Advanced Numerical and Experimental Transient Modelling of Water and Gas Pipeline Flows Incorporating Distributed and Local Effects

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Thesis for Doctor of Philosophy (PhD)
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July 2008

CHAPTER 9

THE EFFECT OF VISCOELASTIC PIPES ON TRANSIENT PIPE FLOWS

Changes of pipe wall condition may affect the magnitude, phase, and shape of pressure wave propagation along pipeline systems during a transient event. The geometrical changes of an inside pipe can be predicted by the proper use of orifice and blockage models as mentioned in the previous chapter. However, the changes of the pipe material should be determined by the mechanical behaviour of the material on transient events. Most transient analysis models use the assumption of linear-elastic behaviour of the pipe wall. Linear-elastic model is relatively accurate for describing hydraulic transients in metal or concrete pipes. However, recent tests in water distribution pipe networks show significant viscoelastic behaviour due to soil-pipe interaction, flexible pipe joints and/or household water service pipes. In addition, polymer pipes, especially polyethylene pipes, have been increasingly used in the water and gas industry due to their low price, cost-effective installation methods and high resistant properties against corrosion. The viscoelastic behaviour of polymers influences the pressure response during transient events by attenuating the pressure fluctuations and by increasing the dispersion of the pressure wave. A mechanical strain principle model (spring-dashpot element model) may be used to describe this viscoelastic behaviour. The total strain can be decomposed into an instantaneous and a retarded wall strain. The instantaneous wall strain is analysed by a linear-elastic model in the basic equations. In this research, a viscoelastic model has been added to the linear-elastic model in the conservative solution scheme. Unlike the traditional waterhammer model, the developed transient model is capable of accurately predicting transient pressure waves both where the entire pipeline is plastic and in a pipeline with a local plastic section. This chapter focuses on the analysis of hydraulic transients in a pressurised pipeline system with a local polyethylene pipe component and presents a number of experimental results illustrating how a localised plastic pipe section affects the pressure wave in a copper pipe system.

9.1 ADVANTAGES OF POLYETHYLENE PIPE

Polyethylene has grown to become one of the world's most widely used and recognized thermoplastic polymer materials, since its discovery in 1933, because of the diversity of its use [PPI, 2006]. The original application for polyethylene was as a substitute for rubber. Today's modern polyethylene resins are highly engineered for much more rigorous applications such as pressure-rated gas and water pipe. Polyethylene's use as a piping material was first developed in the mid 1950's. Its original use was in oil field production where a flexible, tough, and lightweight piping product was needed to fulfil the needs of a rapidly developing oil and gas production industry. The success of polyethylene pipe in these installations quickly led to its use in natural gas and water distribution systems where a coilable corrosion-free piping material could be fusion joined in the field to assure a leak-free method of transporting products to homes and businesses. Now in North America, nearly 95% of all new gas distribution pipe installation for 12 inch in diameter or smaller are polyethylene pipe [PPI, 2006]. The performance benefits of polyethylene pipe in oil and gas related applications have led to its use in equally demanding piping installations such as water distributions, industrial and mining pipes, marine pipes and other critical applications where a tough and ductile material is needed to assure long-term performance.

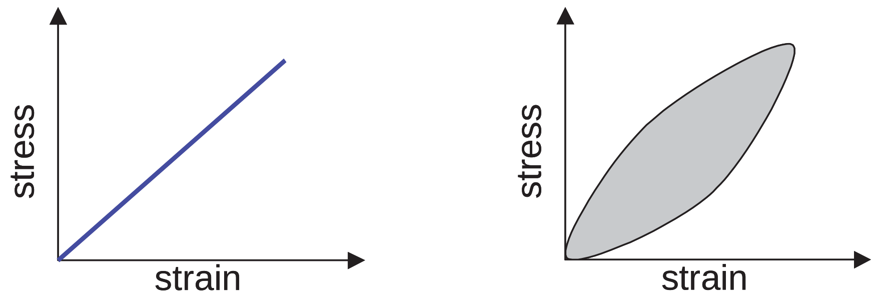
The major reasons for the growth in the use of the plastic pipe, especially polyethylene pipe, are the cost savings in installation, labor and equipment, the lower maintenance costs, and increased service life as compared to traditional piping materials. According to the plastics pipe institute [PPI, 2006], some of the specific benefits of polyethylene pipe (PE) are introduced in the below.

1) ***Life Cycle Cost Savings***: The life cycle cost of PE pipe can be significantly less than other pipe materials. The extremely smooth inside surface of PE pipe maintains its exceptional flow characteristics.

2) ***Leak Free, Fully Restrained Joints***: PE heat fusion joining forms leak-free joints as strong as, or stronger than, the pipe itself. Fused joints can significantly reduce the potential leak points that exist every 10 to 20 feet when using the bell and spigot type joints associated with other piping products such as polyvinyl chloride (PVC) or ductile iron.
3) ***Corrosion and Chemical Resistance***: PE pipe will not rust, rot, pit, corrode, or tuberculate. It has superb chemical resistance.
4) ***Fatigue Resistance and Flexibility***: PE pipe can be field bent to a radius of 30 times the nominal pipe diameter or less depending on wall thickness. This eliminates a lot of the fittings otherwise required for directional changes in piping systems. PE has exceptional fatigue resistance when operating at maximum pressure. It can withstand multiple surge pressure events up to 100% above its maximum operating pressure without any negative effect to its long-term performance capability.
5) ***Seismic Resistance***: The natural flexibility of PE pipe makes it well suited for installation in dynamic soil environments and in areas prone to earthquakes or other seismic activity.
6) ***Construction Advantage***: The combination of light weight, flexibility, fully restrained joints permits considerable time saving and cost-effective installation methods, such as horizontal directional drilling, pipe bursting, slip-lining, plow and plant, and submerged or floating pipe. It does not need heavy lifting equipment because of approximately one-eighth the weight of comparable steel pipe. PE pipe can be produced over 1,000 feet coiled lengths in certain diameters.
7) ***Durability***: The polyethylene pipe industry estimates a service life for PE pipe to be 50-100 years.
8) ***Hydraulic Efficiency***: The friction factor for other typical pipe materials declines dramatically over time due to corrosion and tuberculation. However, for water applications, the PE pipe maintains its smooth interior wall and its flow capabilities to insure hydraulic efficiency over the intended design life because of their excellent corrosion and chemical resistance.
9) ***Temperature Resistance***: PE materials retain greater strength at elevated temperatures or cold weather installations compared to other thermoplastic materials such as PVC.

9.2 MECHANICAL PROPERTIES OF PLASTIC PIPE

In the case of metal pipes, the conventional tensile test is relied upon to define basic mechanical properties such as elastic strength, proportional limit and yield strength. These are important for defining and specifying the pipe material. There are also basic constants for use in the many design equations that have been developed based upon elastic theory, where strain is always assumed to be proportional to stress. With plastics there is no such proportionality. The relationship between stress and strain of plastic material is greatly influenced by duration of loading and temperature. The stress-stain response shows hysteresis with the area of the loop being equal to the energy lost during the loading cycle in Fig. 9.1b, even though near the origin there might appear to be an essentially linear response. Plastics have no true elastic constants, nor do they have sharply defined yield points. The values of moduli of plastic materials derived from tensile tests only represent the initial portion of the stress-strain curve.



(a) Purely Elastic Material **(b) Viscoelastic Material**

Figure 9.1 Stress-Strain Relationship

9.2.1 Viscoelasticity

Plastic pipe is a viscoelastic material that exhibits both viscous and elastic characteristics due to its molecular nature when undergoing deformation. Unlike purely elastic substances, a viscoelastic substance is a complex combination of elastic-like and fluid-like (amorphous) elements that displays properties of crystalline metals and very highly viscosity fluids. The viscosity of a viscoelastic substance gives the substance a strain rate that is dependent on time. Purely elastic materials do not dissipate energy when a load is applied, and then removed. However, viscoelastic materials lose energy during loading and unloading cycle because viscosity is the resistance to activate the deformation. [Meyers and Chawla, 1998].

The properties of crystalline metals primarily account for the elastic response to stress, in which elastic materials strain instantaneously when stretched and just as quickly return to their original state once the stress has been removed (the result of bond stretching along crystallographic planes in an ordered solid), whereas the amorphous properties of a vicsoelastic material account for the very high viscosity fluid-like response (the result of the diffusion of molecules). The overall mechanical response to applied stress is called viscoelastic since it lies between these two types of behaviour [Ferry, 1970].

The viscoelastic nature of a polymer results in two unique engineering characteristics, including creep and stress relaxation. These aspects are employed in the design of liquid piping systems. Creep is the time-dependent viscous flow component of deformation. It refers to the response of polyethylene, over time, to a constant static load. When a polymer pipe is subjected to a constant static load, it deforms immediately to a strain predicted by the stress-strain modulus determined from the tensile stress-strain curve. At high loads, the material continues to deform at an ever decreasing rate of the load [PPI, 2006]. Stress relaxation is another unique property arising from the viscoelastic nature of polymer. When subjected to a constant strain that is maintained over time, the deformation generated by load or stress slowly decreases over time. Stress relaxation describes how polymers relieve stress under constant strain [Aklonis et al., 1972; Miller, 1996].

Purely elastic materials show an immediate deformation after the application of a sudden increase in stress and an immediate reformation after removal of the stress. For viscoelastic samples, this elastic behaviour occurs with a certain time delay. To evaluate this time-dependent deformation behaviour, two parameters have been defined, relaxation time and retardation time. Relaxation is the process in a state at rest after a forced deformation. On the other hand, the term “retardation time” is used for tests when presetting the stress and when performing creep tests. Retardation is the delayed response to an applied force or stress and can be described as delay of the elasticity [Mezger and Westphal, 2006]. The response of viscoelastic pipe systems to loading is time-dependent. The effective modulus of elasticity can be significantly reduced according to the duration of the loading because of the creep and stress relaxation characteristics of polymer. The time-dependent moduli according to retardation time are a key criterion for the design of polyethylene pipe systems.

9.2.2 Linear Viscoelastic Models

Viscoelastic models have been developed to determine stress-strain interactions and temporal dependencies of viscoelastic materials. There are two types of viscoelasticity from the point of modelling. One is linear viscoelastic model when the function is separable in both creep response and load. It is usually applicable for small deformations. Another is a nonlinear viscoelastic model where the function is not separable and the deformations are large. For the large deformations, geometrical non-linearity should be included. This research focuses on linear viscoelastic models for plastic pipe having relatively small deformations.

Linear viscoelastic models, which can be expressed by the Maxwell model, Kelvin-Voigt model, Standard Linear Solid model, and Generalized model [Miller, 1996; Ram, 1997; McCrum et al., 1997], are based on the mechanical principle associated with viscoelasticity. For these cases, the viscoelastic behaviour is comprised of elastic and viscous components modelled as linear combinations of Hookean springs having different spring constants and Newtonian dashpots containing different viscosity fluids, respectively. The spring is used to demonstrate ideal elastic behaviour. The deformation of the spring is directly proportional to the force needed to pull the spring and purely elastic materials return to their original length when the load is removed as shown in Fig. 9.1a. This relationship is similar to the Hooke's Law (linear elastic relationship between stress and strain).

$$\sigma = E\varepsilon \tag{9.1}$$

where σ is the stress, E is the elastic modulus of the material, and ε is the strain that occurs under the given stress. A dashpot can be used to represent the behaviour of viscous material. When a force is applied to pull the dashpot, the amount of deformation (strain) is independent of the force but proportional to the velocity at which the force is applied. The dashpot will not return to its original position once the force is released. The stress-strain relationship in the dashpot is given as

$$\sigma = \eta \frac{d\varepsilon}{dt} \tag{9.2}$$

where η is the viscosity of the material and $d\varepsilon/dt$ is the time derivative of strain. By combining various numbers of springs and dashpots, the stress-strain relationships for different plastics can be approximated. The temperature also affects the strain. For a given stress level and time, a higher temperature increases the strain.

1) Maxwell Model

Viscoelastic behaviour can be modelled by a purely elastic spring (Hookean spring) and viscous dashpot (Newtonian dashpot) connected in series known as the Maxwell model as shown in Fig. 9.5a. The stresses in both elements will be identical. This model represents a fluid-like material with additional elastic (reversible) deformations. The total deformation is not reversible. Under an applied axial stress, the total stress and total strain can be defined as follows

$$\begin{aligned} \sigma_{Total} &= \sigma_D = \sigma_S \\ \varepsilon_{Total} &= \varepsilon_D + \varepsilon_S \end{aligned} \tag{9.3}$$

where the subscript D indicates the strain in the dashpot and the subscript S indicates the strain in the spring. Taking the derivative of strain with respect to time, the relationship between stress and strain can be defined as follows

$$\frac{d\varepsilon_{Total}}{dt} = \frac{d\varepsilon_D}{dt} + \frac{d\varepsilon_S}{dt} = \frac{\sigma}{\eta} + \frac{1}{E}\frac{d\sigma}{dt} \tag{9.4}$$

If a material is put under a constant strain, the stress gradually relaxes. If a material is put under a constant stress, the strain has two components, elastic and viscous components as previously mentioned. The Maxwell model predicts that the stress decays exponentially with time, which is accurate for most polymers. However, it is unable to predict creep in materials based on a dashpot and a spring connected in series. Although this model is inadequate for quantitative correlation of polymer properties, it provides a good qualitative description of linear viscoelastic behaviour [McCrum et al., 1997; Rodriguez, 1982].

