SIMON W. FREESE ENVIRONMENTAL ENGINEERING LECTURE

Waterhammer Analysis—Essential and Easy (and Efficient)

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Abstract: For most piping systems the maximum and minimum operating pressures occur during transient operations. Therefore it is essential to good design and operation to perform a transient analysis for normal startup and shutdown and for unplanned events such as a pump trip associated with a power outage. This author also claims that waterhammer (transient) analysis is easy. Hydraulic engineers who have studied the traditional approach to transient analysis might dispute this claim but, in fact, carrying out an analysis using the concept of pressure wave action provides an accurate, intuitive, and simple method for transient pipe system analysis of simple or complex pipe systems. Not only is this approach simple, it is extremely efficient producing accurate solutions with far fewer calculations making this approach suitable for analyzing large pipe distribution systems.

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Introduction

Waterhammer analysis has traditionally not received the attention it deserves in our engineering curriculums and the consideration it requires for safe and effective design and operation of piping systems. The principal reason for this situation is that transient analysis has been presented to engineers in a manner which is complex and difficult to apply to pipe system hydraulic design when, in fact, this topic can be presented in an intuitive and easily applied manner. In this paper an approach to transient flow analysis based on the action of pressure waves is presented. It is shown that this approach produces accurate solutions using far fewer calculations. In addition the approach provides the engineer with an intuitive understanding of pipeline hydraulic transients which will result in improved designs and operations.

Importance of Hydraulic Transient Analysis (Essential)

Transient analysis of the performance of piping systems is often more important than the analysis of the steady state operating conditions that engineers normally use as the basis for system design. Transient pressures are most important when the rate of flow is changed rapidly, such as resulting from rapid valve closures or pump stoppages. Such disturbances, whether caused by design or accident, may create traveling pressure waves of large magnitudes. These transient pressures are superimposed on the steady state conditions present in the line at the time the transient occurs. The severity of transient pressures must be determined so that the water mains can be properly designed to withstand these additional loads. In fact, pipes are often characterized by their "pressure ratings" that define their mechanical strength and have a significant influence on their cost (Boulos et al. 2003, 2004).

Transient regimes in water distribution systems are inevitable and will normally be most severe at pump stations and control valves, high elevation areas, locations with low static pressures, and remote locations that are distanced from overhead storage (Friedman 2003). All systems will, at some time, be started up, switched off, undergo unexpected flow changes, etc., and will likely experience the effects of human errors, equipment breakdowns, earthquakes, or other risky disturbances. Although transient conditions can result in many situations, the engineer is most concerned with those that might endanger the safety of a plant and its personnel, that have the potential to cause equipment or device damage, that results in operational difficulties, or pose a risk to the public health.

Transient events have significant water quality implications. These events can generate high intensities of fluid shear and may cause resuspension of settled particles as well as biofilm detachment. So-called red water events have often been associated with transient disturbances. Moreover, a low-pressure transient event, say arising from a power failure or pipe break, has the potential to cause the intrusion of contaminated groundwater into a pipe at a leaky joint or break. Depending on the size of the leaks, the volume of intrusion can range from a few gallons to hundreds of gallons (Funk et al. 1999; LeChevallier 1999; Karim et al. 2003; Le Chevallier et al. 2003). Negative pressures induce backsiphonage of nonpotable water from domestic, industrial, and institutional piping into the distribution system. Dissolved air (gas) can also be released steel and iron sections with subsequent rust formation and pipe damage. Even some common transient protection strategies, such as relief valves or air/vacuum valves, if not properly designed and maintained, may permit pathogens or

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other contaminants to find a “back door” route into the potable water distribution system.

Engineers must carefully consider all potential dangers for their pipe designs and estimate and eliminate the weak spots. They should then embark upon a detailed transient analysis to make informed decisions on how to best strengthen their systems and ensure safe, reliable operations (Karney and McInnis 1990; McInnis and Karney 1995).

Causes of Hydraulic Transients

Hydraulic transient events are disturbances in the water caused during a change in state, typically from one steady or equilibrium condition to another. The principle components of the disturbances are pressure and flow changes at a point that causes propagation of pressure waves throughout the distribution system. The pressure waves travel with the velocity of sound (acoustic or sonic speed), which depends on the elasticity of the water and that of the pipe walls. As these waves propagate, they create transient pressure and flow conditions. Over time, damping actions and friction reduces the waves until the system stabilizes at a new steady state. Normally, only extremely slow flow regulation can result in smooth transitions from one steady state to another without large fluctuations in pressure or flow.

In general, any disturbance in the water generated during a change in mean flow conditions will initiate a sequence of transient pressures (waves) in the water distribution system. Disturbances will normally originate from changes or actions that affect hydraulic devices or boundary conditions. Typical events that require transient considerations include:

1. pump startup or shutdown;
2. valve opening or closing (variation in cross-sectional flow area);
3. changes in boundary pressures (e.g., losing overhead storage tank, adjustments in the water level at reservoirs, pressure changes in tanks, etc.);
4. rapid changes in demand conditions (e.g., hydrant flushing);
5. changes in transmission conditions (e.g., main break or line freezing);
6. pipe filling or draining—air release from pipes; and
7. check valve or regulator valve action.

