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# ENERGY DISSIPATION MECHANISMS IN WATER DISTRIBUTION SYSTEMS

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**ABSTRACT:** An important issue in the context of design and analysis of a water distribution system is the rate of energy dissipation of a transient disturbance. In this paper, a preliminary numerical investigation is undertaken to establish the role and significance of primary energy dissipation mechanisms commonly found in water transmission and distribution systems. The role of steady friction, unwanted leaks, topological complexity and surge control devices in the decay of transient energy is preliminarily investigated. An energy approach previously derived is reviewed and used to track the progress of dissipation in a system. Transient simulations are run on a hypothetical series pipeline and distribution network with a waterhammer simulator to explore the dissipative effectiveness of some of the primary mechanisms.

## INTRODUCTION

The interchange and dissipation of mechanical energy during any dynamic process is a challenging, insightful and, sometimes, problematic phenomenon. Energy losses must usually be "bought" from external supplies, often at significant financial and environmental cost. Yet, almost as often, the same dissipation mechanisms play an essential and positive role in system control, allowing dynamic conditions in the system to be stopped, adjusted, mitigated or deflected. Typical of such conversion processes are the hydraulic losses in a control valve, the heat associated with friction losses when a car's breaks are applied, or the distributed pressure drop in a pipe or conduit. Overall, energy dissipation plays a dual role, both helping and hindering system performance and behavior, and it is critical that analysts account for the dialectical nature of mechanical energy losses.

Of particular importance in the current context is the fact that hydraulic conditions in most water distribution networks are in an almost constant state of change. Various users are continually adjusting their flow requirements, valves are frequently being adjusted and pumps are often switched on and off. Yet, despite this never-ending activity, hydraulic conditions are frequently well behaved; transients tend to decay rapidly as the system moves between near steady states. Moreover, the superposition or overlap of transient events is seldom required by designers or justified by analysts. The obvious implication is that there are many important and effective conversion and dissipation mechanisms taking place during the dynamic evolution of conditions in a water distribution network.

## Historical Perspective

Recently, numerous researchers have studied the energy conversion and dissipation mechanisms that operate on a pipeline-fluid system during waterhammer conditions. Karney [1] developed an energy expression to track the conversion of fluid kinetic energy to elastic (internal) energy and back again, as well as work and mechanical-energy dissipation interactions in a pipeline. Kung and Yang [2] adapted the energy expression developed by Karney [1] to simulate energy processes and interactions in a simple hydropower system comprising a penstock, surge-tank and throttling valve at the downstream end. More recently, Ghidaoui, Karney and McInnis [3] have adapted the energy expression to quantify discretization errors and energy dissipation levels associated with wave speed adjustment, time-line interpolation and space-line interpolation methods.

In the past fifty years, researchers have progressively studied the problem of frictional dissipation in unsteady pipe flow. This collective research effort has been focused on developing unsteady pipe flow friction models for use in hydraulic transient simulators in the place of steady friction models (i.e., Darcy-Weisbach and Hazen-Williams) which typically underestimate energy dissipation in a pipe system during fast transients. As a result, a panoply of 1-D models have been developed to account explicitly for boundary-layer effects and unsteady shear stress between fluid and pipe wall during waterhammer events (e.g., Dailey *et al*. [4], Zeilke [5], Wood and Funk [6], Funk and Wood [7], Safwat and Polder [8], Trikha [9], Suo and Wylie [10], Vardy *et al.* [11], Vardy and Brown [12], Shuy [13], Shuy [14]). To simplify matters, Greco, Brunone and Golia and Brunone *et al.* [15-17] have developed 1-D unsteady friction models in which fluid shear stress is taken to be proportional to the instantaneous acceleration of the fluid in the pipe. In these models, the constant of proportionality is determined by way of experimentation. In a similar vein, Axworthy *et al.* [18] used extended irreversible thermodynamic (EIT) theory to demonstrate the physical validity of the instantaneous fluid acceleration model and establish the range of flow conditions within which it yields accurate results. Other researchers have attempted to tackle the unsteady dissipation problem more directly by developing quasi 2-D unsteady friction models which account explicitly for transient velocity profiles, fluid shear stress and fluid vorticity near the pipe wall through turbulence equations (e.g., Vardy and Hwang [19], Eichinger and Lein [20], Silva-Araya and Chaudhry [21-23], Pezzinga [24], Ghidaoui and Mansour [25]). So far, these sophisticated and cumbersome quasi 2-D models have been used mostly to calibrate 1-D unsteady models.

