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

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Abstract: Unsteady friction and its modeling 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 using laboratory experiments and field tests as well as 1D/2D numerical simulations in simple pipeline systems. Realistic ranges of both initial (pretransient) conditions and geometrical characteristics are considered. The data collected in experimental tests are first used to calibrate the unsteady friction models under investigation. 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. DOI: 10.1061/(ASCE)HY.1943-7900.0001304. © 2017 American Society of Civil Engineers.

Author keywords: Unsteady friction; Transient pipe flows; Weighting function-based (WFB) model; Instantaneous acceleration-based (IAB) model; Local transient analysis; Integral total energy.

Introduction

The modeling 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 modeling 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, for example, the action of automatic control devices (Brunone and Morelli 1999), the inadequacy of such a method for simulating the friction term was evident. The problems associated with the standard quasi-steady modeling of pipe friction form the driving force behind the research activity on unsteady friction.

In this context, the Zielke’s (1968) solution 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, $\tau_w$, into two distinct components, as

$$\tau_w = \tau_{wx} + \tau_{wu}$$  \hspace{1cm} (1)

with $\tau_{wx}$ and $\tau_{wu}$ being the quasi-steady and unsteady components of $\tau_w$, respectively. The Darcy-Weisbach equation has been commonly used to model the steady wall shear stress in pipe flows (Chaudhry 1987):

$$\tau_{wx} = \frac{\rho f}{8} V^2$$  \hspace{1cm} (2)

where $\rho$ = fluid (water) density; $f$ = Darcy-Weisbach friction factor; and $V$ = flow velocity. Moreover, Zielke’s (1968) approach—where $\tau_{wu}$ 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 the 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 the (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 the entire waterhammer process. Many experimental, numerical, and 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)–(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 timescale. Once the longitudinal wave propagation time exceeds the radial diffusion timescale, the turbulence structures begin to change and thus the frozen hypothesis loses its validity. That is, the WFB models are expected to progressively lose their 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., Trikha 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 the 1D water-hammer model does not significantly increase computation time compared to those cases using only the steady friction term (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 (∂V/∂t) and characteristic convection (a · ∂V/∂t), where a is wave speed, together with an empirical coefficient (kd) 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 for precalibration 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 the 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 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, b), 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 better understand the situations requiring these models for transient pipe flow simulations. At the same time, it is also essential to assess each type of model for its applicability domain and accuracy with regard to the importance and relevance of the unsteady friction effect. Much effort has been made to inspect and explain accuracy with regard to the importance and relevance of the unsteady friction models for transient flow simulations. At the same time, it is also essential as to better understand the situations requiring these models for 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 were obtained in that study for reproducing the transient pressure envelope attenuation, especially for highly turbulent flows. Similar to previous studies, their study only considered local transient pressure responses, and the results and findings obtained are mainly limited to the localized section/region of the pipeline system. Thus, the results may not be applicable to characterize a 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 explained in detail in the following section.

To further understand the unsteady friction effect, it is worth investigating 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, a 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 the 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
the 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; 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 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. The first type, the weighting function-based (WFB) model, is expressed as (e.g., Zielke 1968; Vardy and Brown 1995)

\[ \tau_{wu} = \frac{4 \rho \eta_k}{DA} \int_0^t W(t-t') \frac{\partial Q(t')}{\partial t'} dt' \]  

(8a)

where \( W(t) \) = weighting function and \( t' \) = dummy time variable. 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.