Potentially, these disturbances can create serious consequences for water utilities if not properly recognized and addressed by proper analysis and appropriate design and operational considerations. Hydraulic systems must be designed to accommodate both normal and abnormal operations and be safeguarded to handle adverse external events such as power failure, pipeline fracture, etc. (Boulos et al. private communication 2004)

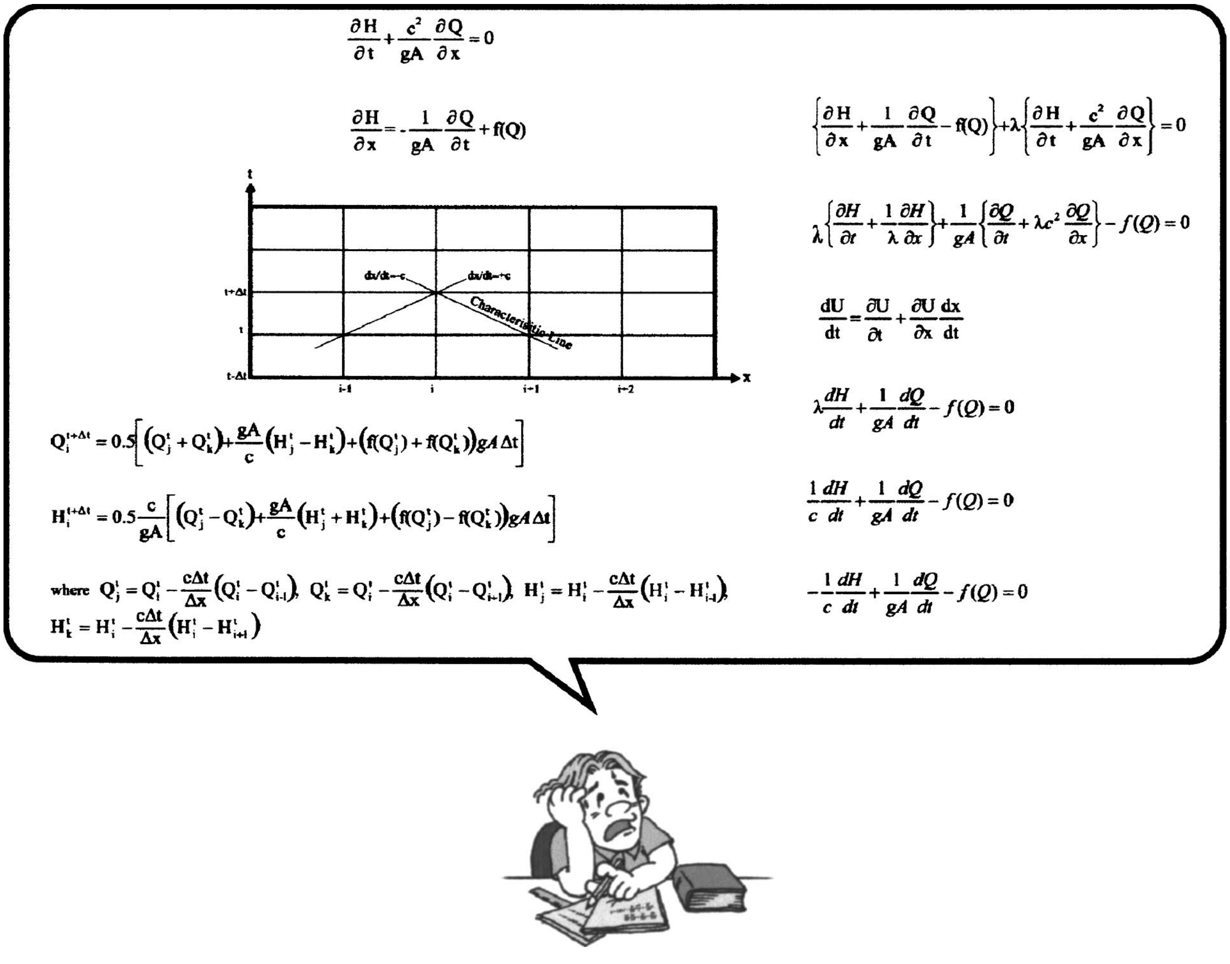


Fig. 1. Ordinary engineer will often become lost in maze of equations

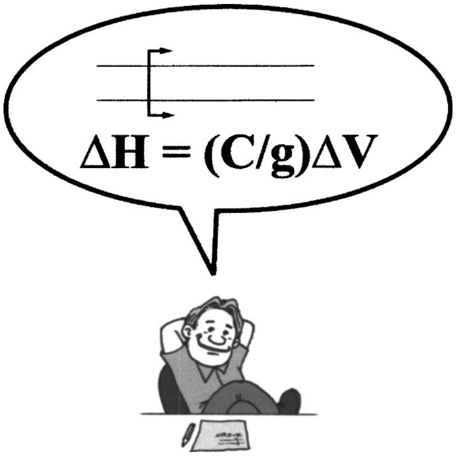


Fig. 2. Calculations and concepts-method of characteristics and wave characteristic method methods