## Current Purpose

The goal of this paper is to begin to assess the effectiveness of primary energy dissipation mechanisms—both natural and designed—that are commonly found in pipeline systems under waterhammer conditions. This goal is motivated by the assumption that a better understanding of these processes is desirable and necessary in the rational design and operation of systems. However, there are several practical issues that also further motivate the study. These involve the following:

1. The need to better design transient protection strategies that should ideally balance natural dissipation mechanisms with specifically designed ones;

2. The need to optimize the control algorithms embedded in various devices (e.g., pressure reducing valves and variable-speed drives) so that instabilities (i.e., the growth of pressure disturbances) do not occur;

3. The need to produce better numerical models of transient conditions so that they can be properly employed in the inverse fashion to calibrate friction factors, to locate leaks, and evaluate the magnitude of water demand, and;

4. Since systems are not "fixed" but evolve with time, the assessment of dissipation will be time-dependent. For example, if leaks are found to have a particularly effective role in dissipating transient energy under low-flow conditions, should an effective leak control strategy be coupled with a surge mitigation thrust? If demand for water helps to limit transient events during times of water use, is special protection sometimes required during periods of low water demand?

The paper begins with an overview of the primary energy dissipation mechanisms found in a pipeline system. The energy approach derived in Karney [1] is reviewed and applied to calculate the energy dissipation in the transient simulations presented. A group of numerical simulations are run on a series pipeline to underline the central role of dissipation in system operation. The scope of these numerical simulations is extended to the case of networks. Here, simulations are run on a looped, symmetrical network to determine the impact of steady state friction, orifice leaks, topological complexities and surge-mitigation devices on the energy balance and dissipation occurring in it during waterhammer conditions.

## PRIMARY ENERGY DISSIPATION MECHANISMS

The intense research efforts of the last century have uncovered numerous energy dissipation mechanisms present in fluid transmission and distribution systems. These mechanisms are as diverse as they are numerous—ranging from losses accelerated by air-entrainment in a pipe system to pipe-wall hysteresis losses. In the midst of this plurality, the authors have identified 6 primary mechanisms for dissipating transient energy in a distribution system:

1. The first and most obvious mechanism is conventional fluid friction. Although this subject has been studied for years, it still holds some challenge. In fact, fluid friction can be quite difficult to quantify, as in the case of determining friction factors for older pipes or pipes with many fittings and service connections.

2. The second dissipation mechanism arises from the nature of network demand. For example, if flow increases in response to an increase in pressure, as it will for showers, sprinklers, dishwashers, and many other devices, demands also increase and an effective dissipative outlet is provided for transient energy. If demand is assumed constant, as it commonly is in network models, this decay mechanism is under-represented and transient energy will persist for an unrealistically long duration. How demand is modeled directly effects the impact and magnitude of transient events, and either hastens or prolongs the decay of transient energy as the system converges to a new steady state.

3. The third mechanism arises from the presence of leaks. This energy loss is essentially identical to that of demand, with one key difference being that a leak is generally unwanted and un-designed, whereas satisfying water demand is both expected and desirable. By allowing work to be done during the exchange of water between a system and the environment, leaks cause a more rapid convergence to steady conditions.

4. The fourth mechanism for dissipating transient pressure waves in a system arises from the distributed nature of most pipe networks. The complexity of a looped pipe system, the frequency of branch connections, the almost universal existence of service connections, the presence of many devices such as isolation valves and junctions—all these factors tend to fragment a coherent pressure signal into a multitude of scattered pieces, thus accelerating the dissipation of energy which tends to spread out any events that might concentrate energy.

5. The fifth decay mechanism arises due to unsteady friction. Although this mechanism also arises from fluid turbulence, its specific role can be quite different from that of steady friction. Under transient conditions, the rapid acceleration/deceleration of fluid can cause significant distortion of the velocity profile, and can thus cause much higher rates of energy dissipation or loss. As mentioned in the introduction, this topic has recently received considerable attention in the literature.

6. The first five of these mechanisms, in a sense, "come for free." That is, they are intrinsically present in the general nature of a water distribution system, in its complexity and interconnections, and in the disturbances it experiences. The sixth dissipative mechanism is different; it is the dissipation designed into the system explicitly for the purposes of surge protection. This mechanism includes the possibility of surge relief valves, air-vacuum valves, accumulation devices and other specialized appurtenances in the system.