The behaviour of this model is considered in creep and stress relaxation. When a fixed stress σ_0 is applied to a material at an initial state, we can find the deformation as a function of time. With constant stress in the spring, ε_S is constant and $d\varepsilon_S /dt = 0$.

$$\frac{d\varepsilon_{Total}}{dt} = \frac{d\varepsilon_D}{dt} + \frac{d\varepsilon_S}{dt} = \frac{\sigma_0}{\eta} \tag{9.5}$$

By integrating Eq. 9.5, we obtain the deformation as function of time.

$$\varepsilon(t) = \varepsilon_0 + \frac{\sigma_0 t}{\eta} = \sigma_0\left(E^{-1} + \frac{t}{\eta}\right) \tag{9.6}$$

Eq. 9.6 is useful to express results as a time-dependent compliance $J(t) = \varepsilon(t)/\sigma_0 = E^{-1} + t/\eta$. On the other hand, when a fixed deformation ε_0 is applied at initial state and held, we can find stress as a function of time.

$$\frac{d\varepsilon_{Total}}{dt} = \frac{d\varepsilon_D}{dt} + \frac{d\varepsilon_S}{dt} = \frac{\sigma}{\eta} + \frac{1}{E}\frac{d\sigma}{dt} = 0 \tag{9.7}$$

By integrating Eq. 9.7, the time-dependent modulus can be defined as

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} = Ee^{-Et/\eta} \tag{9.8}$$

The term η/E, the relaxation time, is the reciprocal of the rate at which stress decays. The linear viscoelastic region corresponds to $E(t)$ being independent of ε_0 [Rodriguez, 1982]. Fig. 9.2 shows the creep and stress relaxation diagrams of Maxwell material model. When the stress is removed, only the deformation of the spring is recovered. The dashpot retained permanent deformation.

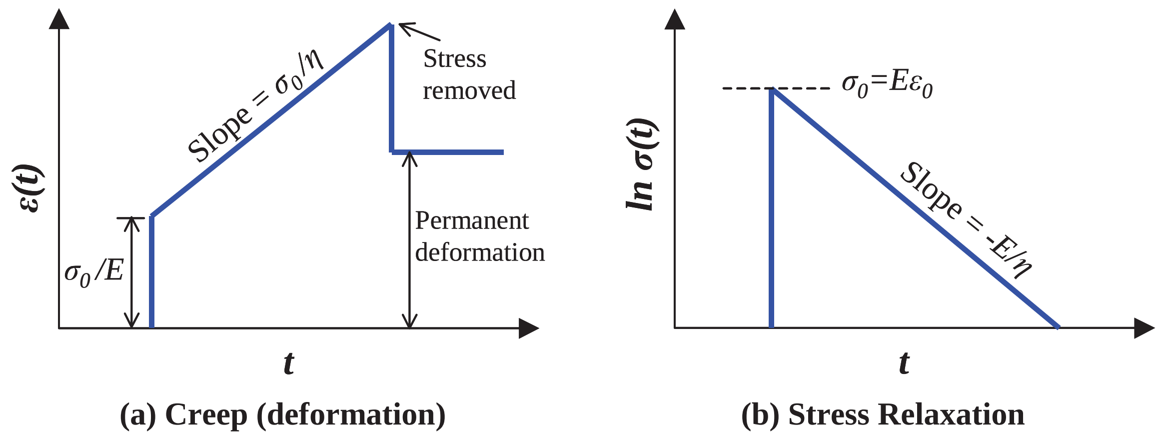


Figure 9.2 Creep and Stress Relaxation Diagrams of Maxwell Material Model

2) Kelvin-Voigt Model

Kelvin-Voigt model can be represented by a purely viscous damper and elastic spring connected in parallel as shown in Fig. 9.5b. This model represents a solid material with reversible process of deformation when considering a longer duration, rather than a very short time. The strains in each component are identical and the total stress is the sum of the stresses in each component because two components are arranged in parallel.

$$\begin{aligned} \sigma_{Total} &= \sigma_D + \sigma_S \\ \varepsilon_{Total} &= \varepsilon_D = \varepsilon_S \end{aligned} \tag{9.9}$$

The stress-strain relationship is expressed as a linear first-order differential equation that can be applied to either to the shear stress or normal stress of a material.

$$\sigma(t) = E \cdot \varepsilon(t) + \eta \frac{d\varepsilon(t)}{dt} \tag{9.10}$$

If we suddenly supply a constant stress σ_0 to the viscoelastic material, the deformation would approach the deformation for a purely elastic material σ_0/E with the difference decaying exponentially.

$$\varepsilon(t) = \frac{\sigma_0}{E}(1 - e^{-\lambda t}) \tag{9.11}$$

where t is the relaxation time and λ ($=E/\eta$) is the rate of relaxation. Fig. 9.3 shows the dependence of dimensionless deformation $E \cdot \varepsilon(t)/\sigma_0$ on the dimensionless time λt. For a partially liquid viscoelastic material, a certain extent of deformation still remains permanently even after removing a stress. This value represents the viscous portion. Both concentrated polymer solutions and polymer melts show this behaviour. The load cycle is an irreversible process. For a completely solid viscoelastic material, the deformation is delayed but completely reformed if the period of testing is sufficiently long. The load cycle is a reversible process because the shape of material will be the same finally when compared to the initial shape [Mezger and Westphal, 2006].

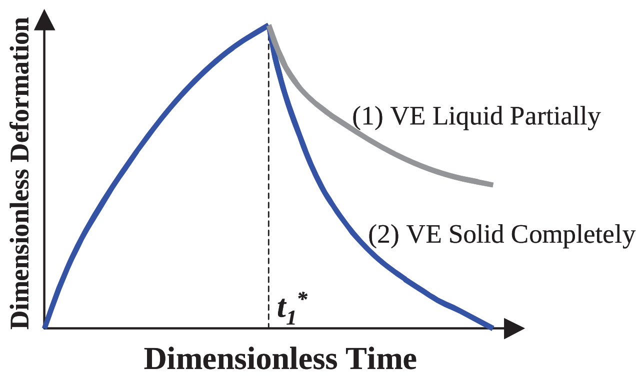


Figure 9.3 Creep and Creep Recovery of Kelvin-Voigt Material

When the solid material is unloaded at time dimensionless time t_1^*, the elastic element retards the material back until the deformation becomes zero. The retardation obeys the following equation.

$$\varepsilon(t > t_1^*) = \varepsilon(t_1^*) e^{-\lambda t} \tag{9.12}$$

Although Kelvin-Voigt model is not good at describing the relaxation behaviour after the stress is removed, it is effective for predicting the creep in the material when contrasted to the Maxwell model because of reversible process ($\lim \varepsilon_{(t \to \infty)} = \sigma_0/E$) of deformation on long time duration [Meyers and Chawla, 1998].

3) Standard Linear Solid Model

This model is the combination of the Maxwell model and Kelvin-Voigt model involving elements both in series and in parallel as shown in Fig. 9.5c. This alternative is introduced as the Maxwell model does not describe creep and Kelvin-Voigt model does not effectively predict stress relaxation. The standard linear solid model is the simplest model that predicts both creep and stress relaxation. Fig. 9.4 shows the creep response of standard linear solid model. The process is a combination of creep responses of both the Maxwell model (shown in Fig. 9.2a) and the Kelvin-Voigt (shown in Fig. 9.3) model.

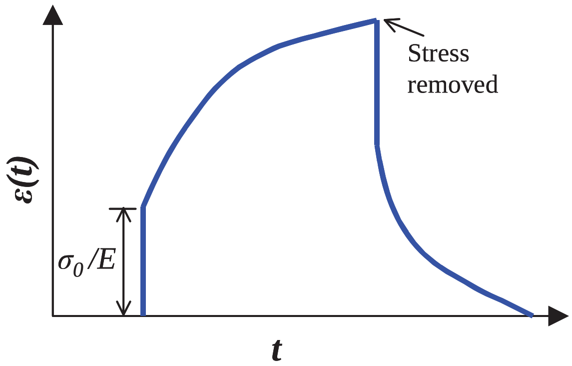


Figure. 9.4 Creep Response of Standard Linear Solid Material Model

The total stress and total strain in the overall system are expressed by Maxwell model as referred by subscript *M*.

$$\begin{aligned}
\sigma_{Total} &= \sigma_M + \sigma_{S1} \\
\varepsilon_{Total} &= \varepsilon_M = \varepsilon_{S1} \\
\sigma_M &= \sigma_D = \sigma_{S2} \\
\varepsilon_M &= \varepsilon_D + \varepsilon_{S2}
\end{aligned} \tag{9.13}$$

The stress-strain relationship is expressed as follows

$$\frac{d\varepsilon}{dt} = \frac{\dfrac{E_2}{\eta}\left(\dfrac{\eta}{E_2}\dfrac{d\sigma}{dt} + \sigma - E_1\varepsilon\right)}{E_1 + E_2} \tag{9.14}$$

Although the standard linear solid model can be used to accurately predict the general shape of the strain curve for viscoelastic materials as well as behaviour for long time and instantaneous loads, the model shows inaccurate results for strain under specific loading conditions.

4) Generalized Maxwell or Kelvin-Voigt Model

The Maxwell and Kelvin-Voigt models assume that a single relaxation time and creep governs the response of the material to a mechanical perturbation. However, there exists experimental evidence of a distribution of relaxation or creep, which may be considered either discrete or continuous. It is possible to generalize the Maxwell or Kelvin-Voigt models so that they more closely represent the actual behaviour of viscoelastic materials [Riande et al., 2000]. These generalizations can be carried out by assuming an arrangement of Maxwell elements in parallel or Kelvin-Voigt elements in series as shown in Figs. 9.5d and 9.5e.

The Maxwell model can be generalized by the concept of a distribution of relaxation times so that it becomes adequate for quantitative evaluation. This model, also known as the Maxwell-Weichert model, is the most general form of the models for describing the viscoelastic behaviour of materials. The generalized Maxwell model expresses the stress relaxation by using various time distributions. The total time-dependent stress $\sigma_T(t)$ is the sum of the stresses acting on the individual elements σ_i.

$$\sigma_T(t) = \sum \sigma_i = \sum \varepsilon_T E_i e^{-E_i t/\eta_i} \tag{9.15}$$

The overall time-dependent modulus is also defined as follows.

$$E_T(t) = \frac{\sigma_T(t)}{\varepsilon_T} = \sum E_i e^{-E_i t/\eta_i} \tag{9.16}$$

The generalized Kelvin-Voigt model is used to analyse the creep and creep recovery behaviour of solid viscoelastic materials. Each one of the individual Kelvin-Voigt elements represents the behaviour of individual polymer fraction, which correspondingly results in an individual retardation time. The total deformation value, by applying the principle of superposition according to Ludwig Boltzmann, is the sum of all individual deformation values. If the dashpot η_0 shown in Fig. 9.5e is eliminated, the model describes the complete solid viscoelatic materials, such as polyethylene and PVC, and is usually used for transient analysis for plastic pipeline systems. The details of generalized Kelvin-Voigt model for pipeline systems are discussed in the section for mathematical model.

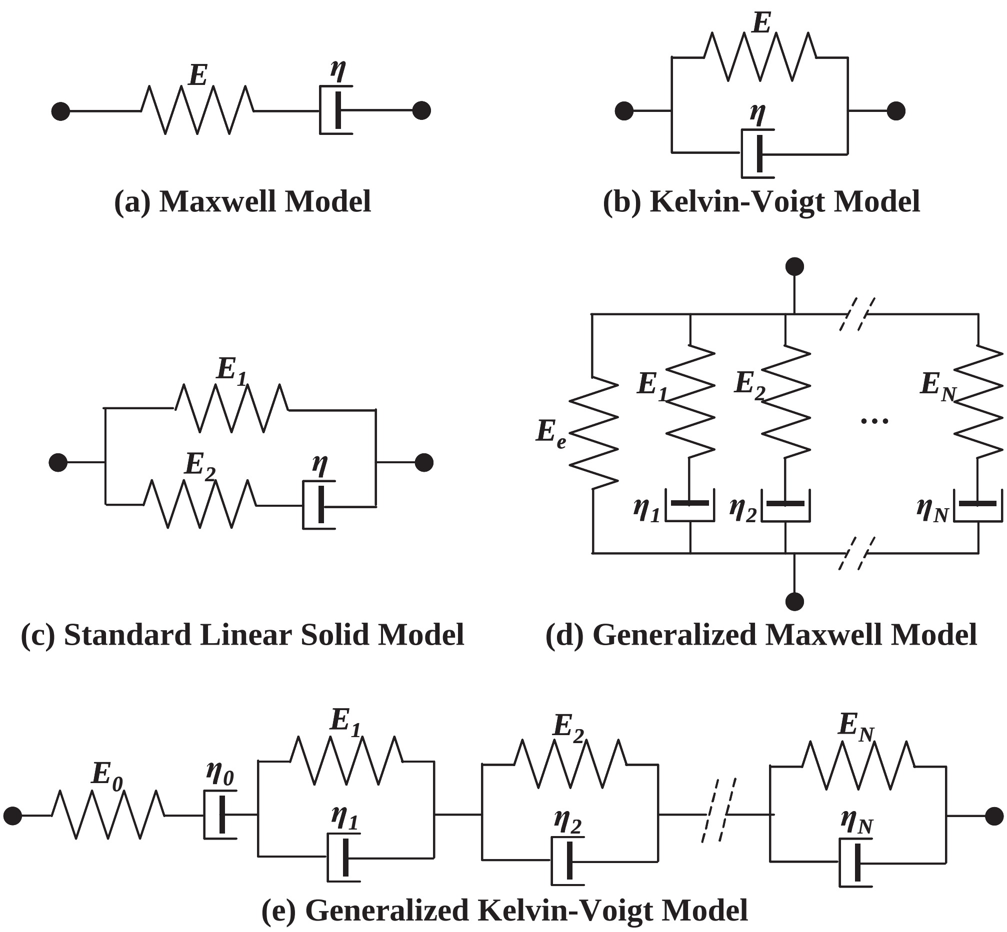


Figure 9.5 Diagrams of Linear Viscoelastic Models

9.3 VISCOELASTIC BEHAVIOUR ON PIPE FLOWS

Transient analysis model based on linear-elastic behaviour of pipe wall is relatively accurate to describe transient flows in metal or concrete pipes. However, sometimes linear-elastic models show significant discrepancies in the magnitude and phase of the travelling pressure wave for simulating plastic pipes with the property of viscoelastic behaviour during transient events generated by a rapid change of flow conditions. There are two different approaches to simulate viscoelastic bahavior of pipeline systems.