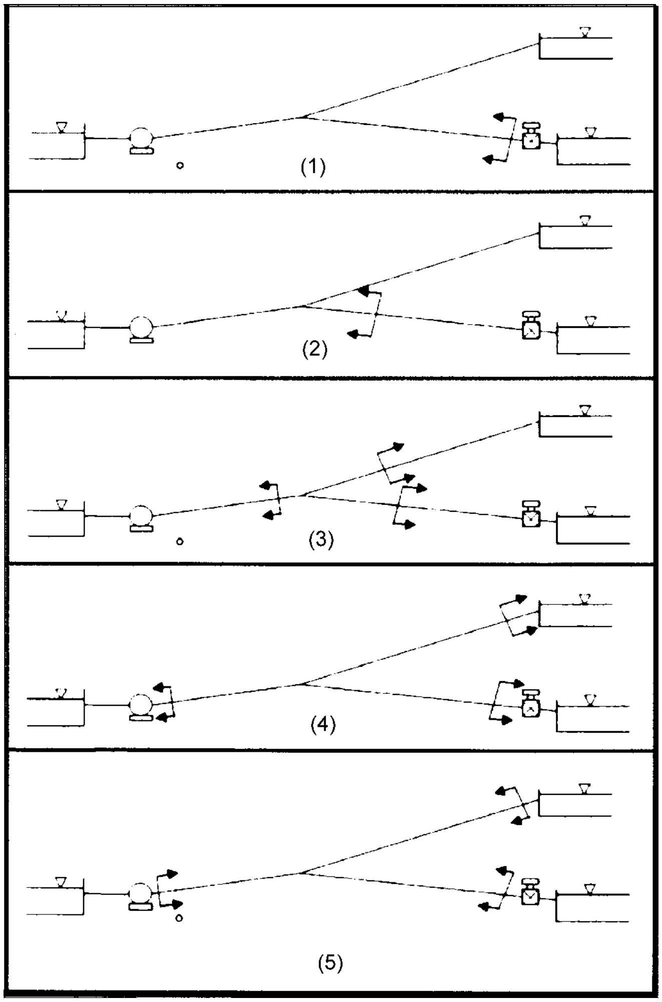
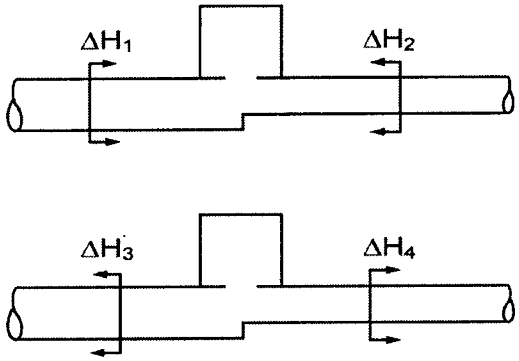
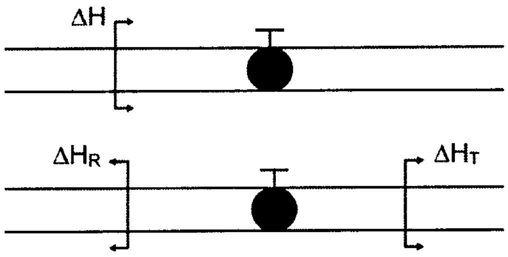


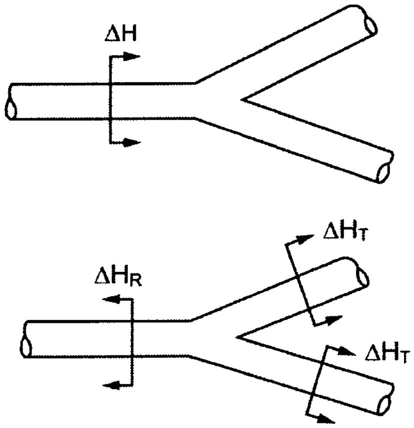
Fig. 3. Illustration of wave characteristic method



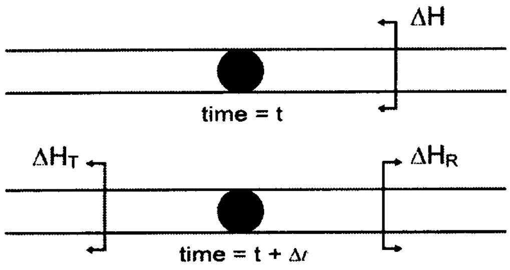
Surge control device



Component



Junction



Effect of friction

Fig. 4. Analysis of pressure wave action for wave characteristic method

Table 1. Comparison of Required Calculations [Method of Characteristics (MOC) and Wave Characteristic Method (WCM)]

Example number	Number of nodes	Number of pipes	Δt (s)	Number of intersecting points	Calculations/Δt MOC	WCM	MOC/WCM
1	7	9	0.1	41	48	16	3.0
2	36	40	0.0139	680	716	76	9.4
3	589	788	0.0056	15,117	15,708	1,377	11.4
4	1,170	1,676	0.0067	81,508	82,678	2,846	29.0
5	1,849	2,649	0.0056	159,640	161,486	4,495	35.9