From a design point of view, some key questions naturally arise: How much dissipation exists naturally in the system and how much additional protection should be explicitly added? How much dissipation arises from leaks alone? Will pipes be less well protected from transient-induced breaks if leaks are repaired or reduced? At the moment, no one is in a good position to answer all these questions, for data has yet to be systematically collected and assessed. In fact, the irony is that many SCADA and data acquisition systems in supply networks have been specifically designed to filter out the influence of transient events, rather than measuring, recording and assessing them.

At present it is all but impossible to efficiently design protection strategies in a way that gives appropriate credit to natural dissipation mechanisms. Yet, many designers actually have gone to the opposite extreme, assuming that energy decay in a distribution network is completely efficacious, and often ruling that little or no surge protection is required. Clearly, an urgent need exists for more study and understanding of this important area.

## ENERGY APPROACH

Karney [1] developed an energy expression that compactly summarizes the energy interactions in a pipeline for flow conditions ranging from steady state to waterhammer. The energy approach of Karney [1] is summarized here because it is used to track energy conversion and dissipation processes in the numerical simulations performed in the series pipeline and network examples that follow.

### Internal Energy

The dynamic waterhammer process in System A can be linked to the slow-compression process indicated in System B of Fig. 1 by means of a "thermodynamic equivalency" argument.

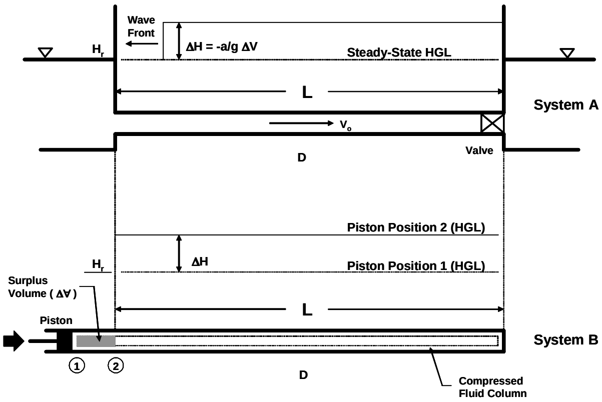

**Figure 1. Systems A and B.**

Karney proposed that if a second valve at the upstream end of the pipe in System A is closed at the instant the pressure wave reaches the upstream reservoir, a static pressure condition can be preserved indefinitely. The terminal, thermodynamic state defined by the static-pressure condition in the pipe system can also be reached by slowly moving a piston (frictionless) at the end of the pipe from position 1 to position 2, in System B, to force a surplus of fluid $\Delta\forall = gLA/a^2\Delta H$ in the pipe (equal to that in System A), where $\forall$ = fluid volume in pipe; $g$ = acceleration due to gravity; $L$ = pipe length; $A$ = pipe cross sectional area; $a$ = pipe wave speed; $H$ = change in pressure head. Therefore, given the right circumstances, the internal (elastic) energy stored in a pipeline under transient conditions (System A) is equivalent to that stored in a pipeline which undergoes quasi-equilibrium, reversible, mechanical fluid compression (System B) according to the first law $dU = \delta W = p\, d\forall$, where $U$ = total internal energy in the pipeline; $\delta W$ = external work done on system; $p$ = fluid pressure. Substituting the surplus volume expression into the first law expression and integrating over the length of the pipe, while recognizing that $p = \rho gH$, we get:

$$U(t) = \frac{\rho A g^2}{2a^2}\int H^2(x,t)dx \qquad (1)$$

$\rho$ = fluid density; $H$ = pressure head rise (datum taken at static-head level, $H_r = 0$); $x$ = distance along pipe; $t$ = time.
It is evident from Eq. 1 that the amount of internal (elastic) energy stored in a pipeline system is directly related to the extent of pressure head change occurring in a pipeline system.

### Total Energy

With a convenient expression to calculate internal energy, Karney formulated an energy expression which accounts for the internal and kinetic energy of the fluid as well as work and mechanical-dissipation processes. The energy expression was derived by manipulating the standard equations of transient pipe flow presented in Chaudhry [26] and Wylie and Streeter [27]. The interested reader can refer to Karney [1] for the details of those manipulations. The final energy expression is written as follows:

$$\frac{\rho A g^2}{2a^2}\frac{d}{dt}\int H^2(x,t)dx + \frac{\rho A}{2}\frac{d}{dt}\int V^2(x,t)dx + \frac{f\rho A}{2D}\int |V|^3 dx$$
$$+\rho gAV(L,t)H(L,t) - \rho gAV(0,t)H(0,t) = 0 \qquad (2)$$

in which $f$ = Darcy-Weisbach friction factor; $D$ = pipeline diameter; $V$ = average fluid velocity. The first term denotes the rate of change of internal energy and is exactly equal to the expression presented in (1). The second and third terms in (2) denote the rate of change of kinetic energy and the rate of viscous dissipation in the system. The fourth term denotes the thermodynamic work (either equilibrium or non-equilibrium work) performed at the ends of the pipeline. The energy expression in its present form does not explicitly describe dissipation caused by trapped or entrained air, acoustic and mechanical vibrations, hysteresis effects in the elastic behavior of pipe walls and confining soil. However, some or all of these processes could potentially be incorporated into the standard equations of transient pipe flow and, by way of manipulation, into the energy approach summarized here.