One approach is to consider the frequency-dependent factors in actual pipeline systems. This approach assumes that the effect of the viscoelastic behaviour of the pipe wall can be described by a frequency-dependent wavespeed. Therefore, a frequency-dependent creep function is used to calculate the wavespeed during transient events in the frequency domain. A complex-valued frequency-dependent wavespeed was derived by solving the wave equation, Eq. 3.36, along with the equation of motion of the rock mass surrounding the rock-bored tunnel filled with water [Suo and Wylie, 1990a]. The theory of hydraulic resonance in pipelines is extended to tunnels with frequency-dependent wavespeeds. Their results show significant changes in resonance conditions by non-linear elastic behaviour of rock-bored tunnels. Similarly, the frequency-dependent wavespeed in pipeline systems filled with fluid is considered due to the dynamic effect of the viscoelasticity of the pipe wall material. Meiβner and Franke [1977] analysed and compared the damping behaviour of conduits made of the three different polymers during waterhammer oscillations. They derived a frequency-dependent wavespeed and the damping factor for an oscillating pressure wave. In order to take into account the properties of viscoelastic pipes two frequency-domain methods were developed. Rieutord [1982] used the Laplace-Carson transform that gave a method that was well suited to the study of laminar transient flows in linear viscoelastic pipes. The standard impedance or transfer matrix is used to analyse resonance conditions in periodic pipe flow, and the impulse response method based on the theory of linear systems is applied to compute non-periodic hydraulic transient pipe flow [Franke and Seyler, 1983; Suo and Wylie, 1990b].

Another approach is time-domain analysis modelled by analogue spring and dashpot systems as mentioned in the previous section. In these mechanical principle systems associated with viscoelasticity, the total strain of a system can be decomposed into an instantaneous elastic strain and a retarded viscoelastic creep strain. The Kelvin-Voigt or generalized Kelvin-Voigt model is usually used for analysing the viscoelastic behaviour of plastic pipe that has the property of solid material viscoelasticity. Williams [1977] found experimentally that viscoelastic pipes gave rise to strong mechanical damping of the waterhammer. He measured the transient pressure variation and pipe wall strain in rubber, PVC, and steel pipes during transient events. Also, he made mention of the expansion joints in the steel pipe. Rieutord and Blanchard [1979], Ghilardi and Paoletti [1986], and Ellis [1986] show theoretical studies of the effect of viscoelastic material properties of a plastic pipe based on the generalized Kelvin-Voigt model. Their numerical results showed the exponential attenuations of wave fronts according to various relaxation times of plastic pipe. Gally et al. [1979] and Guney [1983] presented a complete mathematical model for analysing viscoelastic effects on transient pipe flows based on generalized Kelvin-Voigt model. The calculated results based on the method of characteristics were compared with experimental results.

Pezzinga and Scandura, [1995] and Pezzinga [2002] presented the results of a theoretical and experimental study on the use of a high-density polyethylene (HDPE) additional pipe inserted downstream of a pump in a hydraulic network as a surge suppressor. The mechanical behaviour of the HDPE was described both by a linear elastic model and by a Kelvin-Voigt viscoelastic model. Their numerical results showed that the viscoelastic model better describes the phenomena, but the elastic model adequately estimates the maximum and minimum oscillations. Covas et al. [2004 and 2005] observed transient data collected in a high-density polyethylene pipeline system to investigate viscoelastic behaviour. Their results showed major dissipation and dispersion of pressure waves, and transient mechanical hysteresis. These measured data were simulated by a generalized Kelvin-Voigt model, and the creep function of the HDPE pipe was experimentally determined by creep tests. They noticed that the mechanical tests for the creep function only provided an estimate of the actual mechanical behaviour of the pipe system when PE was integrated in a pipeline system, because the creep function depended on not only the molecular structure of the material and temperature but also on the pipe axial and circumferential constraints and the stress-time history of the pipeline system. Recent field tests in water distribution pipe networks showed that concrete, asbestos cement and steel pipes exhibited some significant viscoelastic behaviour due to soil-pipe interaction, flexible pipe joints, or household water services [Stephens et al., 2005].

9.4 MATHEMATICAL MODEL

The deformability of the pipe wall is a function of the flow conditions as well as of the pipe wall characteristics. Pipe distensibility can be a vital part of the transient response for pressurised liquid pipe flow. The characteristics of pipe deformation are related to the pipe wall material, cross section geometry and structural constraints. Most transient analysis models assume linear-elastic behaviour of the pipe wall. Linear-elastic model is relatively accurate for describing hydraulic transients in metal or concrete pipes. However, transients in plastic pipes exhibit significant viscoelastic behaviour because these materials have a different rheological behaviour in comparison to metal and concrete pipes. This section focuses on the mathematical modelling of hydraulic transients in polyethylene pipes by adding a retarded strain in the transient pipe flow equations. For linear-elastic behaviour of the pipe wall, the elasticity of the pipe wall and its rate of deformation are a function of pressure only as mentioned in Chapter 3. The evaluation of the conduit elasticity is expressed by $\Delta A/(\Delta pA)$.

$$\frac{dA}{A} = \frac{D}{eE} dp \tag{9.17}$$

where e is the pipe wall thickness and E is Young's modulus of elasticity for the pipe wall. Plastic pipes have both an immediate elastic response and a retarded viscous response. Therefore, the total strain can be decomposed into an instantaneous elastic strain ε_e at the initial state of every process and a retarded strain ε_r depending on time.

$$\varepsilon(t) = \varepsilon_e(t) + \varepsilon_r(t) \tag{9.18}$$

According to the Boltzmann superposition principle, for small strains, a combination of stresses that act independently in a system results in strains that can be added linearly [Aklonis et al., 1972; Covas et al., 2005]. The total strain generated by a continuous application of stress is

$$\varepsilon(t) = \sigma(t) J_0 + \int_0^t \sigma\left(t - t^*\right) \frac{\partial J(t^*)}{\partial t^*} dt^* \tag{9.19}$$

where J_0 is instantaneous elastic creep compliance and $J(t^*)$ is the creep compliance function at time t^*. The instantaneous creep compliance J_0 is equal to the inverse of Young's modulus of elasticity, $J_0 = 1/E_0$. According to the following assumptions that i) the pipe material is homogeneous and isotropic, ii) Poisson's ratio v is constant for small strains and a linear viscoelastic behaviour [Gally et al., 1979], the mechanical behaviour of the deformation of viscoelastic materials is assumed to be only a function of the creep compliance and the total circumferential strain $\varepsilon = (D-D_0)/D_0$ is given directly by the transposition of the usual strain-stress relationship.

$$\varepsilon(t) = \frac{\alpha_0 D_0}{2e_0}\left[p(t) - p_0\right] J_0 + \frac{\alpha(t-t^*) D(t-t^*)}{2e(t-t^*)} \int_0^t \left[p(t-t^*) - p_0\right] \frac{\partial J(t^*)}{\partial t^*} dt^* \qquad (9.20)$$

where $p(t)$ is the local pressure, the subscript 0 denotes the initial steady state value, and α is the parameter function of the pipe constraint [Guney, 1983]. For a pipe anchored at both ends to eliminate axial strain, α is to be

$$\alpha = 1 + \frac{e^2}{D^2} + \mu \frac{2e}{D} - \mu^2 \left(1 - \frac{e}{D}\right)^2 \qquad (9.21)$$

For a pipe free at both ends

$$\alpha = 1 + \frac{e^2}{D^2} + \mu \frac{2e}{D} \qquad (9.22)$$

where μ is Poisson's ratio. The first and integral term on the right hand side of Eq. 9.20 represent the elastic and retarded strain respectively. To evaluate the time derivative of retarded strain, it is necessary to know the creep compliance function $J(t)$. The creep compliance is a function to characterize the time-dependent strain of a viscoelastic material depending on the molecular structure of the material, temperature and stress-time history. This function is obtained from dynamic tests carried out on a Rheovibron apparatus using direct measurements of a sinusoidally varying stress and strain over a restricted frequency range [Murayama, 1978; Gally et al., 1979]. Nakayasu et al. [1961] presented data on the viscoelastic behaviour of a HDPE over a wide time scale and a considerable span of temperature. Schwarzl [1970] proposed a number of approximation formulae for calculating the storage compliance from creep compliance of viscoelastic materials, together with bounds for their errors. Short and long term tensile creep tests and their analysis for obtaining non-linear creep functions of polymers was performed at different stress levels under various temperature conditions, and the effects of stress and physical ageing on the creep compliance were studied [Lai and Bakker, 1995; Zhang and Moore, 1997; Mano et al., 2001; Barbero and Julius, 2004; Barbero and Ford, 2004].

Gally et al. [1979] presented the values of creep compliance and retardation time for polyethylene at a different temperature as shown in Table 9.1. These values were obtained by the calculations of the approximation formulae for the creep compliance and the retardation time of viscoelastic material. Although the creep compliance function can be obtained by creep or a dynamic test of the material under idealized test conditions, the mechanical tests for the creep function only provided an estimate of the actual mechanical behaviour of the material in a real pipeline system because the creep function also depends on the pipe axial and circumferential constraints, the pipeline support system and the various stress-time history of the pipeline as a result of flow change.

Table 9.1 Creep Compliances and Retardation Times for Polyethylene at Different Temperatures [Gally et al., 1979]

NOTE: This table is included on page 308 of the print copy of the thesis held in the University of Adelaide Library.

The creep compliance function of a pipe wall is described by using the generalized Kelvin-Voigt model for the complete solid viscoelastic materials as shown in Fig. 9.5e after eliminating the dashpot η_0 [Aklonis et al., 1972].

$$J(t) = J_0 + \sum_{k=1}^{N} J_k (1 - e^{-t/\tau_k}) \qquad (9.23)$$

where the modulus of elasticity of each spring is $E_k = 1/J_k$. The viscosity of each dashpot is η_k and the associated retardation time is $\tau_k = \eta_k/E_k$. The parameters J_k and τ_k of the viscoelastic mechanical model should be adjusted based on the creep experimental data. By the combination of the relationship between cross-sectional area and total hoop strain, $dA/dt = 2Ad\varepsilon/dt$, and Eq. 9.17, the equation of area state for viscoelastic materials in the conservative solution scheme is expressed by the following equation.

$$\frac{\partial A}{\partial t} = \frac{D}{eE} A \frac{\partial p}{\partial t} + 2A \frac{\partial \varepsilon_r}{\partial t} \tag{9.24}$$

where the first term on the right hand side corresponds to the elastic strain and the second term represents retarded strain. The relations between retarded strain ε_r, its time derivative $\partial\varepsilon_r/\partial t$ and pressure are evaluated as the sum of each Kelvin-Voigt element [Gally et al., 1979; Guney, 1983; Covas et al., 2005].

$$\varepsilon_r(x,t) = \sum_{k=1}^{N} \varepsilon_{rk}(x,t) = \sum_{k=1}^{N} \left\{ \frac{\alpha D}{2e} \int_0^t \overline{p}(x,t-t^*) \frac{J_k}{\tau_k} e^{-t^*/\tau_k} dt^* \right\} \tag{9.25}$$

where $\overline{p}(x,t-t^*) = p(x,t-t^*) - p(x,0)$

$$\frac{\partial}{\partial t}\varepsilon_r(x,t) = \sum_{k=1}^{N} \frac{\partial \varepsilon_{rk}(x,t)}{\partial t} = \sum_{k=1}^{N} \left\{ \frac{\alpha D}{2e} \frac{J_k}{\tau_k} \overline{p}(x,t) - \frac{\varepsilon_{rk}(x,t)}{\tau_k} \right\} \tag{9.26}$$

where $\overline{p}(x,t) = p(x,t) - p(x,0)$

The time derivative of retarded strain for each Kelvin-Voigt element is calculated by analytical differentiation. After mathematical manipulations for each element, it yields the following numerical first-order approximation [Covas et al., 2005].

$$\frac{\partial \varepsilon_{rk}(x,t)}{\partial t} = \frac{J_k}{\tau_k} \frac{\alpha D}{2e} \overline{p}(x,t) - \frac{\tilde{\varepsilon}_{rk}(x,t)}{\tau_k}$$

$$\begin{aligned} \tilde{\varepsilon}_{rk}(x,t) &= J_k \frac{\alpha D}{2e} \overline{p}(x,t) - J_k e^{-\Delta t/\tau_k} \frac{\alpha D}{2e} \overline{p}(x,t-\Delta t) \\ &\quad - J_k \tau_k \left(1 - e^{-\Delta t/\tau_k}\right) \frac{\frac{\alpha D}{2e} \overline{p}(x,t) - \frac{\alpha D}{2e} \overline{p}(x,t-\Delta t)}{\Delta t} + e^{-\Delta t/\tau_k} \tilde{\varepsilon}_{rk}(x,t-\Delta t) \end{aligned} \tag{9.27}$$

After rearranging, the time derivative of total retarded strain is

$$\frac{\partial \varepsilon_r(x,t)}{\partial t} = \sum_{K=1}^{N} \frac{\partial \varepsilon_{rk}(x,t)}{\partial t}$$

$$= \sum_{K=1}^{N} \left\langle \begin{array}{l} \dfrac{J_k}{\tau_k} \dfrac{\alpha D}{2e} \overline{p}(x,t) \\ -\dfrac{1}{\tau_k} \left\{ \begin{array}{l} \dfrac{\alpha D}{2e} J_k \overline{p}(x,t) \left[1 - \left(1 - e^{-\Delta t/\tau_k}\right) \dfrac{\tau_k}{\Delta t} \right] \\ + \dfrac{\alpha D}{2e} J_k \overline{p}(x,t-\Delta t) \left[\left(1 - e^{-\Delta t/\tau_k}\right) \dfrac{\tau_k}{\Delta t} - e^{-\Delta t/\tau_k} \right] \\ + e^{-\Delta t/\tau_k} \tilde{\varepsilon}_{rk}(x,t-\Delta t) \end{array} \right\} \end{array} \right\rangle \tag{9.28}$$

This equation is incorporated into the first-order approximated form of Eq. 9.24 to calculate the retarded stain of viscoelastic material in the conservative solution scheme. In the following sections, a numerical and experimental investigation is given for the viscoelastic effects on the rapid transient pipe flows. Each pipe axis is assumed to be fixed and the pipe wall response is only characterized by the radial distensibility capacity.