Analyzing Transients in Pipe Systens

Rapidly varying pressure and flow conditions (waterhammer) in pipe systems are characterized by variations, which are both position (x) and time (t) dependent. These conditions are described by the continuity equation

$$\frac{\partial H}{\partial t} = -\frac{c^2}{gA_L}\frac{\partial Q}{\partial x} \tag{1}$$

and the momentum equation

$$\frac{\partial H}{\partial x} = -\frac{1}{gA_L}\frac{\partial Q}{\partial t} + f(Q). \tag{2}$$

Here H=pressure head (pressure/density); Q=volumetric flowrate; c=sonic wave speed in the pipe; A_L=cross sectional area; g=gravitational acceleration; P=mass density; and $f(Q)$ represents a pipe resistance term which is a function of flowrate. Eqs. (1) and (2) have been simplified by considering only changes along the pipe axis (one dimensional flow) and discarding terms that can be shown to be of minor significance. A transient flow solution is obtained by solving Eqs. (1) and (2) along with the appropriate initial and boundary conditions. However, except for very simple applications that neglect or greatly simplify the boundary conditions and the pipe resistance term, it is not possible to obtain a direct solution.

Graphical and algebraic methods for solving the basic transient flow (waterhammer) equations have been developed (Streeter and Wylie 1967). These procedures are generally based on a numerical procedure using the method of characteristics (MOC). The MOC is conceptually somewhat complex and requires numerous steps or calculations to solve a typical transient pipe flow problem. As the complexity of the pipe system increases, the number of required calculations increases and for practical applications a computer program is required. Various computer programs have been developed based on the MOC and procedures for handling pipe junctions, pumps, surge tanks, and cavitation have been included is most of these programs. The method of characteristics has been described in detain in numerous publications (Streeter and Wylie 1967; Watters 1984; Chaudhry 1987; and Martin 2000).

Table 2. Pipe Characteristics for Example 1

Pipe number	Length ft (m)	Diameter in. (mm)	Roughness	Minor loss
1	2,000 (610)	36 (914)	92	0
2	3,000 (914)	30 (762)	107	0
3	2,000 (610)	24 (610)	98	0
4	1,500 (457)	18 (457)	105	0
5	1,800 (549)	18 (457)	100	0
6	2,200 (671)	30 (762)	93	0
7	2,000 (610)	36 (914)	105	0
8	1,500 (457)	24 (610)	105	0
9	1,600 (488)	18 (457)	140	0

This paper describes an alternate numerical scheme for carrying out transient flow analysis in piping systems. This procedure, initially developed as the "wave plan method" (Wood et al. 1966) yields solutions which are virtually identical to those obtained from exact solutions or those based on the method of characteristics. This approach, however, normally requires orders of magnitude fewer calculations and has the additional advantage of using a conceptually simple physical model as the basis for its development. Because of this, the engineer will gain a better understanding of the mechanics of transient pipe flow.

This method is based on the physically accurate concept that the transient pipe flow results from the generation and propagation of pressure waves that occur as a result of a disturbance in the pipe system (valve closure, pump trip, etc.). A pressure wave, which represents a rapid pressure and associated flow change, travels at sonic velocity for the liquid-pipe medium, and the wave is partially transmitted and reflected at all discontinuities in the pipe system (pipe junctions, pumps, open or closed ends, surge tanks, etc). A pressure wave can also be modified by pipe wall resistance. This description is one that closely represents the actual mechanism of transient pipe flow. In this paper this method is referred to as the wave characteristic method (WCM).

The primary purpose of this paper is illustrated in the first two figures. As shown in Fig. 1, transient analysis can be presented is such a manner that only selected engineering gurus will master the techniques and be able to follow this maze of manipulations and carry out these important calculations. The ordinary engineer will often become lost in the maze of equations and procedures. Or, as shown in Fig. 2, the simple, intuitive calculations based

