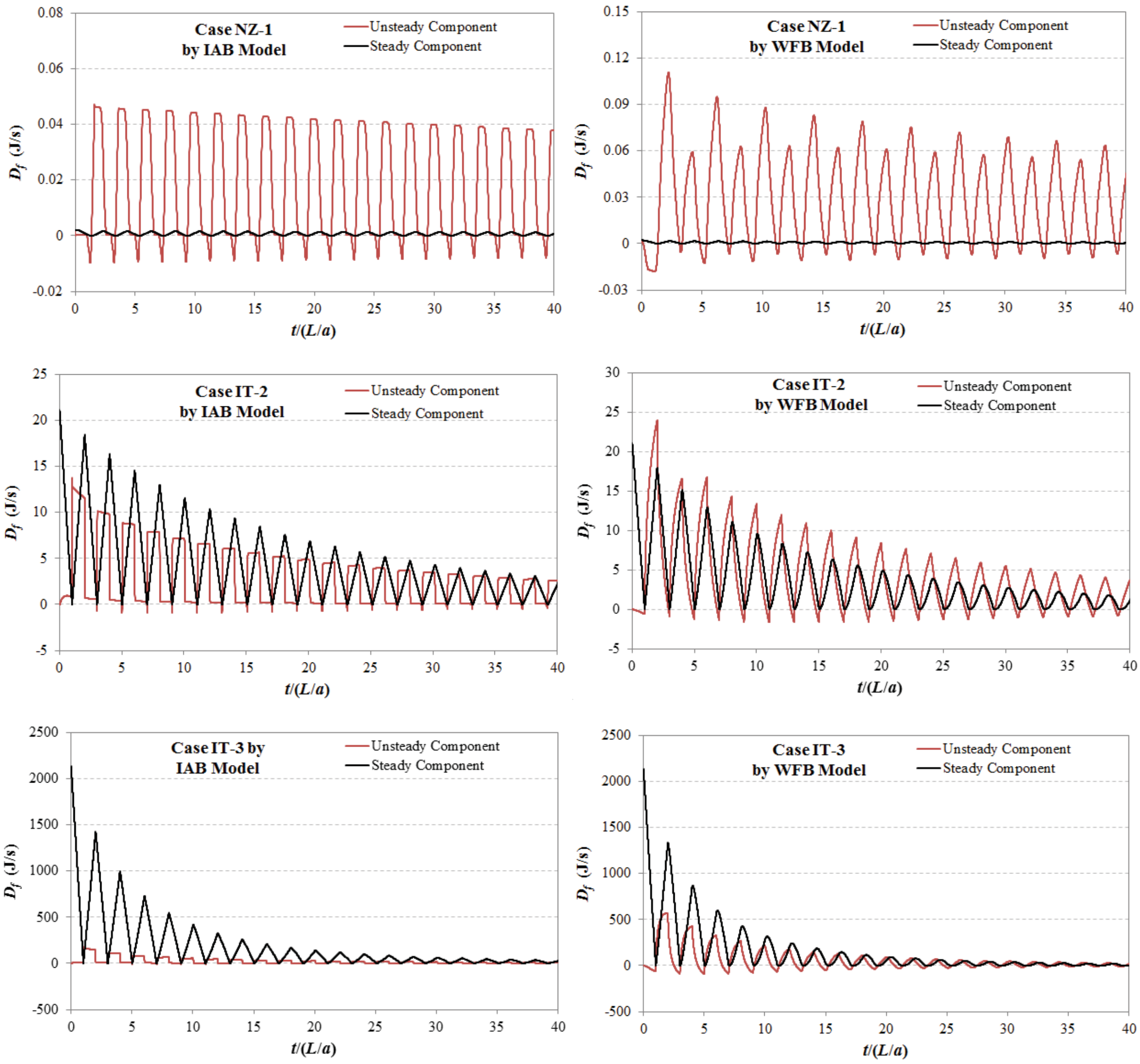

Fig. 4: ITE method: results of steady and unsteady dissipation rates by IAB and WFB models