9.5 NUMERICAL INVESTIGATION OF VISCOELASTIC PIPE RESPONSE

Numerical experiments have been undertaken to verify the proposed model and for investigating the dynamic behaviour of transient pipe flows with polyethylene pipes. The pipeline system shown in Fig. 9.6 has been used for numerical experiments. This system is identical with the laboratory pipeline system used for the experimental verification. Transients are generated by instantaneous valve closure at node 5. The pressure data are observed at the middle of pipe (node 3) and the downstream valve (node 5).

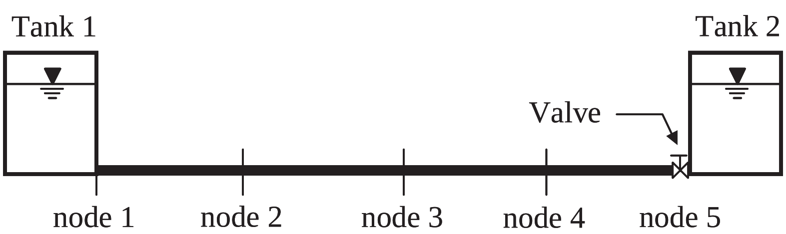


Figure 9.6 Pipeline System for Numerical Experiments

Figs. 9.7 and 9.8 shows the observed pressure waves when the whole pipe material is made of polyethylene (viscoelastic material) or copper (linear elastic material). The Young's modulus of elasticity of polyethylene and copper are 0.649 and 124.1 GPa respectively. The initial flow velocity is 0.142 m/s with a Reynolds number of 3,662 at 25^{o}C. Fig. 9.7 shows the results of linear elastic model for copper pipe and polyethylene pipe. The results of polyethylene pipe show a much slower wavespeed and a smaller pressure magnitude when compared to the results of copper pipe because of the soft pipe material characteristic.

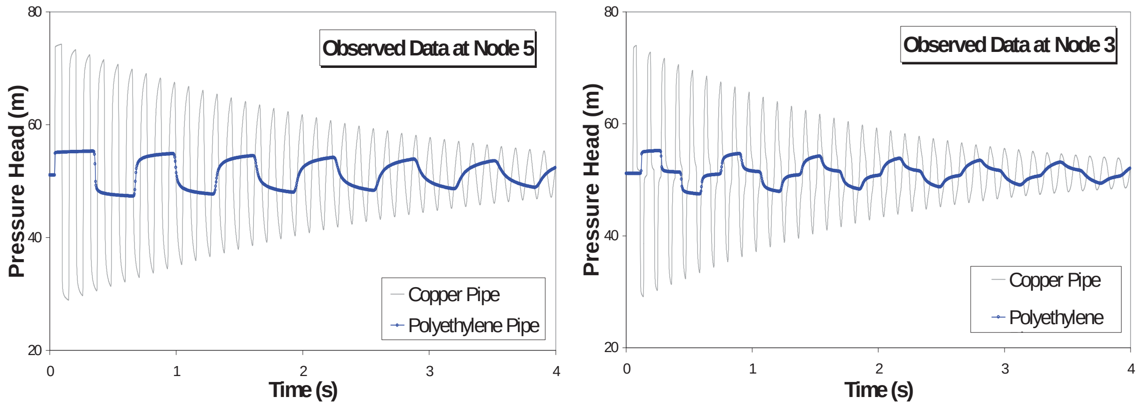


Figure 9.7 Numerical Results by Linear Elastic Model

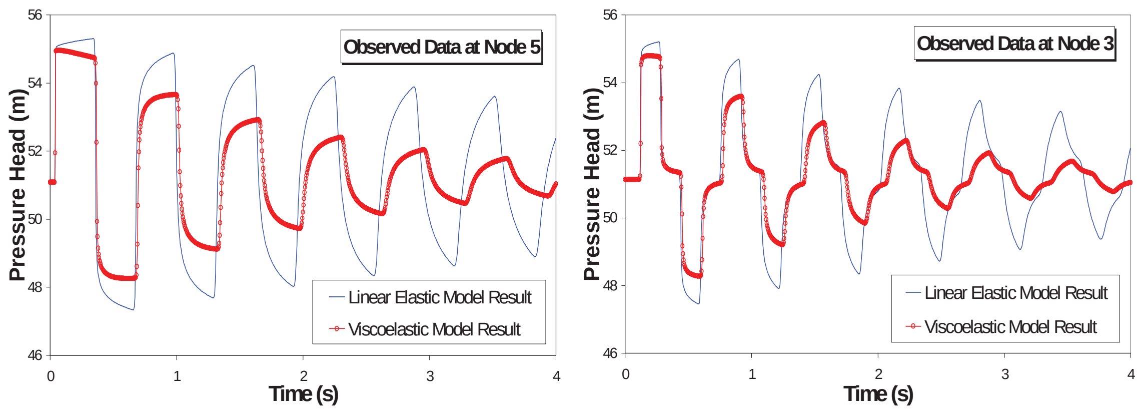


Figure 9.8 Comparisons between the Results by Linear Elastic and Viscoelastic Models for Polyethylene Pipe

Fig. 9.8 is the comparison between the results by a linear elastic model and a viscoelastic model for polyethylene pipe. The values of Table 9.1 are used for creep compliances and retarded times of the generalized Kelvin-Voigt model. The results of the viscoelastic model show a significant damping effect of pressure wave magnitude and lagging effect of the wavespeed when compared to the results of linear elastic model. In particular, the first pressure rise that is mainly affected by a line-packing effect shows a downward pressure wave because of the additional distensibility of pipe wall related with viscoelasticity.

The following section shows the analysis of hydraulic transients in pressurised pipeline system with a local polyethylene pipe section at the middle of the pipeline as shown in Fig. 9.6. The effect of the local viscoelastic pipe is important because the section of existing old steel and concrete pipes are frequently replaced by polyethylene pipe due to their high resistant properties against corrosion, low price, and cost-effective installation methods. The viscoelastic behaviour of a local polymer pipe influences the pressure response during transient events by attenuating the pressure magnitude and by increasing the dispersion of the pressure wave. Figs. 9.9 and 9.10 show the simulation results for a linear elastic and a viscoelastic model at the middle and end of pipe when the copper pipeline has a local polyethylene section in the middle of pipe. The percentage of each graph presents the length of local polyethylene section in proportion to the total pipe length.

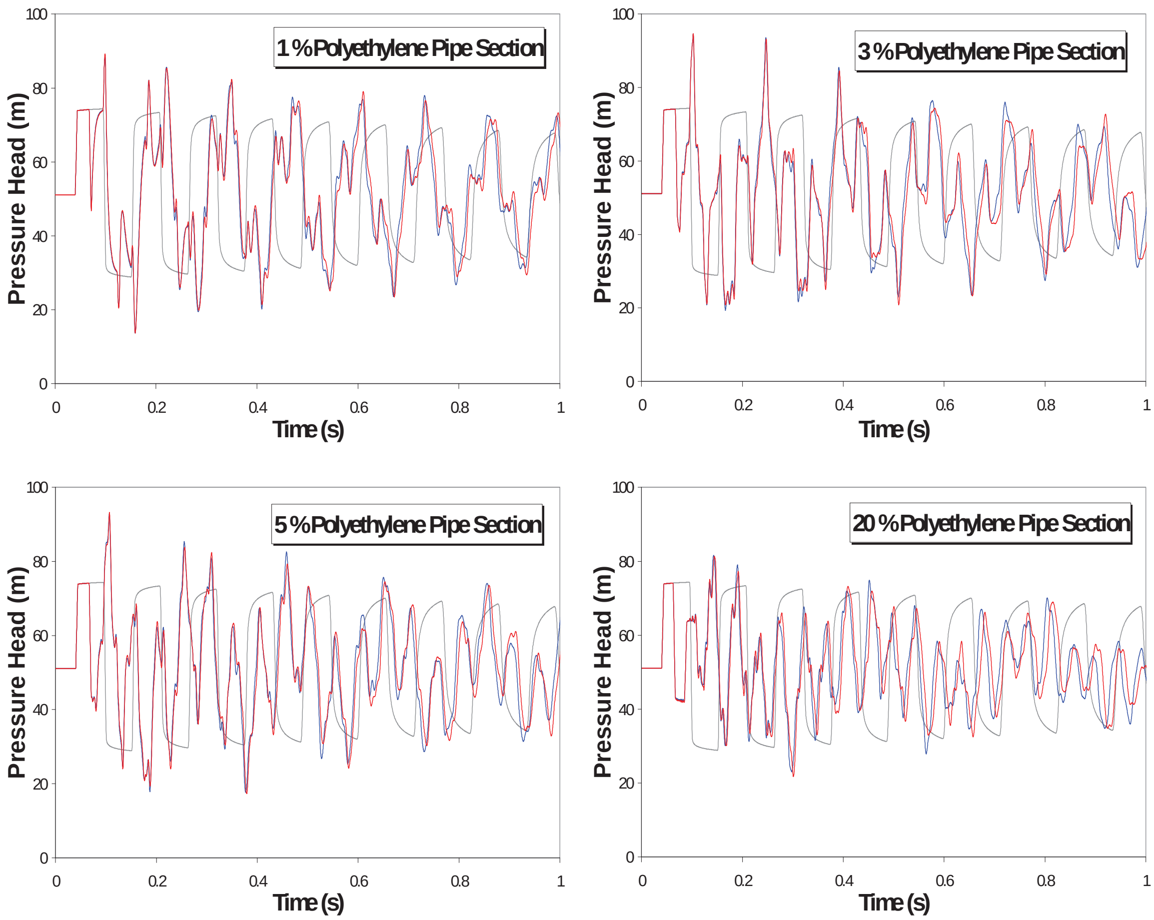


Figure 9.9 Viscoelastic Behaviour of Local Polyethylene Pipe (at the End of Pipe)

(gray line: result of whole copper pipeline, blue line: result by linear elastic model, red line: result by viscoelastic model)

Similar to the effect of an entrapped air pocket on transient pipe flows as mentioned in Chapter 7, the presence of a local polymer section of even a small percentage has a significant effect on the character of transients in the copper pipeline. The local polyethylene sections can either suppress pressure fluctuations or increase the maximum pressure in pipe. The soft local polyethylene section can be considered as a buffer loaded with the liquid, so even a small portion of polymer pipe greatly decreases the wavespeed and pressure magnitude as shown in Figs. 9.9 and 9.10. Also, the graphs show high frequency excessive pressure spikes caused by interaction between pressure waves and the polymer section and they can increase the maximum pressure. Unlike the results of whole polyethylene pipeline system, the simulation results by viscoelastic model for pipeline system with local polyethylene section show only a slight decrease of wavespeed and pressure magnitude. Instantaneous linear elastic effect seems to be more dominant physical phenomenon on transient pipe flow with a local polymer pipe.