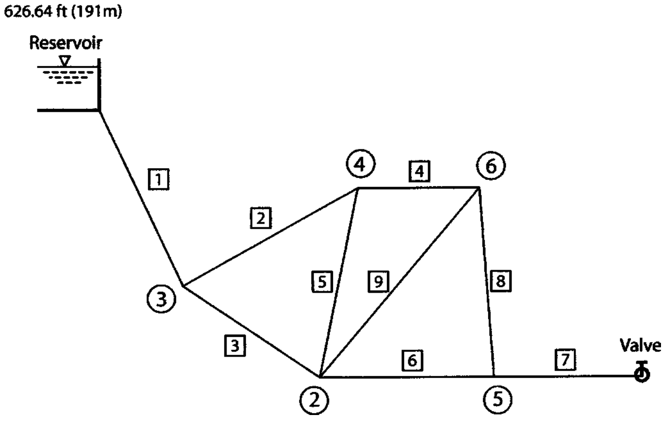


Fig. 5. Example 1 schematic

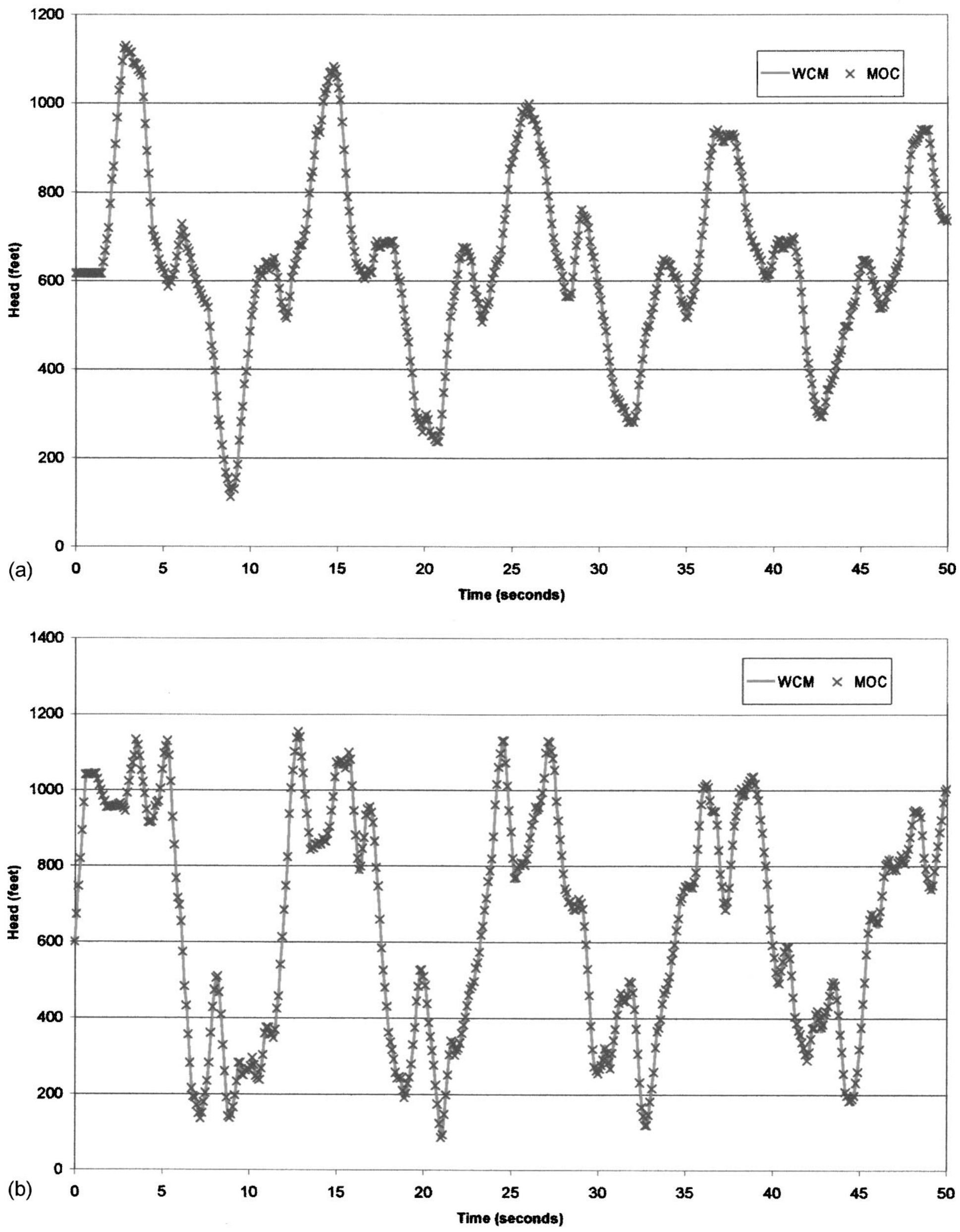


Fig. 6. Comparison of results of wave characteristic and method of characteristics comparison (valve closure 0.6 s) for Example 1: (a) Junction 4 and (b) upstream of valve

on pressure wave action and the basic waterhammer equation will be learned and utilized by all hydraulic engineers resulting in improved pipeline designs and operations which give full consideration to transient operations.

Transient Analysis of Pipe Systems Using Wave Method (Easy)

Pressure waves are generated at any point in a flow system where a disturbance that results in a change in flowrate is introduced. This can include a valve that is opening or closing, a pump that is started up or shut down, a change in a reservoir pressure, or a change in an inflow or outflow for the system. Pressure and flow conditions at a component are also affected by pressure waves impinging on the component. This approach to transient analysis is illustrated in Fig. 3. (1) A valve closes and a pressure wave is generated. (2) The wave travels toward the three pipe junction at sonic speed in the pipe. (3) The wave is transmitted into the two connecting pipes and reflected back into the original pipe producing three new pressure waves. (4) Each pressure wave travels at sonic speed toward the opposite end of the pipes and impinge on the elements located there. (5) The pressure waves modify conditions at the reservoir, valve, and pump and new pressure waves are generated and travel back toward the junction.

This approach to transient analysis requires the calculation of the effects of pressure waves impinging on (1) components (such as valves and pumps), (2) junctions, (3) surge control elements, and (4) a calculation the effect of line friction on the magnitude of pressure waves. These pressure wave action calculations required for general applications to pipe systems are illustrated in Fig. 4.