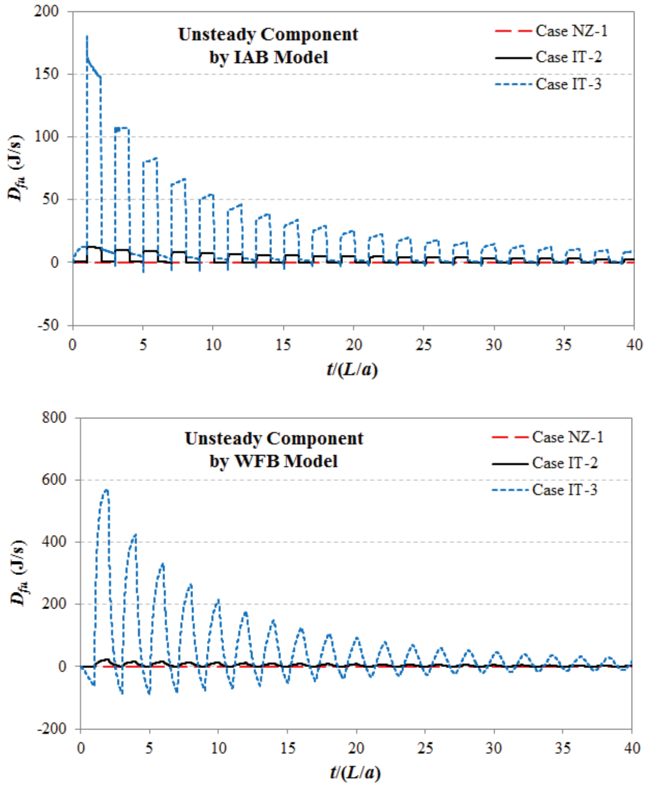

Fig. 5: ITE method: comparison of unsteady friction dissipation rates by IAB and WFB models

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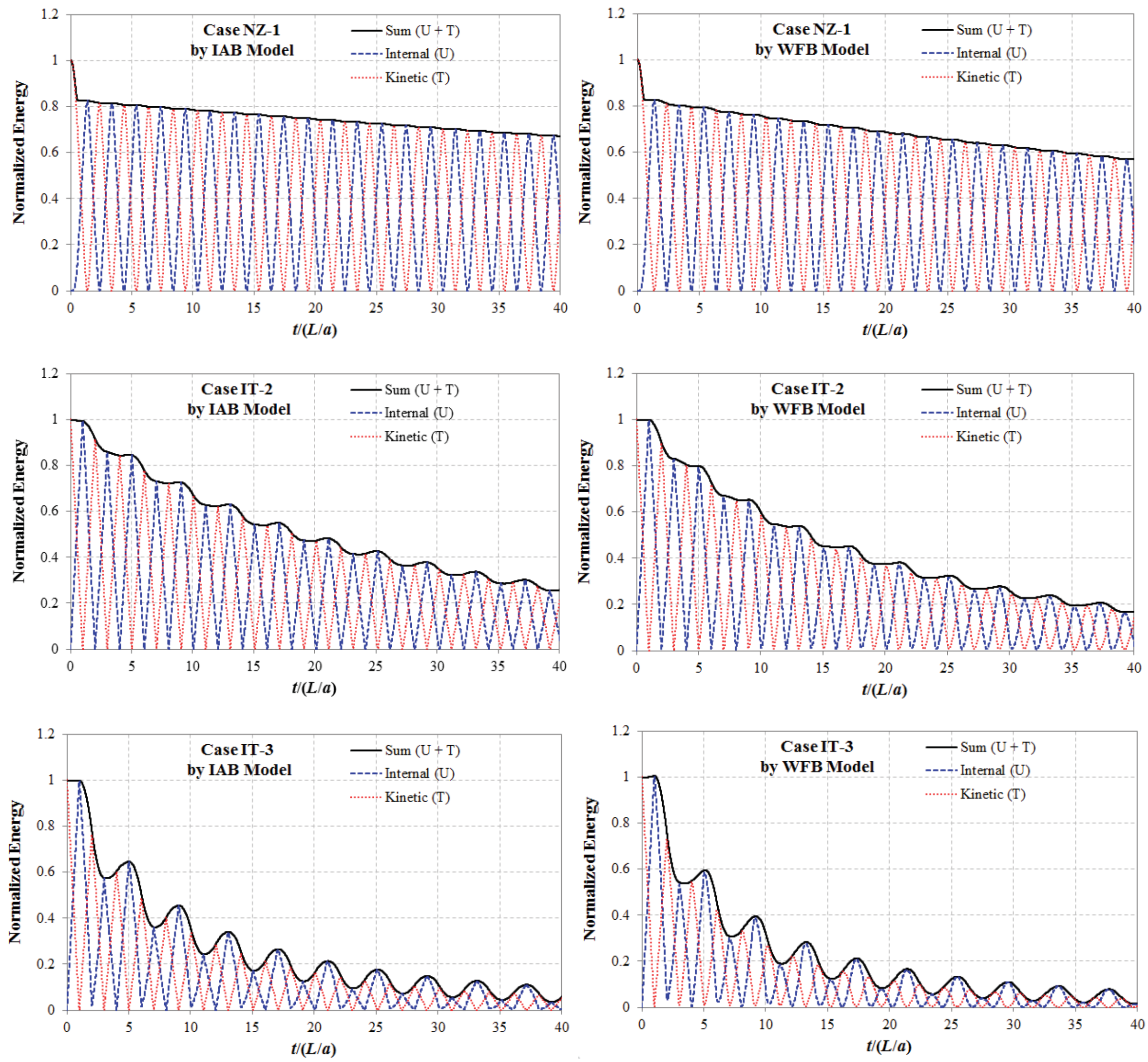