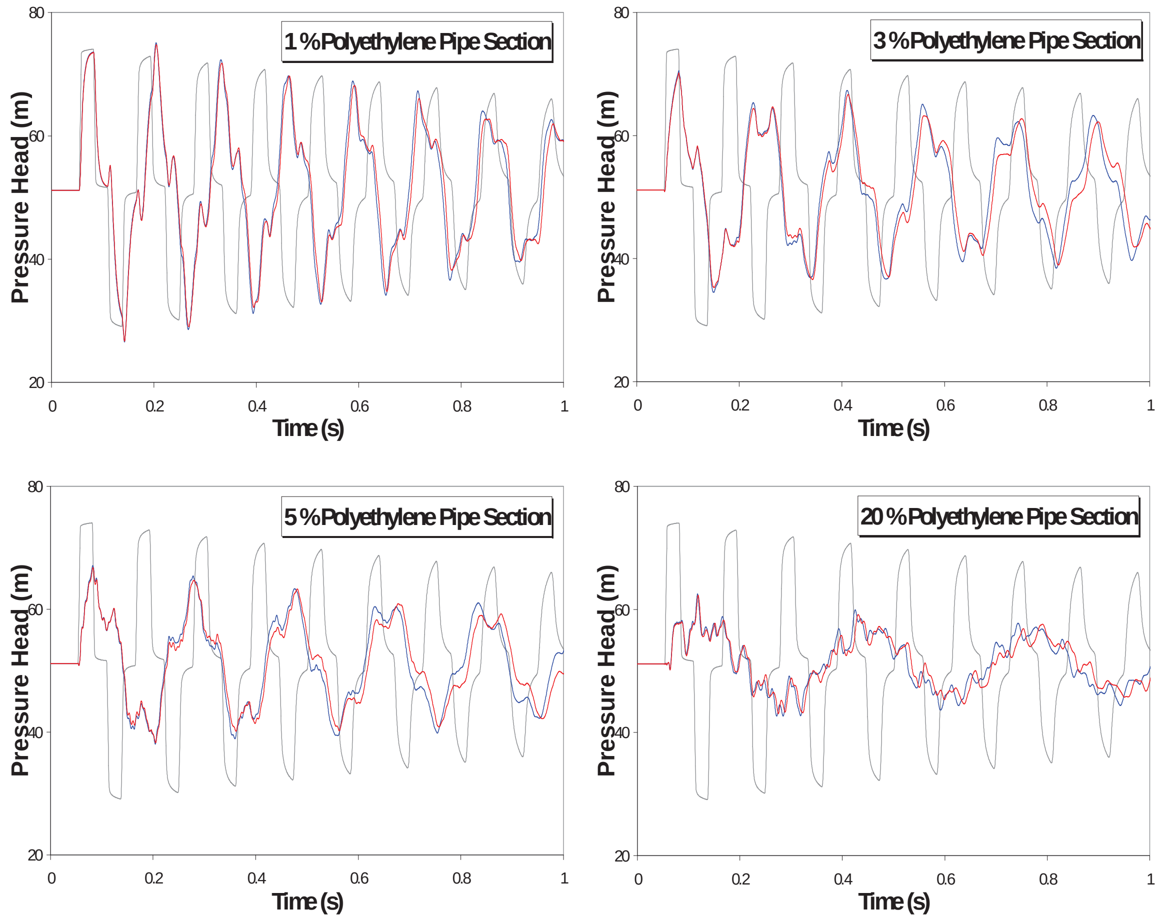


Figure 9.10 Viscoelastic Behaviour of Local Polyethylene Pipe (at the Middle of Pipe)

(gray line: result of whole copper pipeline, blue line: result by linear elastic model, red line: result by viscoelastic model)

9.6 MEASURED TRANSIENT DATA WITH LOCAL POLYMER PIPES

Laboratory experiments have been carried out for the verification of the proposed viscoelastic model and investigation of the real physical phenomena of a local polymer pipe during transients. The experimental apparatus is described in detail in Chapter 4. The layout of the pipeline system is repeated in Fig. 9.11.

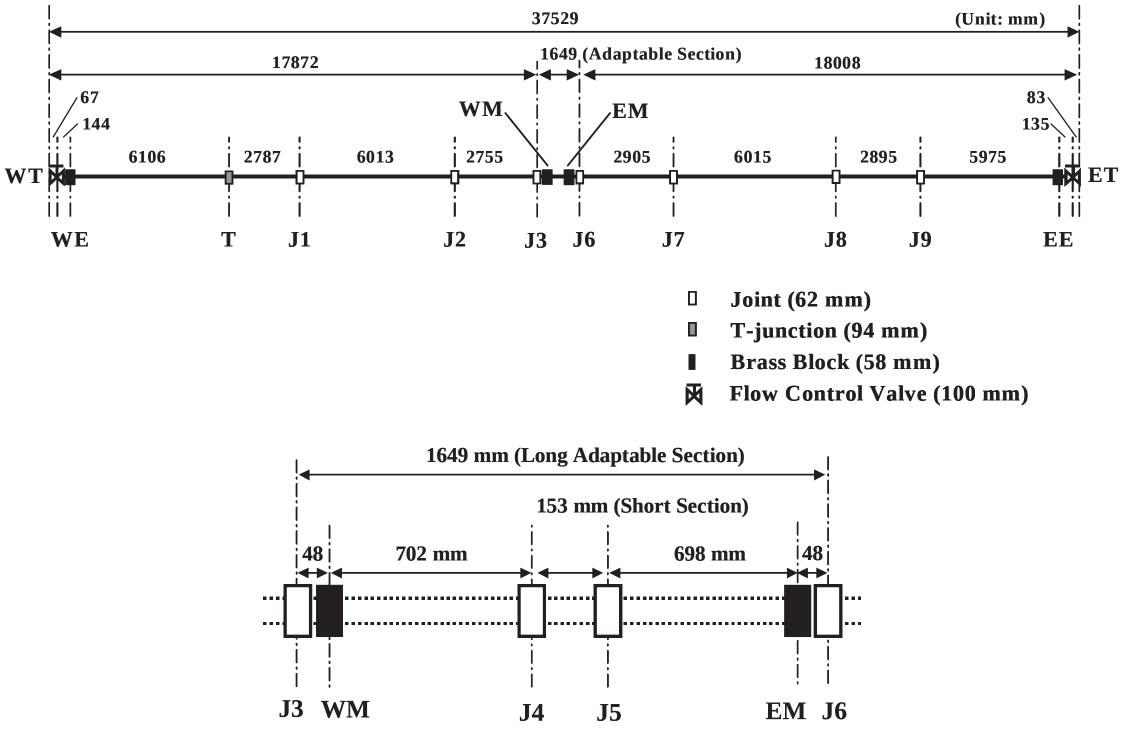


Figure 9.11 Pipeline System Layout

Transients are generated at the WE by a side-discharge solenoid valve with a fast operating time after closing the west flow control valve, thus the pipeline system can be regarded as a tank-pipe-valve system. The sampling frequency of measured data is 4 kHz. The water and surrounding temperature is 25^{o}C. The initial steady-state velocities are estimated by the volumetric method. All transient tests for polymer pipes are undertaken under the specified 6 different flow condition by adjusting tank pressure as mentioned in previous chapters. Medium-density polyethylene pipes (PE80B, NP12.5) with three different pipe lengths are used for local viscoelastic pipe test after insertion into the adaptable section (between two joints) in Fig. 9.11. The outside diameter is 25 mm and the wall thickness is 2.273 mm. Table 9.2 shows each polyethylene pipe length and the pressure measurement points.

Table 9.2 Three Different Local Viscoelastic Pipes

Length (m)	Location	Pressure Measured Points
0.153	J4 – J5	WE, WM, EM, EE
0.895	J3 – J5	WE, EM, EE
1.630	J3 – J6	WE, EE

Figs. 9.12 to 9.17 show the measured transient data at the end of pipeline (WE) under 6 different test conditions used for previous chapters when the pipeline has a section of polyethylene pipe at the adaptable section. The pressure data with local polyethylene pipe sections are plotted at the same scale graphs to compare each pressure variation, wavespeed and pressure wave shape during the same test condition. The wavespeed of the system is slower when the pipeline has a longer polyethylene section. Also, the section causes a significant change in the shape and the magnitude of the pressure waves. Similar to the results shown by the numerical tests, the presence of the local polymer pipe increases the maximum of surge pressure. The high frequency downward narrow spike of the first pressure rise, which is caused by a sudden pressure drop when the pressure wave meets polyethylene pipe section, indicates the location of the section.

These physical interactions between the pressure wave and the local polymer pipe are much alike with the results of entrapped air pocket on transient pipe flow. However, the effect of air pocket on transients is less when the initial pressure condition is high because the initial size of air pocket is more contracted by higher pressure condition, therefore the actual size of air pocket in the high pressure condition is smaller than that for the low pressure condition. The pressure wave under the low pressure condition is more deformed by a relatively large air volume (compare the results of air pocket #4 between Figs. 7.13 and 7.23). On the other hand, the results of a local polymer pipe on transients do not show the dependency of cavity compressibility according to the initial pressure conditions. When compared to the results of 1.630 m PE pipe between Figs. 9.12 and 9.17, the shapes of pressure waves are almost the same because the surface area itself of polymer pipe is an important physical factor.

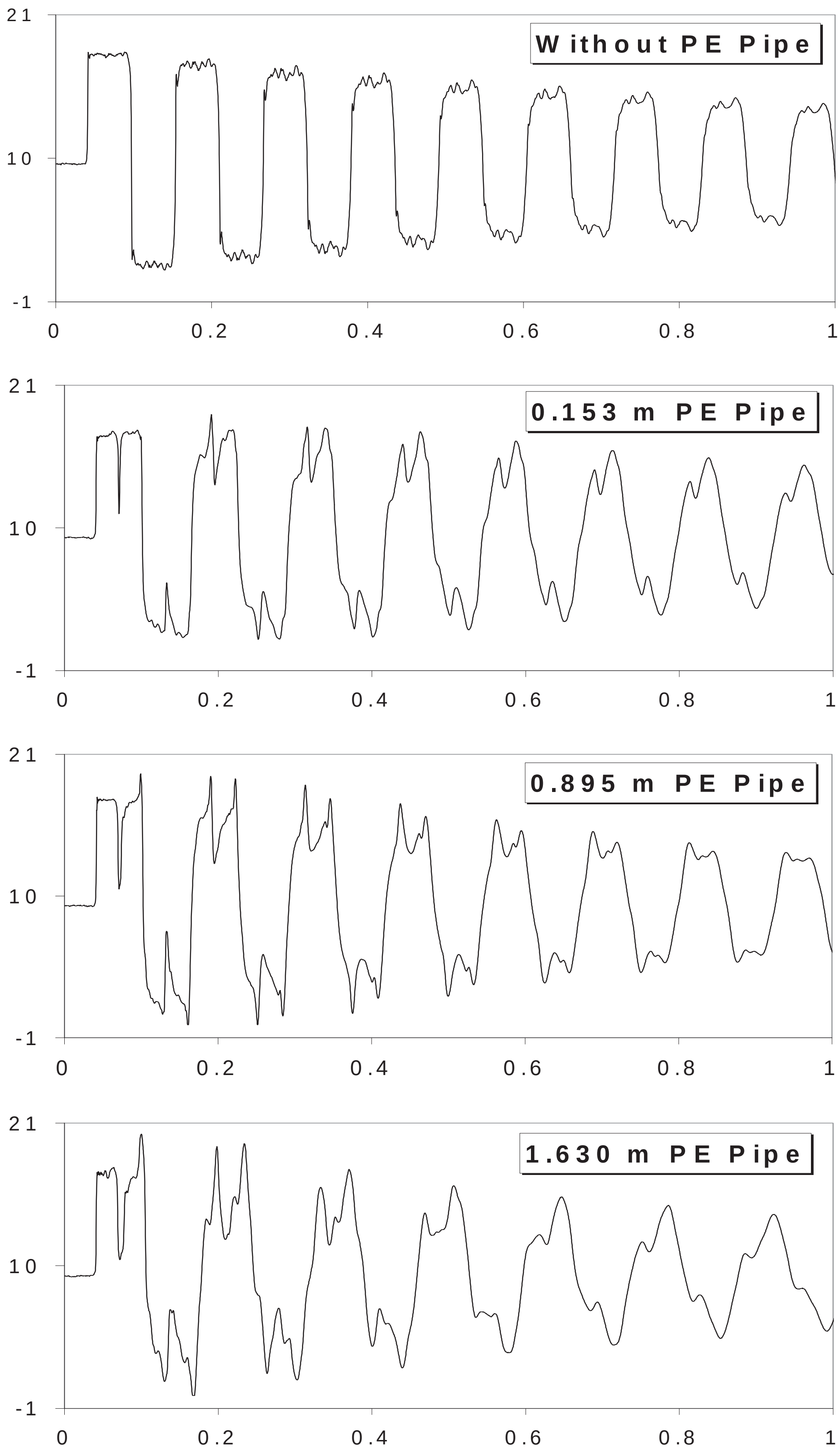


Figure 9.12 Measured Data at the End of Pipeline (WE) under Flow Condition 1 (initial velocity is 0.0599 m/s)

(x-axis: measured time (s) and y-axis: pressure head (m))

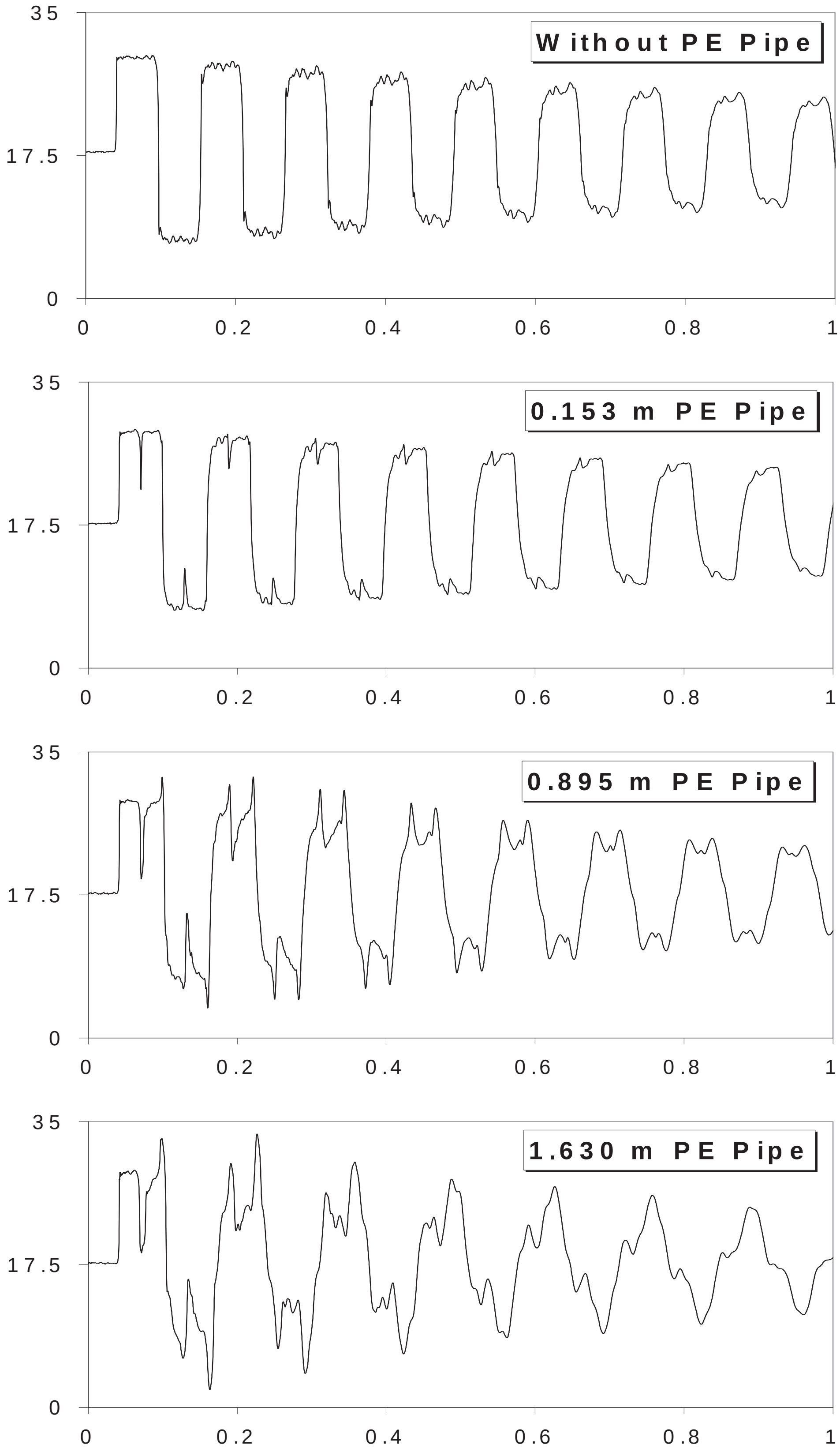


Figure 9.13 Measured Data at the End of Pipeline (WE) under Flow Condition 2 (initial velocity is 0.0824 m/s)