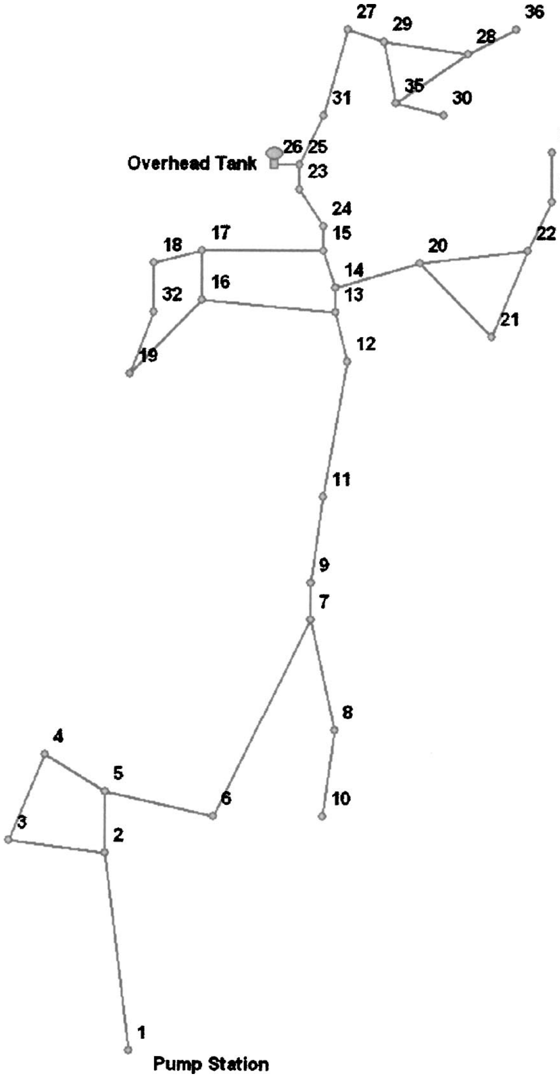


Fig. 7. Example 2 schematic

Computer routines developed for wave action at (1) components, (2) junctions, (3) surge control devices, and (4) the effect of pipe friction have been utilized to create a general purpose computer model for pipe system transient analysis based on the wave method. The program uses the fact that pressure waves are transmitted between elements at known speeds and are modified by pipeline friction to determine the characteristics of the impinging waves at any time during the simulation. This technique may be applied to complex pipe systems (the WCM) and has been widely used in commercially available software for over 20 years (Wood and Funk 1996). A textbook presenting this technique in detail is available (Wood et al. 2004).

Comparing Wave Charcteristic Method and Method of Characteristics (Efficient)

Method of Charcteristics and Wave Charcteristics Method Numerical Techniques

The strategy employed by the MOC is to convert the governing partial differential equations to ordinary differential equations and then to a difference form for solution by a numerical method. The equations express the head and flow for small time steps (Δt) at numerous locations along the pipe sections. Calculations during the transient analysis must begin with a known initial steady state and boundary conditions. That is head and flow at time $t=0$ will be known along with head and/or flows at the boundaries at all time periods. To handle the wave characteristics of the transient flow head and flow values at time $t+\Delta t$ at interior locations are calculated making use of known values of head and flow at the previous time step at adjacent locations using the ordinary differential equations expressed in difference form. Exact solutions of the basic wave equations have been compared to numerical solutions based on the MOC and WCM and have been shown to be identical (Boulos et al. 1990). However these comparisons were limited to extremely simple systems.

The WCM is based on the concept that the transient pipe flow results from the generation and propagation of pressure waves that occur as a result of a disturbance in the pipe system (valve closure, pump trip, etc.). The wave characteristics are handled using pressure waves, which represents rapid pressure and associated flow changes that travel at sonic velocity for the liquid-pipe medium. A pressure wave is partially transmitted and reflected at all discontinuities in the pipe system (pipe junctions, pumps, open or closed ends, surge tanks, etc). The pressure wave will also be modified by pipe wall resistance. This description is one that closely represents the actual mechanism of transient pipe flow (Thorley 1991; Boulos et al., 2004).

Both the MOC and WCM obtain solutions at intervals of Δt at all junctions and components. However, the MOC also requires solutions at all interior points for each time step. This requirement basically handles the effects of pipe wall friction and the wave propagation characteristics of the solutions. The WCM handles these effects by using the pressure wave characteristics. The waves propagate through pipes at sonic speed and are modified for the effects of friction by a single calculation for each pipe section.

Required Number of Calculations

Both the MOC and the WCM require many calculations to solve the transient flow problem. These calculations involve updating the pressure and flow at required locations at increments of the time step Δt. In order to compare the number of calculations required, we define one calculation as the operation required to update the pressure and flow at a single location.

The MOC requires a calculation at all nodes and all interior points at each time step. The WCM requires a calculation at each node and one calculation for each pipe at each time step. The pipe calculations are required to modify the pressure waves in that pipe to account for the effect of pipe wall and fittings friction.