A more concise version of the energy equation is written as:

$$\frac{dU}{dt} + \frac{dT}{dt} + \dot{D} + \dot{W} = 0 \qquad (3)$$

in which $T$ = total kinetic energy; $\dot{D}$ = rate of viscous dissipation; and $\dot{W}$ = rate at which work is done to force fluid into or out of the pipeline.

The energy expression in (2) is computationally convenient because it is uncoupled from the waterhammer solution and yet makes straightforward use of pressure head and velocity values generated by a waterhammer solver. In the numerical experiments that follow, a waterhammer simulator makes use of the method of characteristics (MOC) solution and Eq. (2) to calculate the energy balance in a test network.

## SERIES PIPELINE EXAMPLE

The focus of the first example is a simple series pipeline system. In this system, water is conveyed through a gently sloping plastic pipeline (roughly at datum elevation, with a wave speed of 250 m/s, and Hazen-Williams C of 130) from an upstream reservoir (elevation of water surface 50 m) to a downstream reservoir (elevation 35 m). The pipeline comprises two segments or lengths: the upstream segment is 750 m long and 390 mm in diameter and the downstream segment is 1250 m long and 310 mm in diameter.

At the entrance to the downstream reservoir there is a control valve that is adjusted during the simulation. In particular, this valve is closed at the beginning of the transient run, indicating an initial steady state velocity of zero. The valve is opened in 8 s (linear changes in effective gate area are assumed for this and all valve operations discussed in this system). The valve is maintained in a fully open position until approximately 120 s, a time long enough to establish essentially steady flow in the system. Starting at 120 s, the valve is closed in 8 s.

Four specific variants of this system are analyzed. In the first, with the transient response depicted in Fig. 2a, the system is exactly as has just been described. The plot shows the pressure versus time response both at the valve end of the system and near the junction of the two pipe lengths. In the second case, shown in Fig. 2b, a constant external demand of 0.1 $m^3/s$ is maintained at the junction of the two lengths throughout the simulation. In the third variant, the same demand is established at the junction, but the demand is now represented as an "orifice" or valve discharging to the atmosphere; in this case, the actual discharge will change as the pressure changes in a square root type of relationship. Finally, in the fourth system, the downstream valve is not completely closed at the end of its valve operation but is left open at a mere 1% of its fully open position.

Examining Fig. 2, one can make some interesting observations. In all four cases, the convergence to steady state associated with the valve opening operation is rapid. In essence, the open valve acts as its own relief valve. More technically, the open valve allows work to be done on the environment that permits a rapid decay of transient energy, and thus a rapid convergence to the new steady state.

However, for the valve closure case during the second portion of the simulation, the plots show marked differences. In case (a), the only dissipation mechanism available in the system once the valve closes is the distributed friction along the pipe length. This mechanism alone is ineffective in removing transient energy, particularly since the mean of the flow is zero, and since no unsteady friction mechanisms have been invoked in the model. However, interestingly, the mere presence of the constant demand in case (b) essentially offsets the velocity from the null value and greatly increases the effectiveness of skin friction. The more rapid convergence to steady state in case (b) compared to (a) is immediately obvious.