The second type, the instantaneous acceleration-based (IAB) model, is given as (e.g., Brunone et al. 1995; Bergant et al. 2001)

\[ \tau_{wu} = k \rho D \frac{\partial Q}{\partial t} + \text{sign}(Q) \cdot a \left| \frac{\partial Q}{\partial x} \right| \]  

(8b)

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

 Particularly, in the water-hammer literature (e.g., Daily et al. 1956; Vardy and Brown 1995; Ghidaoui et al. 2002, 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

\[ \text{sign}(Q) \frac{\partial Q}{\partial x} \begin{cases} > 0 & \text{acceleration} \\ < 0 & \text{deceleration} \end{cases} \]  

(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):

\[ k_d = 5.44R^{0.5}\log(14.3/R^{109}) \]  

(10)

where \( R = \frac{Q_0 D}{\sqrt{4gh}} \) 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 (R). 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 \( \kappa - \varepsilon \) Turbulence Model

A formula is required for describing the turbulent shear stress in Eq. (5) to close the 2D transient model in Eqs. (3) and (4). In this study, the two-equation-based 2D \( \kappa - \varepsilon \) 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)

\[ \nu_t = C_{\mu}f_\mu \frac{\kappa^2}{\varepsilon} \]  

(11)

where \( C_{\mu}, f_\mu = \) coefficients and \( \kappa, \varepsilon = \) turbulent kinetic energy and dissipation rate, respectively, and can be calculated by the following equations:

\[ \begin{align*}
\frac{\partial \kappa}{\partial t} & = \frac{1}{r \partial r} \left[ r \left( \nu_k + \frac{\nu_t}{\sigma_k} \right) \frac{\partial \kappa}{\partial r} \right] + \nu_t \left( \frac{\partial \nu_t}{\partial r} \right) \frac{\partial \varepsilon}{\partial r} - \varepsilon \\
\frac{\partial \varepsilon}{\partial t} & = \frac{1}{r \partial r} \left[ r \left( \nu_k + \frac{\nu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial r} \right] + \nu_t C_{\varepsilon} f_\varepsilon \left( \frac{\partial \nu_t}{\partial r} \right) \frac{\partial \nu_t}{\partial \varepsilon} - C_{\varepsilon} f_\varepsilon \frac{\varepsilon^3}{\kappa}
\end{align*} \]  

(13)

where \( f_w = 1.0 - \exp \left\{ - \left( \frac{\sqrt{230}}{8.89} \right) + \frac{\sqrt{230} - R_y}{8.89} \right\} \times \left\{ 1 - \exp \left( \frac{R_y}{20} \right) \right\}^3 ; \quad R_y = \sqrt{\frac{230}{\nu_k}} ; \quad y = \frac{D}{2} - r ; \quad f_2 = f_w^2 \left\{ 1.0 - 0.22 \exp \left[ \left( \frac{R_y}{6} \right)^2 \right] \right\} ; \quad f_\mu = 0.4 \frac{f_w}{\sqrt{\kappa}} \left( 1 - 0.4 \frac{f_w}{\sqrt{\kappa}} \right) \left[ 1 - \exp \left( - \frac{R_y}{42.63} \right) \right] ^3 ; \quad R_y = \frac{\kappa^2}{\nu_k \varepsilon} ; \quad C_{\mu} = 0.09 ; \quad \sigma_k = 1.0 ; \quad \sigma_\varepsilon = 1.3 ; \quad C_{\varepsilon_1} = 1.39 ; \quad C_{\varepsilon_2} = 1.80 ; \quad f_1 = 1.0 ; \quad C_{\varepsilon_2} = 1.80.

Previous studies of Zhao and Ghidaoui (2006) and Duan et al. (2010, 2012) have successfully incorporated the 2D \( \kappa - \varepsilon \) turbulence model in the water-hammer system. Eqs. (3) and (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 \( \kappa - \varepsilon \) 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.
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 \( U = U(t) \) = total internal energy in the system; \( T = T(t) \) = total kinetic energy in the system; \( D_f = D_f(t) = D_f(s) + D_f(u) \) = total rate of frictional dissipation, with \( D_f(s) \) and \( D_f(u) \) being the steady and unsteady components, respectively; \( W_E = W_E(t) \) = total rate of work from the pipe wall (e.g., viscoelastic 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 \( L = \) 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 are given in the recent publications from the authors (Duan et al. 2013; 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, \( R \), in the order of \( 10^3, 10^4, \) and \( 10^5 \), respectively, covering a typical range of flow conditions in practical water supply pipelines.