The time step used in the analysis will be determined by the tolerance set for the accuracy of the model pipe lengths or wave speed. A time step must be chosen such that pressure waves traverse each pipe segment in time which is a multiple of the time step. For the comparisons shown the pipe length tolerance was set to 6 m (20 ft). This means that the largest possible time increment was chosen so that the maximum error in the length of pipes in the model would not exceed 6 m (20 ft).

Table 1 summarizes the calculations requirements for two example systems (Wood et al. private communication 2004). Details for these examples follow. In addition a comparison is made for three additional larger (existing) water distribution systems which have been modeled and analyzed using both approaches but not described herein (Examples 3–5).

Table 3. Network Characteristics for Example 2

Pipe ID	Length ft (m)	Diameter in. (mm)	Roughness	Node ID	Elevation ft (m)	Demand gpm (L/s)
1	2,400 (732)	12 (305)	100	1	50 (15)	−694.4 (−44)
2	800(244)	12(305)	100	2	100 (30)	8 (0.5)
3	1,300(396)	8(203)	100	3	60 (18)	14 (0.9)
4	1,200(366)	8(203)	100	4	60 (18)	8 (0.5)
5	1,000(305)	12(305)	100	5	100 (30)	8 (0.5)
6	1,200(366)	12(305)	100	6	125 (38)	5 (0.3)
7	2,700(823)	12(305)	100	7	160 (49)	4 (0.3)
8	1,200(366)	12(305)	140	8	110 (34)	9 (0.6)
9	400(122)	12(305)	100	9	180 (55)	14 (0.9)
10	1,000(305)	8(203)	140	10	130 (40)	5 (0.3)
11	700(213)	12(305)	100	11	185 (56)	34.78 (2.2)
12	1,900(579)	12(305)	100	12	210 (64)	16 (1)
13	600(183)	12(305)	100	13	210 (64)	2 (0.1)
14	400(122)	12(305)	100	14	200 (61)	2 (0.1)
15	300 (91)	12(305)	100	15	190 (58)	2 (0.1)
16	1,500(457)	8(203)	100	16	150 (46)	20 (1.3)
17	1,500(457)	8(203)	100	17	180 (55)	20 (1.3)
18	600(183)	8(203)	100	18	100 (30)	20 (1.3)
19	700(213)	12(305)	100	19	150 (46)	5 (0.3)
20	350(107)	12(305)	100	20	170 (52)	19 (1.2)
21	1,400(427)	8(203)	100	21	150 (46)	16 (1.0)
22	1,100(335)	12(305)	100	22	200 (61)	10 (0.6)
23	1,300(396)	8(203)	100	23	230 (70)	8 (0.5)
24	1,300(396)	8(203)	100	24	190 (58)	11 (0.7)
25	1,300(396)	8(203)	100	25	230 (70)	6 (0.4)
26	600(183)	12(305)	100	27	130 (40)	8 (0.5)
27	250 (76)	12(305)	100	28	110 (34)	0 (0)
28	300 (91)	12(305)	100	29	110 (34)	7 (0.4)
29	200 (61)	12(305)	100	30	130 (40)	3 (0.2)
30	600(183)	12(305)	100	31	190 (58)	17 (1.1)
31	400(122)	8(203)	100	32	110 (34)	17 (1.1)
32	400(122)	8(203)	100	33	180 (55)	1.5 (0.1)
34	700(213)	8(203)	100	34	190 (58)	1.5 (0.1)
35	1,000(305)	8(203)	100	35	110 (34)	0 (0)
36	400(122)	8(203)	100	36	110 (34)	1 (0.1)
37	500(152)	8(203)	100	26	235 (72)	Tank
38	500(152)	8(203)	100	—	—	—
39	1,000(305)	8(203)	100	—	—	—
40	700(213)	8(203)	100	—	—	—
41	300 (91)	8(203)	100	—	—	—

It should be noted that the number of calculations for the WCM per time step does not change with accuracy. For the MOC the number of calculations per time step is roughly proportional to the accuracy. or the above examples, the calculations/Δt required for the MOC would roughly double if an accuracy of 3 m (10 ft) is required and will be halved if an accuracy of 12 m (40 ft) is called for.

Example 1

The first example network was studied earlier by Streeter and Wylie (1967) and is shown in Fig. 4. The network comprises nine pipes, five junctions, one reservoir, three closed loops, and one valve located at the downstream end of the system. The valve is shut to create the transient. Table 2 summarizes the pertinent pipe system characteristics. The reservoir level is shown in Fig. 5. Fig. 6 compares the transient results obtained using the MOC and WCM solution schemes at the valve and at Junction 4. A 67 m (20 ft) length tolerance was used in the analysis which resulted in a required time step of 0.1 s. In Fig. 6, both solutions are plotted and the two methods produced results that are virtually indistinguishable.