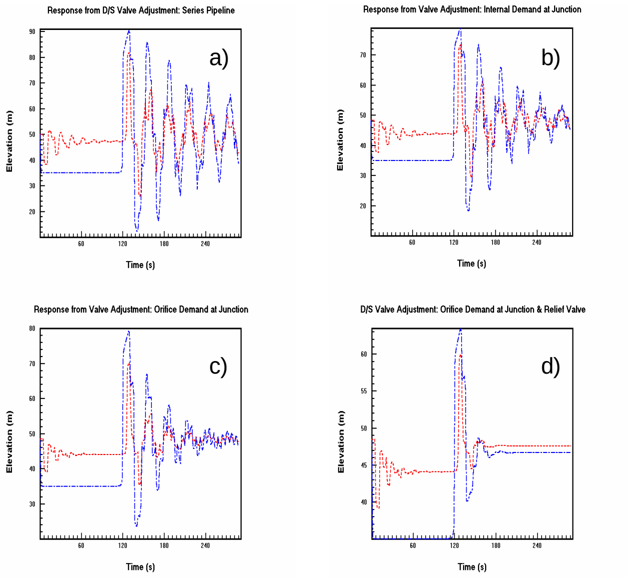

**Figure 2. Head traces: (a) friction decay only; (b) fixed nodal demand; (c) orifice demand; (d) small relief valve.**

If, in addition to the mechanisms in (a) and (b), the demand is made pressure-sensitive, then another way of doing work on the environment is effectively created. This new work mechanism further accelerates the convergence to steady state (Fig. 2c). However, in this system the downstream pipe remains effectively blocked from meaningful participation in the energy decay processes, since the flow in this pipe remains small and there are no physically important work mechanisms present. All this changes in system (d). The mere presence of the seemingly trivial valve opening allows the pipe to "breathe". More technically, the partially closed valve permits the transmission of flow through a pressure difference, thus allowing the dissipation of stored internal energy through this new work process. The simultaneous operation of all four mechanisms associated with Fig. 2d shows a dramatically enhanced energy conversion process and an extremely rapid convergence to the new steady state.

Note that in all four of these cases the energy decay process is remarkably different, even though the systems themselves only differ in apparently trivial ways. That these general observations are also true of networks should come as no surprise, though the implications are if anything even more profound in this context, since a water distribution system plays such a key role in the delivery of a vital resource.

## NETWORK EXAMPLE

To broaden our understanding of energy dissipation mechanisms, the series pipeline example is extended to the case of a simple network. Here, transient simulations are performed on a looped, symmetrical network to demonstrate, and begin to assess, the role and effectiveness of natural mechanisms (steady friction, unwanted leaks, system demands and junction frequency) and artificial mechanisms (surge devices) in converting and dissipating energy.

### Test Network & Simulations

The test network comprises 12 pipes and 9 nodes, all at the same datum elevation and organized in a square grid, as shown in Fig. 3. In this simple pipe network, water is supplied from node 1000—a fixed-head reservoir—and conveyed through the system via 610 mm mains, each measuring 6000 m in length with a Hazen-Williams roughness coefficient of 130 and wave speed of 1000 m/s. The network is perfectly symmetrical with respect to an imaginary line joining nodes 13, 1000 and 1001. At the start of every simulation, water is temporarily discharged via the control valve at node 1001 with a discharge coefficient of 0.2 $m^{5/2}/s$. In select simulations, water is also discharged at 7 node locations 10-16.

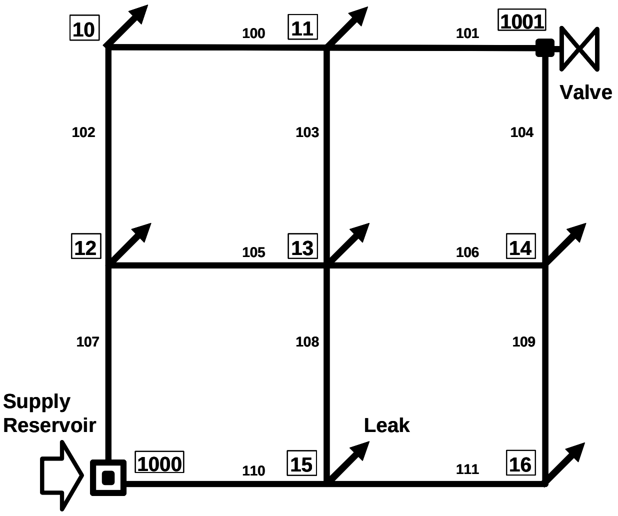

Figure 3. Configuration of test network.

Prior to each simulation, initial, steady state conditions are established in the test network. More specifically, the water level in the reservoir at node 1000 is adjusted to yield a target steady state flow and pressure at the valve of 20 m and 0.893 $m^3/s$, respectively.

With the initial, steady state conditions established in the test network, the valve at node 1001 is closed rapidly in 5 s and the transient response is simulated over an extended period of time ranging between 800 s and 7200 s. The transient program is used specifically to track energy conversion and dissipation in all the pipes of the test network in Fig. 3. The air cavity module in the transient program is left inactive in all simulations. The details and results of each simulation are discussed next.