(x-axis: measured time (s) and y-axis: pressure head (m))

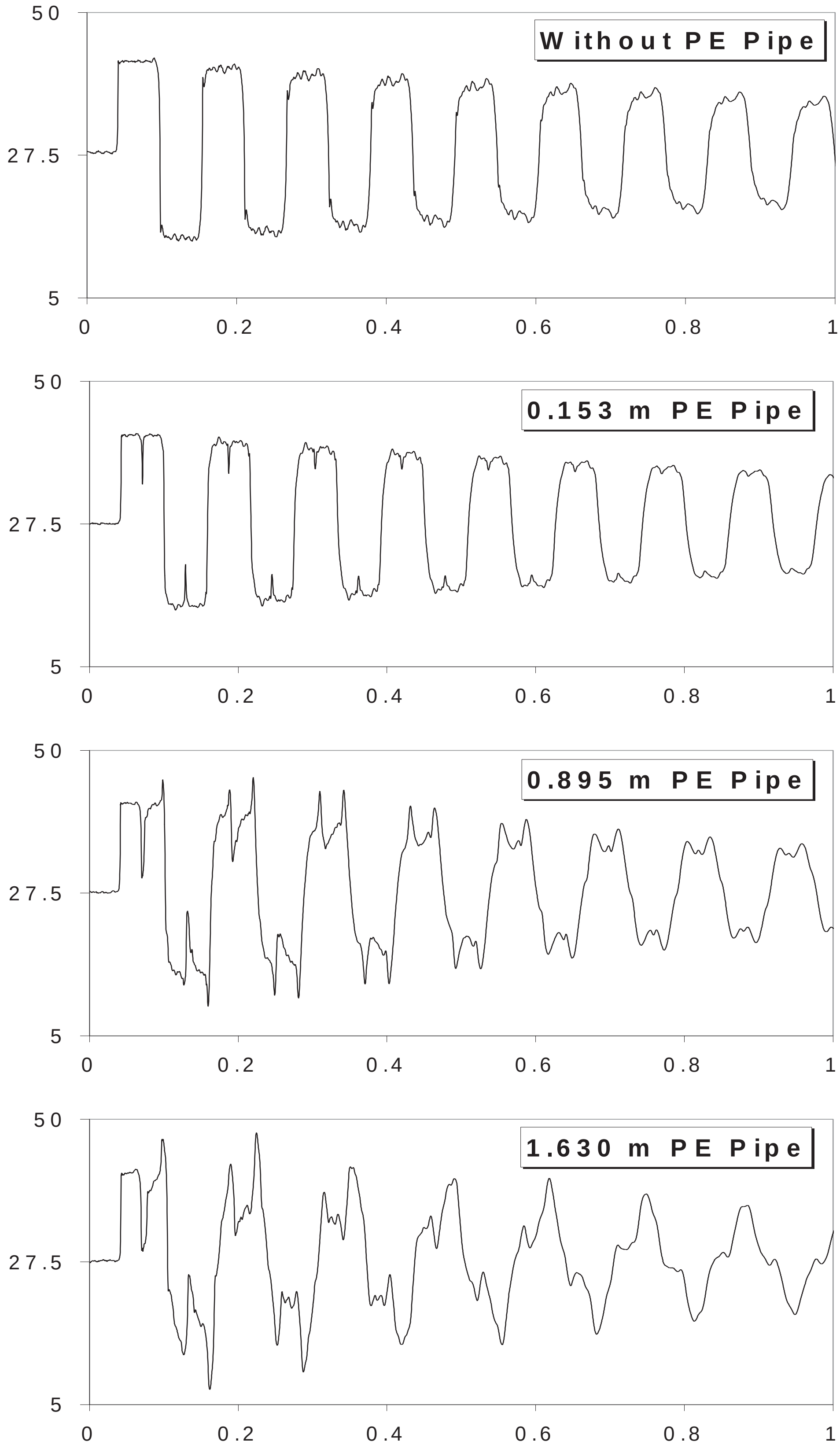


Figure 9.14 Measured Data at the End of Pipeline (WE) under Flow Condition 3 (initial velocity is 0.1031 m/s)

(x-axis: measured time (s) and y-axis: pressure head (m))

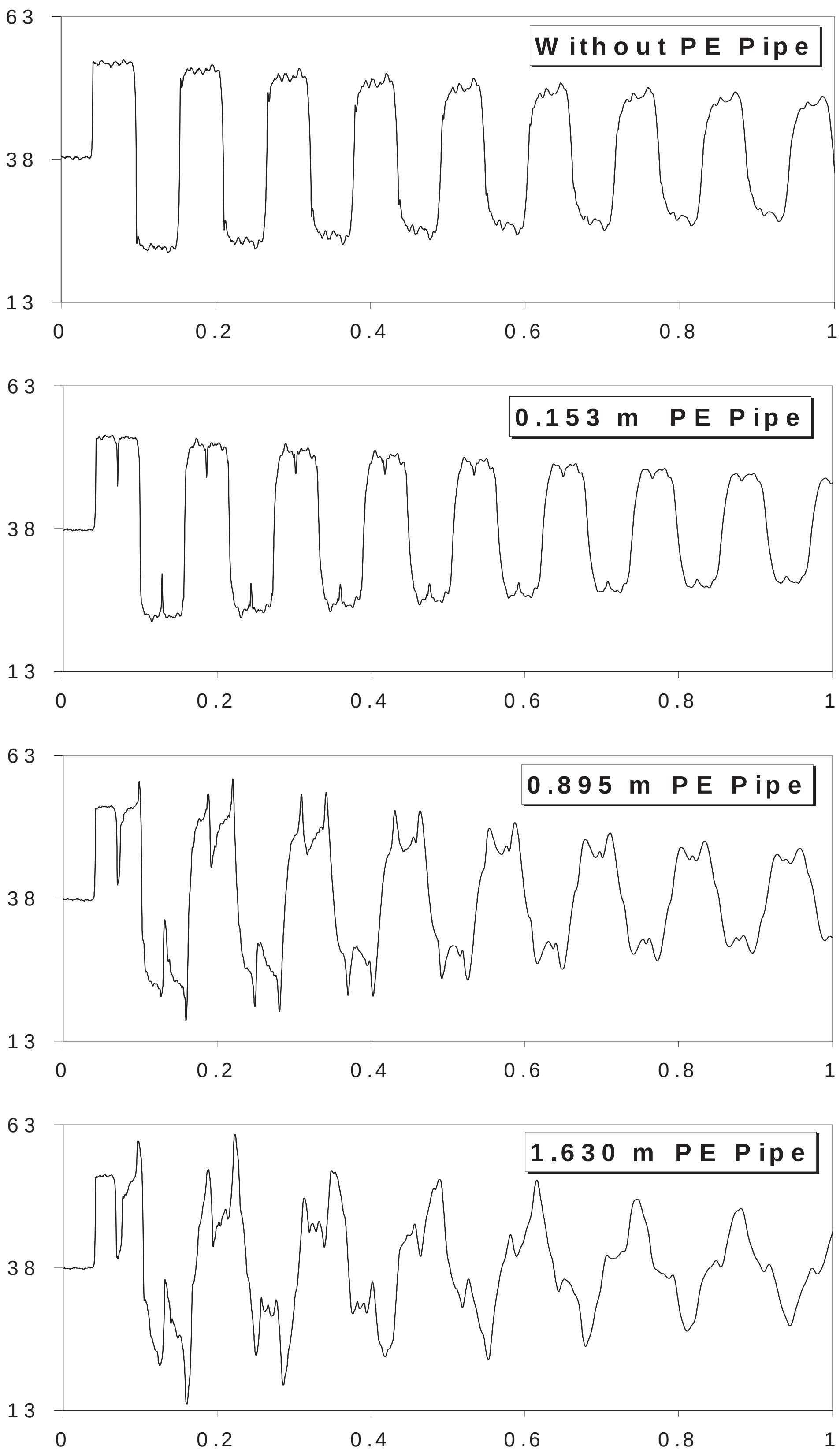


Figure 9.15 Measured Data at the End of Pipeline (WE) under Flow Condition 4 (initial velocity is 0.1208 m/s)

(x-axis: measured time (s) and y-axis: pressure head (m))

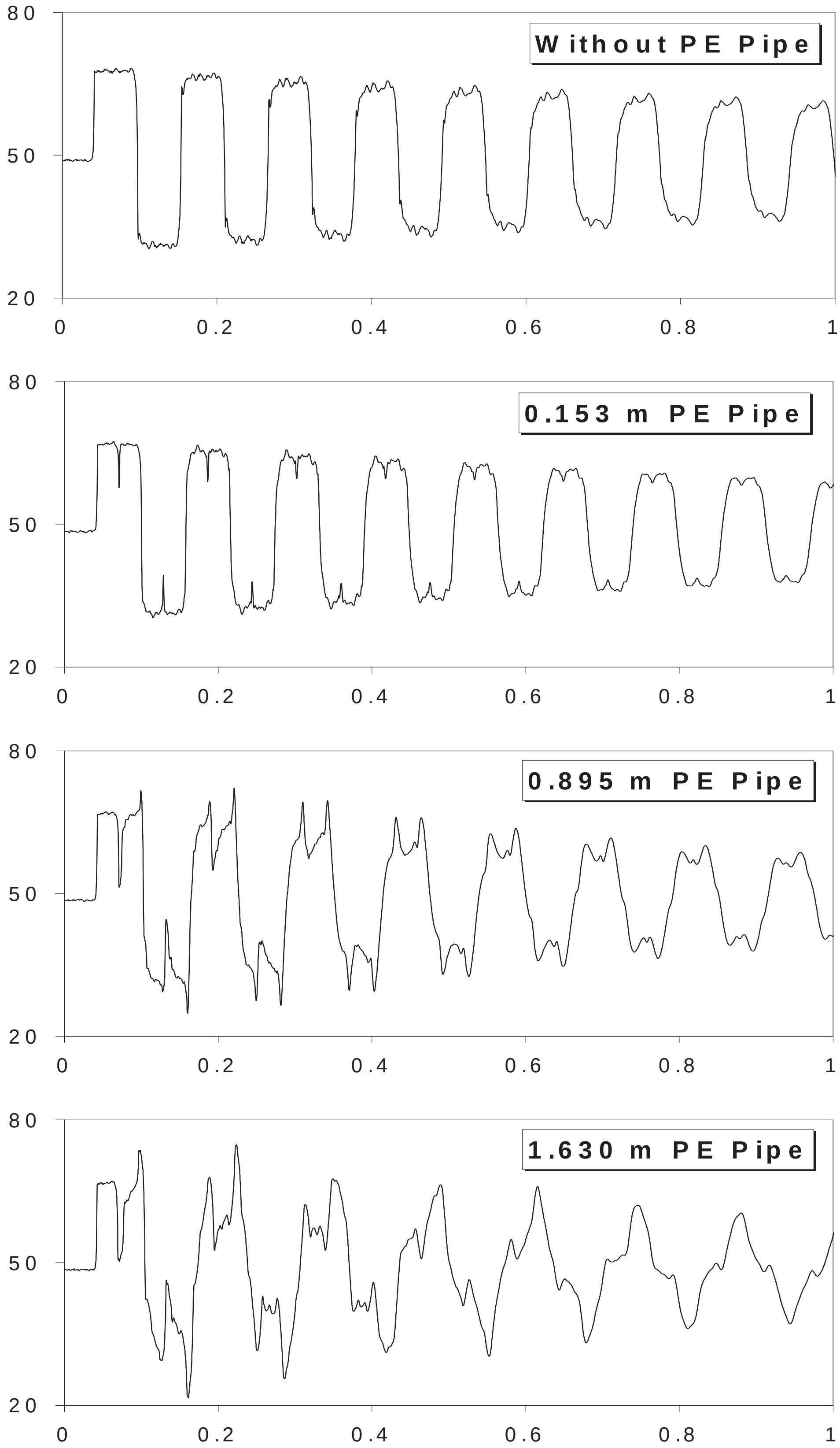


Figure 9.16 Measured Data at the End of Pipeline (WE) under Flow Condition 5 (initial velocity is 0.1368 m/s)