Fig. 6: Variation of different energy forms (normalized by initial total energy in this system) with time by IAB and WFB models

Figure7

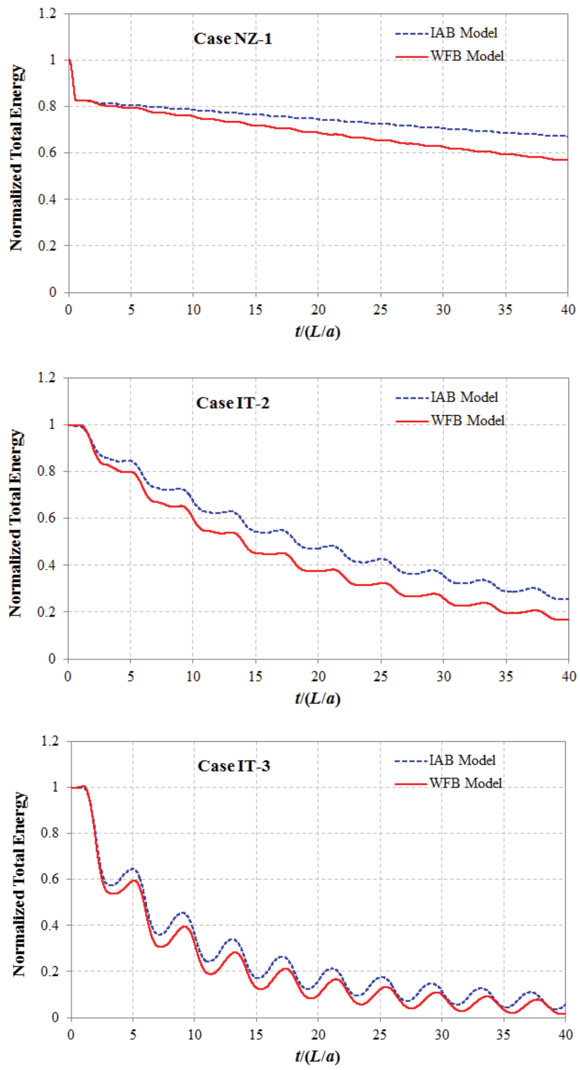

Fig. 7: Comparison of normalized total energy envelope evolutions by different models