### Simulation Results

**Simulation 1: Steady Friction.** In this simulation, all demands are set to zero and steady friction is the only thermodynamic mechanism invoked to dissipate energy in the system once the valve is completely closed (system does work on the environment during 5 s valve closure). The conversion and dissipation of energy which goes on after valve closure is categorized as a *no-work* process. The dissipative effect of turbulent momentum and mass exchange between the pipe wall and main body of fluid is accounted for solely through the mean velocity of the fluid and the empirical Hazen-Williams equation (1-D representation). However, the Hazen-Williams model does not incorporate 2-D unsteady behavior (i.e., velocity profile distortion and diffusion of vorticity ring) which typically accelerate the rate of energy dissipation during transient events (Ghidaoui and Mansour [25]). This “simple” situation serves as the “baseline” case against which all others are compared.

The basic system response is shown in Fig. 4. Closing the valve compresses the fluid and creates large pressures which propagate as a wave towards the reservoir to establish zero-flow conditions (set at the valve) in the system. When the positive pressure wave reaches the reservoir after the first wave cycle 1θ (time to travel from valve to reservoir), the imbalance in hydraulic head at the reservoir causes fluid to flow back into the reservoir. This creates a low pressure wave prompting fluid to flow towards the reservoir, kinetic energy to increase and fluid to expand and restore the internal energy in the pipeline to a point near its steady state position. At time 2θ, the low pressure wave reaches the valve and finds another unbalanced condition─the closed valve cannot supply fluid to sustain the flow to the reservoir. The system overcomes this flow imbalance by lowering pressures further and expanding the fluid (contracting pipe wall) beyond the steady state level to re-establish a zero-flow condition in the system.

A low pressure wave travels upstream setting the fluid velocity to zero─and by extension kinetic energy─and increasing internal energy through fluid expansion. At time 3θ, the wave reaches the reservoir and is reflected towards the valve. This new wave compresses the fluid (expands the pipe), restores internal energy to its steady state level and increases the kinetic energy in the pipeline. At time 4θ, the fluid column is moving towards the valve and the situation is effectively the same as the one encountered immediately after valve closure, save for the energy dissipated during the first 4 wave cycles. This back-and-forth sequence of events is repeated every 4θ cycles until all transient energy is dissipated and conditions regain a steady composure in the system.

**Simulation 2: Orifice Leaks.** In this simulation, energy is dissipated in part by the orifice-type leaks located at nodes 10-16 and, to a lesser extent, by steady friction.

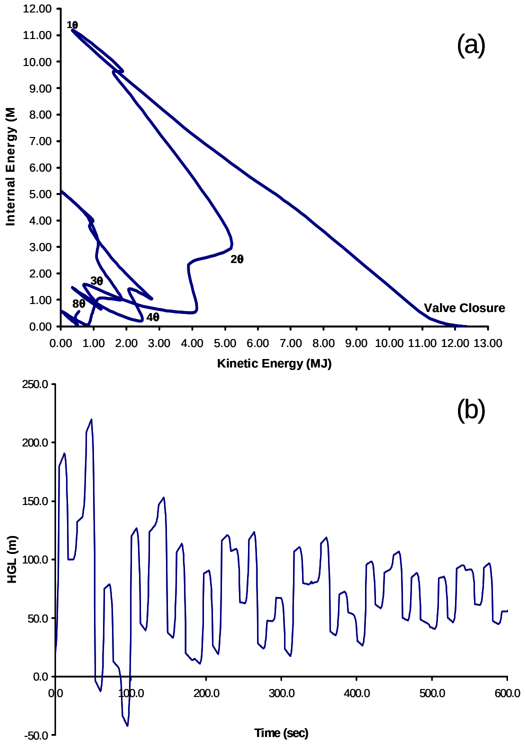

**Figure 4. Simulation 1─Steady friction: (a) kinetic and internal energy in test network; (b) HGL at valve 1001.**

Orifice-type leaks included at nodes 10-16 in the test network are simulated with the conventional orifice equation for atmospheric discharge in (4):

$$Q_l = E_s\sqrt{H - z} \qquad (4)$$

where $H$ = piezometric head and $z$ = elevation; $E_s$ = effective discharge coefficient; and $Q_l$ = leak flow. The effective discharge coefficient of leaks is set to 0.01 $m^{5/2}/s$ (1/20th the size of the control valve's discharge coefficient). With 7 leaks in the system, the total "leak" discharge coefficient tallies to 0.07 $m^{5/2}/s$.