### Table 1. System Settings for Experimental Tests

<table>
<thead>
<tr>
<th>Test number</th>
<th>System information</th>
<th>( L ) (m)</th>
<th>( D ) (mm)</th>
<th>( u ) (m/s)</th>
<th>( R )</th>
<th>Analytical ( k ) value</th>
<th>Transient generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NZ-1</td>
<td>Reservoir-pipe-valve</td>
<td>41.6</td>
<td>72.4</td>
<td>1.180</td>
<td>3,130</td>
<td>0.0051</td>
<td>Fast closure of end valve</td>
</tr>
<tr>
<td>IT-2</td>
<td>Pump-check</td>
<td>4,170</td>
<td>260</td>
<td>1,210</td>
<td>27,734</td>
<td>0.0115</td>
<td>Pump failure and fast</td>
</tr>
<tr>
<td>IT-3</td>
<td>valve-pipe-reservoir</td>
<td>136,139</td>
<td></td>
<td></td>
<td></td>
<td>0.0067</td>
<td>closure of check valve</td>
</tr>
</tbody>
</table>

![Fig. 2. Results of pressure head traces by experimental tests and different numerical models](image-url)
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 the field test system in Italy) are plotted as the solid black 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/α). In the Italian test system, because of the crucial role played by boundary conditions in transient simulation, the actual time behavior of the discharge at the pump, Qp, 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 Qp = 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 Δk 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.

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 the postfix A and B in the title of subfigures for each case. Meanwhile, the results by quasi-steady friction modeling (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, the local transient analysis (LTA) method and integral total energy (ITE) method.

Result Analysis by LTA Method

The measured and calculated local transient pressure traces for all the test cases refer to Fig. 2, and from the result comparison the following can be concluded:

1. The IAB model with instantaneous acceleration form could better reproduce the peak amplitudes 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]; and
3. In test 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 the initial hydraulic condition (R) for all 1D models (IAB and WFB as well as the steady friction models). Particularly, for the very high-R 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 R and time, which demonstrates again the limitation of assuming a constant kε value (which is based on the initial condition only) for modeling the transient process as indicated in previous studies (e.g., Brunone et al. 2004; Storli and Nielsen 2011a, b). Notwithstanding this, the discrepancies are smaller compared to the WFB and steady friction models.

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 R 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; 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 that the unsteady friction effect becomes less relevant and less important for practical and large-scale pipe systems that usually have relative larger values of \( R \) 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 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).

Based on the former definitions in Eqs. (8) and (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 the wave propagation progress. Meanwhile, as stated earlier, 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, b). 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 modeling. 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.

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 the following:

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); and

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 $\kappa - \varepsilon$ model results are used for comparative analysis and shown in Fig. 8. Compared to the 2D $\kappa - \varepsilon$ 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).

To further explain, the time-domain and frequency-domain results of the unsteady wall shear stress at the midlength 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 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 (1) 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; and (2) the WFB model overestimates the peak amplitude of the unsteady wall shear stress 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 an 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.

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 the 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 a frequency-dependent effect in both the low-frequency and high-frequency domains for transient turbulent flows.

**Suggestion and Implication for Model Improvement**

Based on the results and preceding analysis, possible improvements of current 1D unsteady friction formulation and modeling 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-dependent and space-dependent terms of flow condition and system configuration influences (e.g., $R$, $L/D$), may be helpful to improve the simulation results of both the amplitude attenuation and the phase shape evolution of the transient responses. In fact, a 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; and

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 the unsteady friction effect and its modeling 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 paper. 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 ($R$) 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 $(R)$ 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 one 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 the 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 research and engineering applications in the future work.

Acknowledgments

This research was supported by the research grants from (1) the Hong Kong Polytechnic University (HKPU) under the projects 1-ZVCD, 1-ZVGF and 3-RB; (2) the Hong Kong Research Grant Council (RGC) under the projects no. T21-602/15-R and no. 252006/16; (3) the University of Perugia; and (4) the Royal Society of New Zealand (Marsden Grant M1153).

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04017015-10

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