Example 2

Using a slightly larger more complex system, the methods were applied to the network shown in Fig. 7. This represents an actual water system and consists of 40 pipes, 35 junctions, one supply pump, and one tank. This example appears in the *EPANET* (Rossman 1993) documentation. Table 3 summarizes the pertinent pipe system characteristics. The pump station is modeled by designating the inflow at that location. Fig. 8 compares the

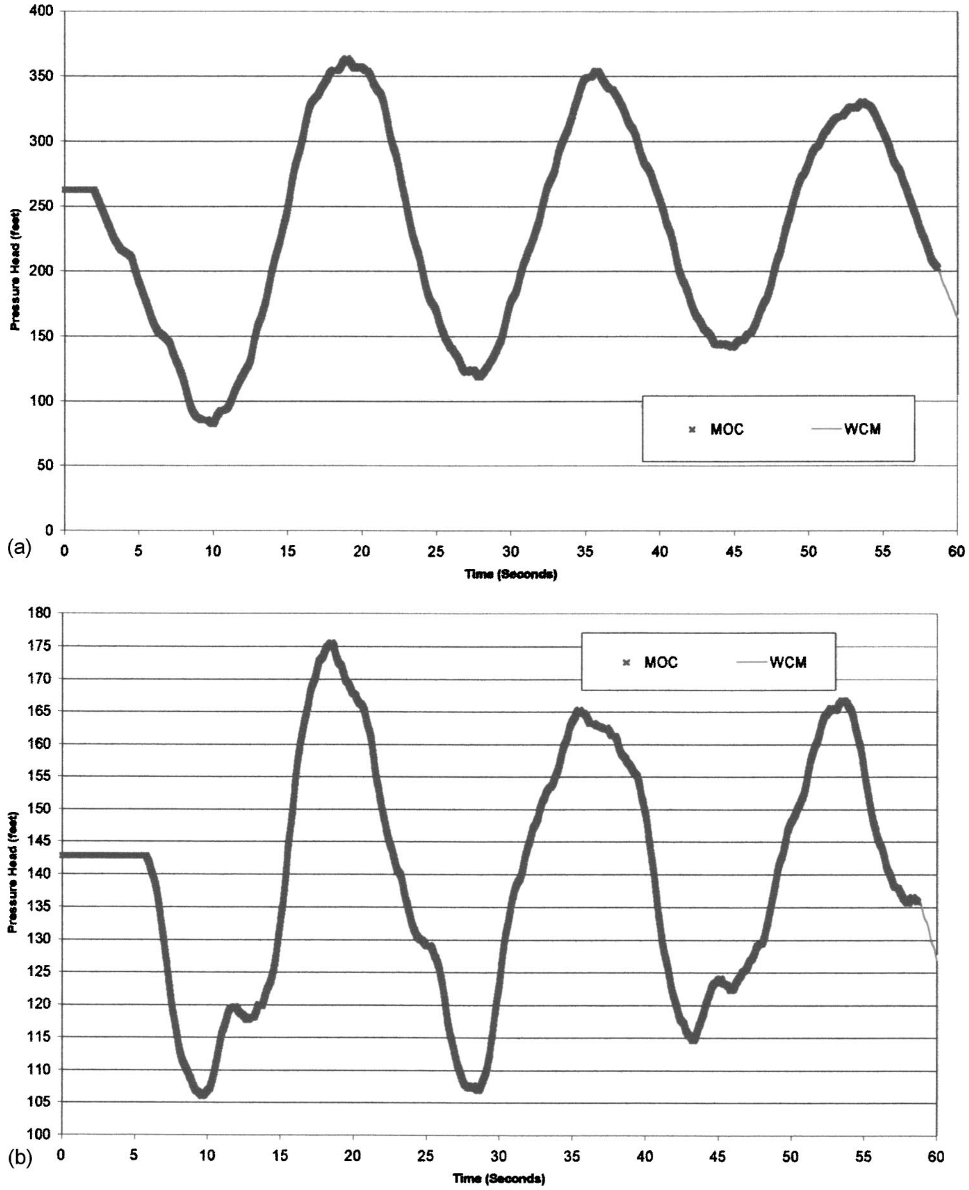


Fig. 8. Comparison of results of wave characteristic and method of characteristics comparison (8 s rundown) for Example 2: (a) Node 1; and (b) Node 19

transient results obtained using the MOC and the WCM solution schemes at Nodes 1 and 19, respectively, following a pump shutdown simulated by reducing the inflow to zero over a period of 6 s. A 6 m (20 ft) length tolerance was employed in the analysis resulting in a required time step of 0.0139 s. As can be seen from Figs. 7 and 8, both methods yielded virtually identical results.

Conclusions

Transient (waterhammer) analysis is essential to good design and operation of piping systems. This important analysis can be done using the mathematically based MOC or the WCM based on the action of pressure waves. The MOC and WCM methods are both capable of accurately solving for transient pressures and flows in water distribution networks including the effects of pipe friction. The MOC requires calculations at interior points to handle the wave propagation and the effects of pipe friction. The WCM handles these effects using pressure waves. Therefore, for the same modeling accuracy the WCM will normally require fewer calculations and faster execution times. In addition, the number of calculations per time step does not increase for the WCM when more accuracy is required. Because of the difference in calculation requirements and the comparable accuracy of the two techniques, the use of the WCM will be more suitable for analyzing large pipe networks.

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