The large impact of orifice-type leaks on energy dissipation and energy-conversion dynamics is shown in Fig. 6. In Fig. 6a, we can see that the introduction of leaks in the system produces an initial base flow of 1.37 $m^3/s$ (before valve closure), which increases the initial kinetic energy to 20.30 MJ (from 12.34 MJ in Simulation 1). Despite the larger amount of kinetic energy initially in the system, Fig. 6 shows that the leaks are able to dissipate transient energy effectively by releasing fluid and transferring energy to the environment. The leaks also introduce a base flow in the system which offsets the average velocity from the null value and which increases the dissipative effectiveness of steady friction in most pipes. Note that this is not the case in pipes 101 and 104 in Fig. 3, as these pipes only participate nominally in the frictional dissipation process because of the presence of the closed valve at node 1001. In light of all these factors, the maximum internal energy in this second simulation is reduced to 7.21 MJ (at time 29 s or 1θ) from 11.10 MJ in Simulation 1. The back-and-forth conversion of kinetic energy to internal energy that characterized the steady friction case (Simulation 1) is less dominant in this simulation as the system quickly finds its new steady state, as is dramatically depicted in Fig. 6b.

**Simulation 3: Junction Frequency.** The test network is expanded to include 16 additional nodes and pipes. The complex network that emerges comprises a total of 40 pipes and 25 nodes─all at a single datum elevation─arranged in 16 adjacent loops configured in a symmetrical pattern. The diameter of pipes is reduced to 550 mm to roughly preserve the original hydraulic capacity. All other elements of the simple system in Fig. 3 are preserved.

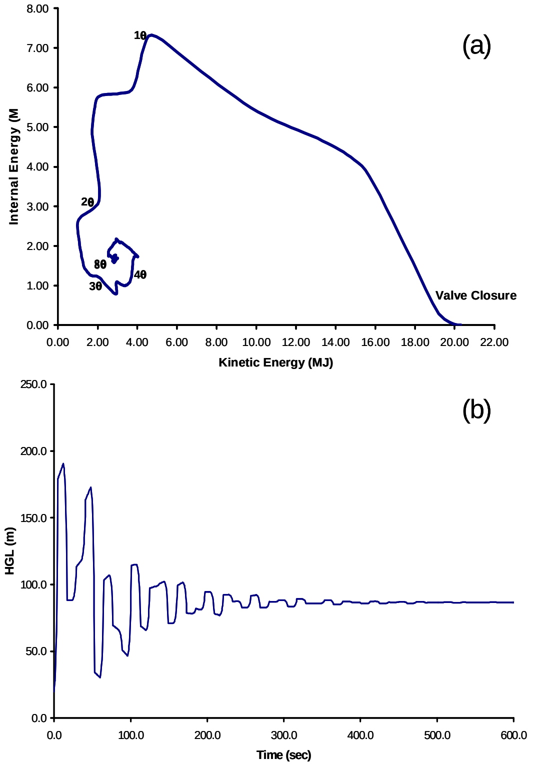

**Figure 5. Simulation 2─Orifice leaks: (a) kinetic and internal energy in test network; (b) HGL at valve 1001.**

A plot of the system response in Simulation 3 (not included) indicates that the basic back-and-forth, kinetic-to-internal energy conversion sequence of Simulation 1 is largely preserved, with some added complexities in the transient signal. The plot confirms, anecdotally, that a greater number of junctions increases the frequency with which pressure waves are transmitted, reflected and fragmented in the system─thus increasing the number of small pressure waves which move quasi-independently to communicate and regulate mass imbalances in the system. This more animated "hydraulic chatter" in the system increases the frequency with which fluid is accelerated and decelerated, and in some cases may hasten unsteady friction losses. However, since a steady friction model was used, no unsteady dissipation was observed. To establish this link with any degree of certainty, additional simulations would have to be performed with an unsteady friction model.

**Simulation 4: Surge Control.** An air chamber (hydropneumatic tank) is added to node 13 of the 12-pipe test network in Fig. 3. The cylindrical chamber (3.6 m diameter and 10.0 m height) is linked to the network by a 2.0 m connector pipe (750 mm dia.). The control valve along the connector pipe is initially open and remains open throughout the simulation to permit hydraulic contact between the chamber and the network. The initial water level in the chamber is set to 2.0 m. The barometric pressure is assumed to be 101.3 kPa (1.0 atm) and the initial gas pressure (gauge) inside the chamber is 420.7 kPa. The polytropic gas exponent is set to 1.2 to simulate an irreversible, non-adiabatic and non-isothermal process inside the chamber. No leakage is modeled in the network so as to isolate the energy-dissipating impact of the chamber.