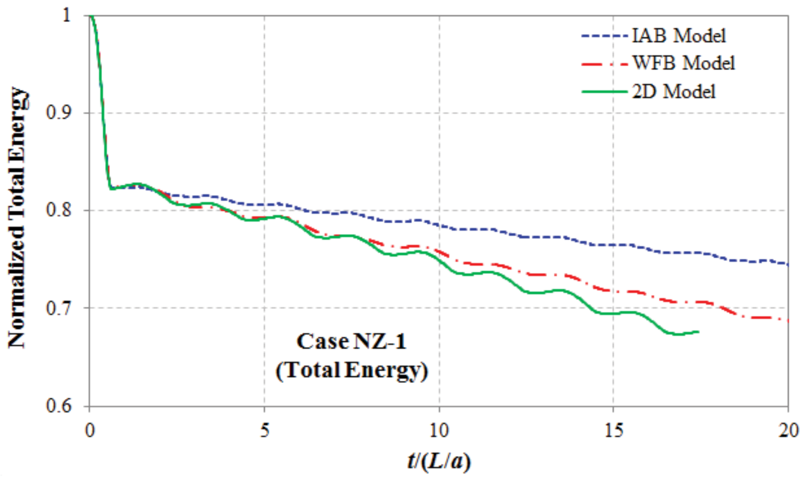

Fig. 8: Result comparison of total energy envelope for test case NZ-1 by different models

Figure9 Click here to download Figure Fig9.pdf

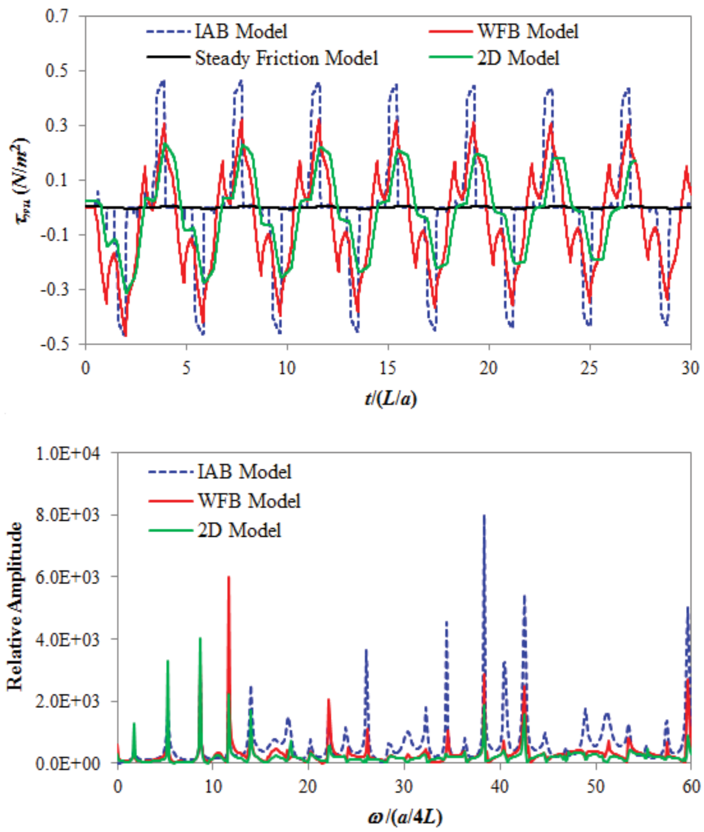

Fig. 9: Comparison of unsteady wall shear stress at mid-length of pipeline by different models for test case NZ-1: (a) Top: results in the time domain; (b) Bottom: results in the frequency domain results with the vertical amplitude normalized by the steady friction result and the axial frequency (ω) normalized by the system fundamental frequency ($a/4L$)

Listing of figure captions

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Fig. 6: Variation of different energy forms (normalized by initial total energy in this system) with time by IAB and WFB models

Fig. 7: Comparison of normalized total energy envelope evolutions by different models

Fig. 8: Result comparison of total energy envelope for test case NZ-1 by different models

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