(x-axis: measured time (s) and y-axis: pressure head (m))

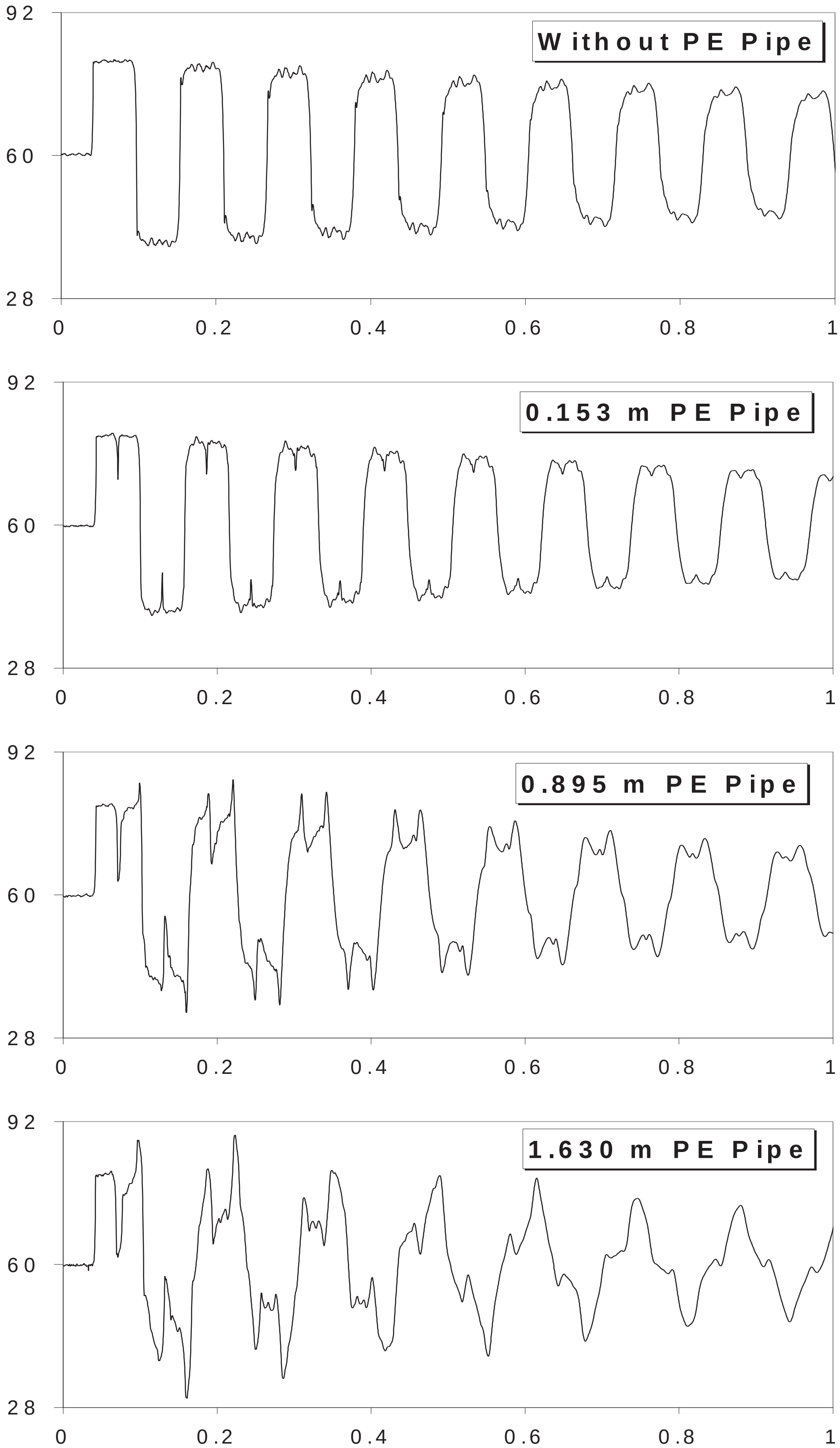


Figure 9.17 Measured Data at the End of Pipeline (WE) under Flow Condition 6 (initial velocity is 0.1495 m/s)

(x-axis: measured time (s) and y-axis: pressure head (m))

The relative proportions of local polyethylene pipe in a pipeline system lead to different patterns of pressure wave and speeds of pressure propagation. Although the whole polymer pipeline system is beneficial in reducing transient pressure loads, the local polymer pipe section can cause shock waves (steepening wave front) with high frequency spikes that significantly increase peak pressures. The formation of shock waves is associated with the dynamic interaction between fluid flow and pipe wall distensibility. When the pressure wave meets the local polymer section, it creates high frequency deep valleys on pressure wave because of the sudden pressure drop due to the instantaneous expansion of the polymer pipe wall. The polymer has the characteristic of recovery from the instantaneous expansion and this recovery of the pipe wall compresses pressure wave, therefore the peak pressure increases.

Fig. 9.18 shows another test example when the pipeline system has a different pipe wall material at local section. The pressure data are measured at the end of pipeline (WE) and middle of pipeline (WM) when the pipeline has 0.153 m length rubber (Young's modulus E = 0.1 GPa) pipe at the middle of the pipeline (between J4 and J5 in Fig. 9.11). The specification of local rubber pipe and test condition is the same as the tests for the 0.153 m polyethylene pipe section mentioned above. The results are similar to the polyethylene pipe. However, the results show a larger damping rate of the whole pressure magnitude and a slower wavespeed when compared to the results of polyethylene pipe because the rubber has a lower modulus of elasticity.

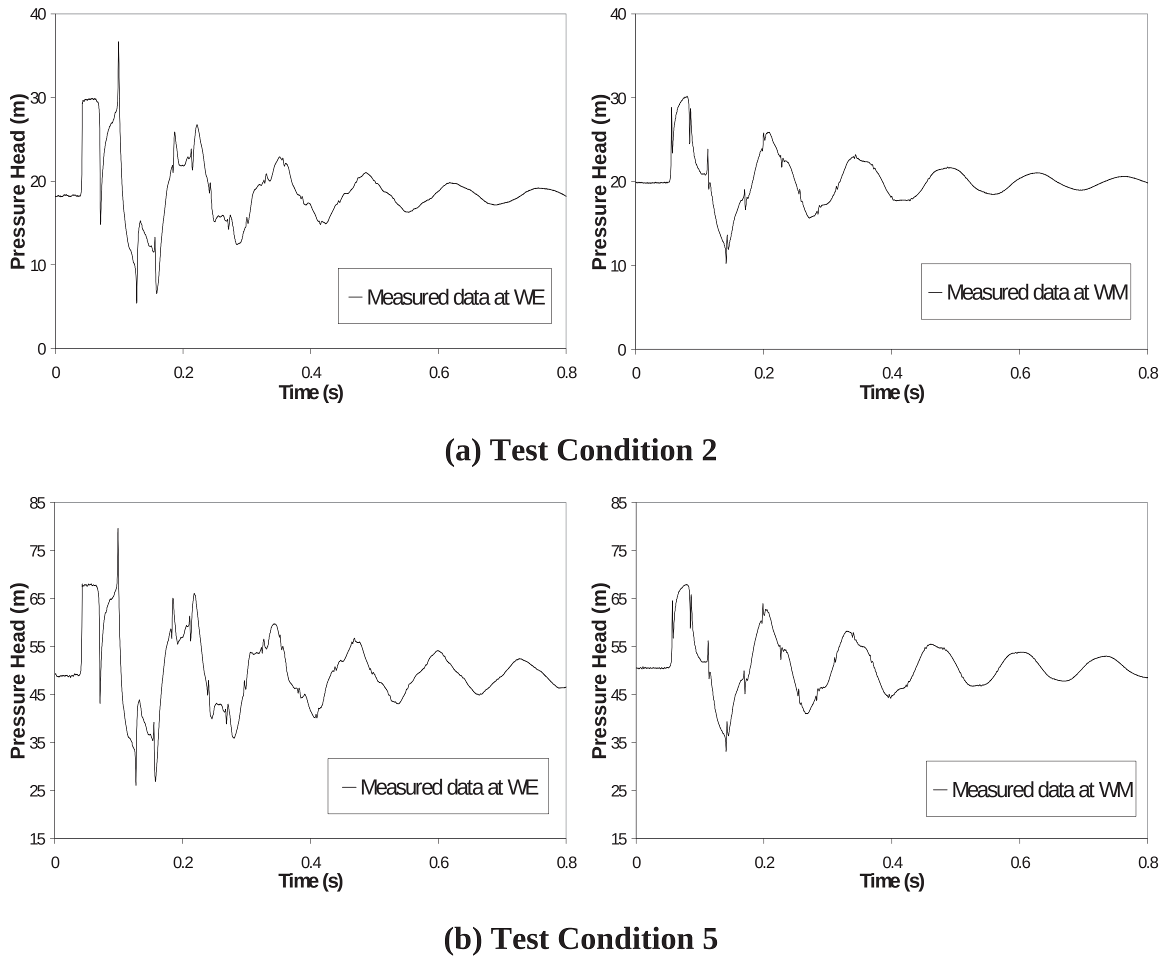


Figure 9.18 Measured Data when the Pipeline has a Rubber Pipe Section

9.7 SIMULATION RESULTS FOR EXPERIMENTAL TESTS

Figs. 9.19 to 9.21 show the comparison between measured pressure data and their simulation results by the proposed viscoelastic model for the polymer pipe section under the test condition 5 when the pipeline has 0.153, 0.895, and 1.630 m polyethylene pipe section at the middle of pipeline. The pressure data for the measurement at the end (WE) of pipeline are shown in Fig. 9.16. The black lines are the measured data, the blue and red lines are the simulation results by the conservative solution scheme including linear elastic model and viscoelastic model respectively. The gray lines indicate simulation results when the pipeline has no polyethylene pipe section (whole copper pipe).

The proposed viscoelastic model, generalized Kelvin-Voigt model, requires a set of creep compliances (J_k) and retarded times (τ_k) as input data for existing the polymer pipe section. These parameters are used to characterize the time-dependent strain of viscoelastic material depending on the molecular structure of the material, temperature, and stress-time history. Creep or dynamic tests under the idealized test conditions can measure these parameters experimentally. However, the mechanical test only provides an estimate of the actual mechanical behaviour of the material in a real pipeline system because the creep compliance and retarded time also depends on the pipe axial and circumferential constraints, pipeline support system, and various stress-time history of the pipeline by flow change as above mentioned.

Alternatively, these parameters can be calibrated by adjusting the measured transient data to the simulated numerical results [Covas et al., 2002]. The creep compliance and retarded time may be estimated by minimizing the difference between measured and computed transient pressure data by an optimisation algorithm. Eq. 9.29 presents the calibrated initial modulus of elasticity and functions for creep compliance and retardation time of the tested polyethylene pipe sections for a temperature of 25^{o}C and flow condition 5.

$$E_o = 3.647\,GPa$$

$$J\,(10^{-9}\,Pa) = 9.5545 \cdot 10^{-3} * \ln(\tau) + 0.27796 \quad \text{When } \tau < 0.005 \qquad (9.29)$$

$$J\,(10^{-9}\,Pa) = 9.1913 \cdot 10^{-3} * \tau + 0.25365 \quad \text{When } \tau > 0.005$$

The results of the whole copper pipe show large discrepancies in both pressure magnitude and phase with experimental data. The presence of a local polyethylene pipe section has a significant effect on the character of transients in the copper pipeline. Even small percentage length (0.153 m polyethylene pipe, 0.4% in proportion to the total pipe length) of polyethylene pipe causes significant lagging of wavespeed as shown in Fig. 9.21. The wavespeed of the system is slower when the pipeline has a longer polyethylene section.

Similar to the results of numerical simulation, the results of the viscoelastic model for a pipeline system with a local polyethylene section show a slight decrease of wavespeed and pressure magnitude when compared to the results for a linear elastic model. Instantaneous linear elastic effect seems to be the more dominant physical phenomena than the effect of viscoelasticity on transient pipe flow with a local polymer pipe section. However, the results of the viscoelastic model improve the simulation results. The timing of the positive and negative pressure waves follows the experimental pressure wave quite closely, and the model accurately predicts the detailed shape of the pressure magnitude affected by local polyethylene pipe section during a transient event, although the pressure peaks of the simulation model slightly exceed the measured data. These results indicate that the pressure transients affected by the local polymer pipe section can be estimated fairly precisely by the conservative solution scheme including the proposed model.