As Fig. 7 makes clear, the impact of the air chamber on energy dissipation and system operation is significant.

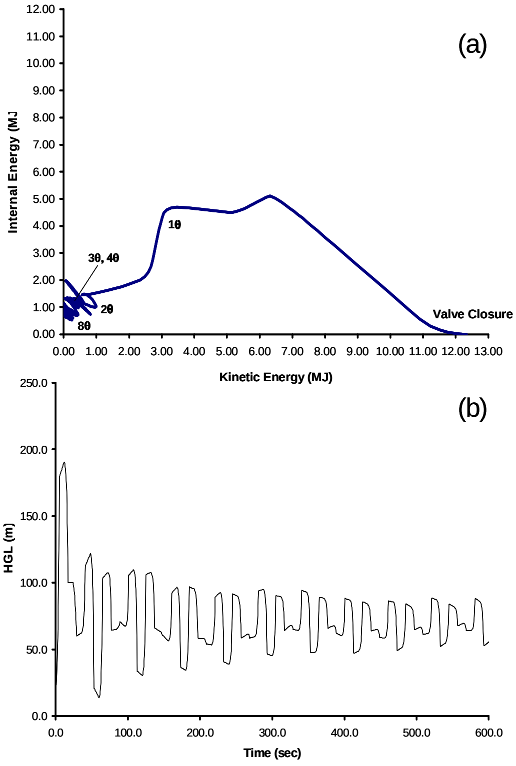

**Figure 6. Simulation 4─Surge control: (a) kinetic and internal energy in test network; (b) HGL at valve 1001.**

The dramatic increase in dissipation rate is largely attributed to the "on line" energy storage capacity of the air chamber. The upsurge and downsurge conditions are explained to elucidate the energy interactions which occur inside a chamber during a waterhammer event. During an upsurge cycle, excess fluid in the pipe is forced into the air chamber where it increases the water level and compresses the gas in the chamber. While the chamber is filling up, internal energy stored in the pipe is temporarily transferred to the chamber by way of thermodynamic work. The energy transferred to the chamber increases both the gravitational potential energy of the fluid column (chamber filling) and the internal or elastic energy of the gas, as it is compressed and gas pressures increase.

During a downsurge cycle, everything happens in a reverse sequence. The fluid in the pipe is expanded by low pressures, thus creating an acute need to force fluid back into the system. The air chamber of course is ready to oblige. As fluid is pulled back into the system, the water level is lowered, the gas expands and the gas pressure drops in the chamber. Now, it is the fluid inside the chamber which is doing work on the network and transferring energy to it. This energy transfer is "powered" by a drop in gravitational potential energy, as the water level decreases in the chamber, and by a release of internal energy as gas in the chamber expands. This set of interactions are repeated over and again as the system gradually finds its new steady state and energy is progressively dissipated.

## CONCLUSIONS

The energy transformations that take place in a pipe system under transient conditions are important, insightful and interesting. The importance arises because of the growing need to better understand system dynamics and behavior. The insight arises out of the relatively simple physical interpretation that energy expressions afford and from the fact that energy is a remarkably simple indicator of a composite of physical interactions in systems. Finally, the interest arises because dynamic systems are always challenging, producing behavior and responses which deserve to be understood.

The current study focuses attention on the wide range of energy decay mechanisms that exist in water distribution systems. More specifically, different hydraulic simulations were run to begin to assess the impact of steady friction, orifice leaks, topological complexities and surge-control devices on the energy balance and dissipation in a simple, hypothetical network. From these numerical simulations, a set of preliminary conclusions can be drawn:

1. In many systems steady friction is ineffective when compared to other natural dissipation mechanisms in transmission and distribution systems;

2. Orifice-type leaks are effective energy dissipators since: 1) they transfer energy to the environment by way of a thermodynamic work mode and, ultimately, in the form of heat, and; 2) they introduce a base flow through a system which keeps the fluid column in constant and continuous motion and forces it to incur frictional losses along the pipes of a system;

3. System topology greatly complicates the “micro” transient behavior of a system by increasing the number of small pressure waves which move quasi-independently to communicate and regulate mass imbalances in the system. It is speculated that this increased hydraulic activity can potentially accelerate the amount of energy dissipated by means of the unsteady component of fluid friction. Further studies are needed to confirm this hypothesis.

4. Surge control devices, such as an air chamber, designed into a system tend to greatly accelerate the rate of dissipation and lower peak pressures in a system.

By beginning to assess more comprehensively the individual role of these primary dissipation mechanisms, a clearer picture of system dynamics will no doubt emerge.

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