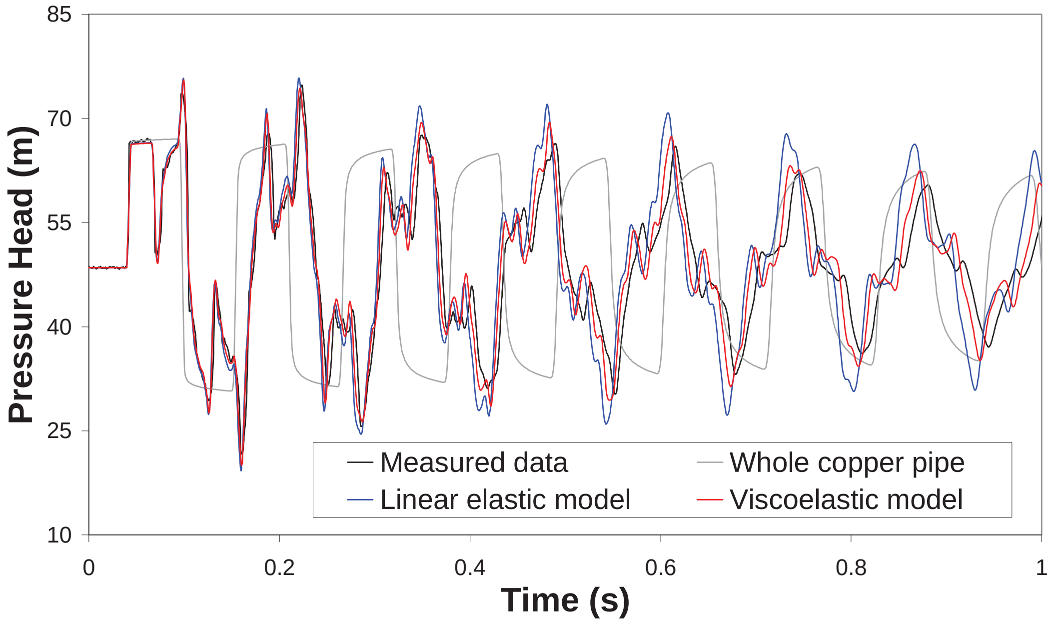


Figure 9.19 Comparison between Measured and Simulation Data when the Pipeline has a 1.630 m Polyethylene Section

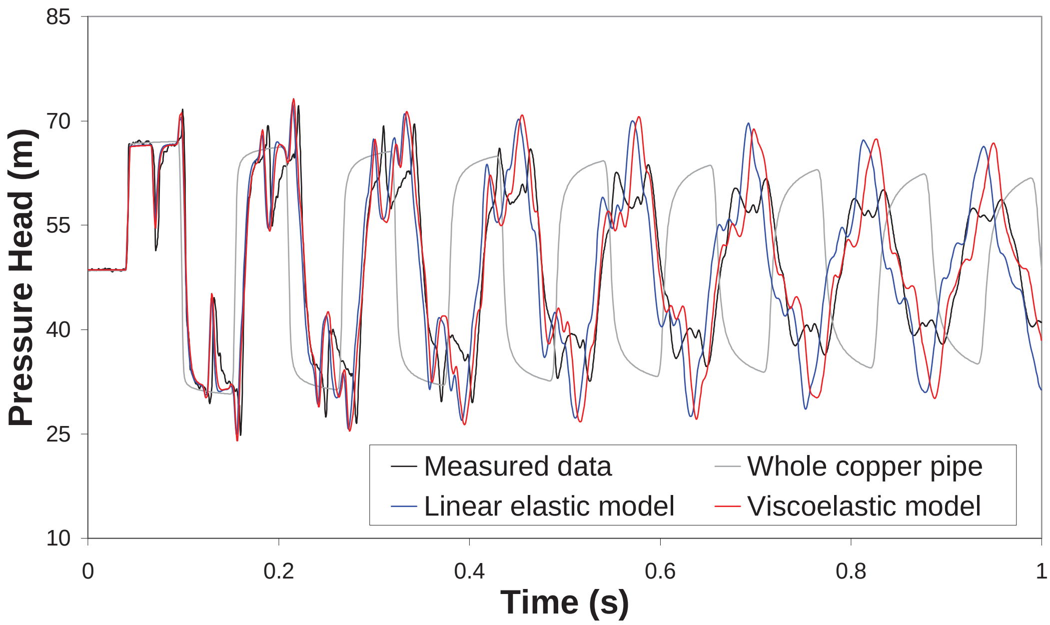


Figure 9.20 Comparison between Measured and Simulation Data when the Pipeline has a 0.895 m Polyethylene Section

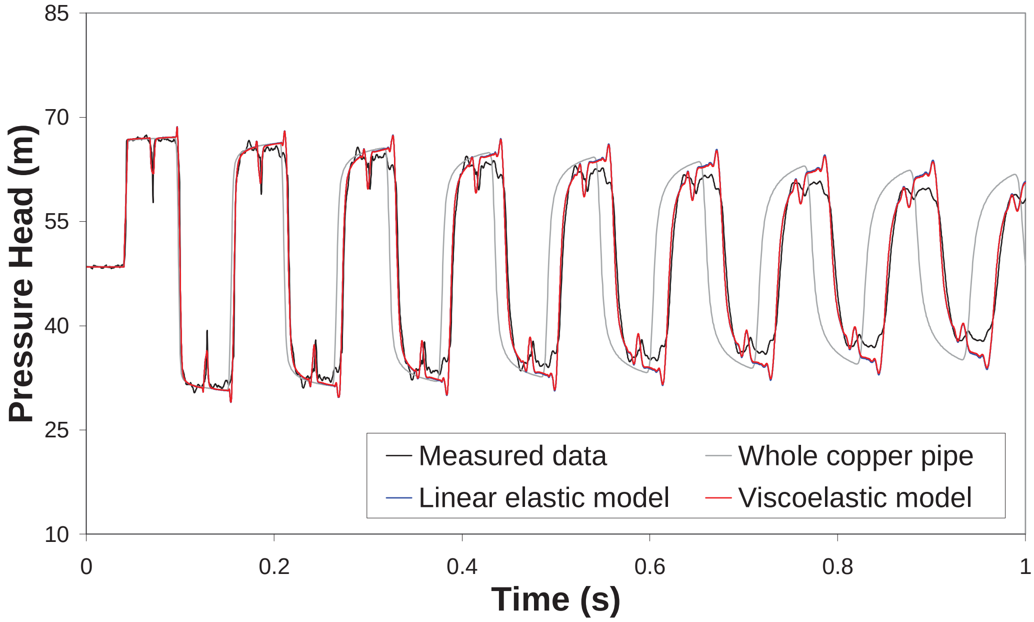


Figure 9.21 Comparison between Measured and Simulation Data when the Pipeline has a 0.153 m Polyethylene Section

9.8 SUMMARY AND CONCLUSIONS

Plastic pipe is a viscoelastic material that exhibits both viscous and elastic characteristics due to its molecular nature when undergoing deformation. Unlike purely elastic substances, viscoelastic substances are a complex combination of elastic-like and fluid-like elements that display properties of crystalline metals and very high viscosity fluids. The viscoelastic behaviour of polymers influences the pressure response during transient events by attenuating pressure fluctuations and by increasing the dispersion of the pressure wave. A generalized Kelvin-Voigt model (mechanical strain principle model with spring-dashpot elements) has been developed for describing the viscoelastic behaviour. Total strain can be decomposed into instantaneous and retarded wall strain. Instantaneous wall strain is analysed by linear-elastic model in the basic equations. A viscoelastic model is added to the linear-elastic model in the conservative solution scheme. The transient model including the viscoelastic term is capable of accurately predicting transient pressure waves in both plastic and metal pipeline system with local plastic sections. This research focuses on the analysis of hydraulic transients in pressurised pipeline system with local polyethylene pipe.

Similar to the effect of entrapped air pocket on transient pipe flows, the presence of local polymer section of even a relatively small size in the copper pipeline greatly decreases the wavespeed. The relative proportions of local polyethylene pipe in a pipeline system lead to different patterns of pressure wave and speeds of pressure propagation. Although the whole polymer pipeline system is beneficial in reducing transient pressure loads, the local polymer pipe can cause shock waves with high frequency spikes that significantly increase peak pressures. The formation of shock waves is associated with the dynamic interaction between fluid flow and pipe wall distensibility. Unlike the simulation results of the pipe that is entirely polyethylene, the simulation results from a viscoelastic model for the pipeline system with a local polyethylene section shows a slight decrease of wavespeed and pressure magnitude when comparing the simulation results to the linear elastic model. Linear elastic effects are more dominant physical phenomena than the effect of viscoelasticity on fast transients with short local polymer section. Nevertheless, the results of viscoelastic model improve simulation results. The timing of the positive and negative pressure waves follows the experimental pressure wave quite closely and the model predicts quite well the detailed shape of pressure magnitude affected by local polyethylene pipe during transients. These results indicate that the pressure transients affected by local polymer pipe can be precisely estimated by the conservative solution scheme including the viscoelastic model.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

The ultimate goal of this research is the development of an appropriate and accurate transient analysis model for various system conditions to improve the performance of pipeline condition assessment as proposed in Chapter 1. To achieve this goal, this thesis presents comprehensive investigations into transient analysis for both water and gas pipeline systems. The dynamic physical behaviour of various system components, such as the effects of unsteady wall resistance, viscoelasticity of polymer pipe, local energy loss elements including leakages, entrapped gas cavities, orifices, and blockages during unsteady pipe flow conditions have been studied. The dynamic characteristics of these system components are modelled based on the conservative solution scheme using the governing equations in their conservative form to improve the accuracy and applicability of transient analysis in both liquid and gas pipelines. Comprehensive laboratory experiments have been undertaken for the verification of the proposed liquid and gas transient analysis models based on the conservative solution scheme and for examining in significant detail the effect of unsteady pipe wall friction and local loss elements during transients. These models are useful tools for pipeline condition assessment and fault detection as well as system modelling and design.

10.1 CONCLUSIONS AND ACHIEVEMENTS

Improvements of transient flow modelling are very important factors for the success of pipeline condition assessment and fault detection based on transient analysis models that rely on the accuracy of the model. This research investigates the effects of unsteady wall resistance, viscoelasticity of polymer pipe, the dynamic behaviour of local losses including leaks, entrapped gas cavities, orifices, and blockages on transient pipe flows. The dynamic characteristics of these system components are modelled based on the conservative solution scheme to improve accuracy, sensitivity, and applicability of transient analysis in both water and gas pipeline systems. The following are the major achievements of this research.

- Development and verification of transient analysis models based on the conservative solution scheme for water and gas pipeline systems.
- Development and verification of unsteady friction models within the conservative solution scheme for water and gas pipeline systems.
- Development and verification of leak estimation models for water and gas transient pipe flows.
- Development and verification of an entrapped gas cavity model for water transient pipe flow.
- Development and verification of unsteady minor loss models for orifice and blockage.
- Development and verification of viscoelastic model for plastic pipe, especially for local plastic pipe section, for water transient pipe flow.

The conservative solution scheme uses fundamental governing equations including all terms and the subsidiary equations for analysing specified features are also expressed by the same generic equations. As a result, the developed distributed and local energy loss models based on the conservative solution scheme are very flexible for the application to other simplified numerical schemes (for example, MOC) according to the degree of simplification for reducing the computational time and numerical complexity. The conservative scheme directly calculates fluid density and pipe wall distensibility at every computational time step. Thus, the wavespeeds of all nodes are updated at every time step. This procedure provides big advantages for analysing systems with variable wavespeeds.

The investigations of the unique dynamic behaviour of pressure waves affected by distributed and local energy loss elements provide fresh insight for pipeline condition assessment as well as system design. The geometrical changes of pipe wall due to system design (valve, connection, or joint) and pipeline fault (corrosion, lining loss, dent, or partially closed valve) can be predicted by the proper use of the proposed dynamic orifice and blockage models. Also, the viscoelastic model can be used for simulating soil-pipe interaction, flexible pipe joint, and household water service that show significant viscoelastic behaviour as noticed in recent tests in water distribution networks.

Each of the simulation results using four different unsteady friction models (original weighting function model, approximated weighting function model, and their modified models for the conservative scheme) in the conservative scheme shows good agreement with experimental results. The modified model effectively decreases the computational time. In the case of gas transients, the fluid compressibility is the dominant physical process for transient analysis rather than the frictional effect. Although the gas transient models including an unsteady friction term can reasonably accurately predict the whole transient traces, the simulation results of models overestimate the line-packing.

The leak model for water transients accurately predicts the phase, magnitude and shape of pressure waves of the experimental data. Unlike the measured data of water transients with leaks, the change of pressure wave by a leak has been shown to be small for gas transients. The compressibility of gas diminishes the impact of leaks during transients. A mathematical model for simulating the effect of entrapped air pockets on transient pipe flows yields practical results. The gas cavity model is effective in treating relatively small gas volumes in a pipeline system. This model has been shown to accurately calculate the overall pressure trace with variable wavespeeds, high frequency pressure spikes, and the change of pressure magnitude.

The measured transient data with orifices or blockages show that the magnitude of pressure waves dramatically decreases as the bore size of an orifice or blockage decreases. The most important characteristics of the measured transient data with restrictions are the apparent change in the wavespeed illustrated by the lagging and phase change of the pressure wave due to the reduction of bore size. The simulation results of the frequency dependent model with wavespeed adjustment for orifices and blockages show good agreement with the measured data in terms of the magnitude, shape and overall pressure trace. In addition, the transient model including the viscoelastic term is capable of accurately predicting transient pressure waves in both polymer pipeline system and metal pipeline system with local polymer section.

10.2 RECOMMENDATIONS FOR FUTURE WORK

The main future research is suggested to be the application of the proposed models to field pipeline systems with large scale and wide range of operational conditions. Real systems have various product characteristics and pipeline parameters, complex topology, and numerous flow system components that generate interactions of pressure waves during transients and offer a challenge to accurate transient analysis. The relatively large computational time and storage of the conservative solution scheme using implicit finite difference method can be improved by a more effective sparse matrix solver or advanced large matrix solver for the problems of large pipeline systems. Moreover, there are still important and essential local loss elements that need to be investigated to improve the sensitivity and accuracy of transient analysis and the performance of pipeline condition/risk assessment and fault detection. Junctions, cross-connections, elbows, and dead-ends are the most common system components for pipe networks and they may also create unique dynamic characteristics involving energy dissipation and dispersion during transient events. Future work will focus on the modelling and investigation of the effects of these network components on transients.