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Direct calculation of fire flows with water distribution network models

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Abstract

Fire demands can have a significant impact on the size of a water distribution system. These demands create additional localized stress on the water system and may induce undesirable areas of low pressures. Sound engineering design practice dictates that the distribution system be capable of delivering all fire flows at the required minimum pressure. The application of computer network models provides an efficient and reliable approach for computing these flows and determining their impacts on system performance. Current fire flow models require changes in the network structure and associated hydraulic equilibrium equations or are based on a repetitive trial-and-error process. The result of using current models is inefficient performance at a greater cost. This paper describes an explicit and rigorous model that is able to directly perform accurate fire flow calculations under a wide range of network loading and operating conditions. The method is formulated analytically from pressure-flow equilibrium relationship to exactly meet targeted minimum pressure requirements at the subject nodes. The proposed approach is illustrated using two actual water distribution systems. The method is shown to be robust and efficient, and converges in an expeditious manner. Moreover, the method is simple to understand and can be effectively implemented in any existing hydraulic network analysis model. Such capabilities will greatly enhance the ability of water engineers to effectively utilize hydraulic network modeling to determine the adequacy of the water system to deliver the required flows and to define necessary facility improvements at minimum cost. Enhancement of distribution system design, planning, and management is a principal benefit of the methodology.

1 Introduction

Water distribution system components, including pipelines, appurtenances, and storage facilities, are generally sized to provide adequate fire protection. Fire flow requirements vary according to size of area and nature of property to be protected. Required fire flow is defined as the "rate of water flow, at a residual pressure of 20 psi (138 kPa) and for a specified duration, that is necessary to control a major fire in a specific structure"[1]. Fire flows are limiting demand conditions and are normally superimposed on the average system demand of the maximum day.

Evaluating the capability of a water distribution system to meet targeted fire flow demands is an essential task for all water utilities. Field testing of fire hydrants can be relatively expensive and time-consuming, and may only provide an approximation of the true fire flows because it ignores the temporal redistribution of pressures throughout the network as flow demands and operating conditions are changed.

Computer-based network simulation models provide the most effective and accurate means of predicting fire flows in water distribution systems[2]. Engineers today use network simulation models to solve a variety of hydraulic problems[3]. These models can determine pressure and flow distribution throughout the network[4-6]. Fire flow analyses are modeling applications that impose fire flow demands on the network model. A properly calibrated network model (with fire flow test data) can be used to simulate fire flows at any location, extrapolate the maximum flows that could be delivered for fire fighting at the minimum required pressure, and determine system response while properly accounting for pressure redistribution effects. The model predicted flows are then compared with the required fire flows to evaluate the adequacy of the overall water system and determine necessary improvements.

Three methods are currently widely used for conducting fire flow analyses with network simulation models. The normal procedure is to run a succession of full network simulations, increasing the fire demand at the node of interest each time until the computed pressure drops to the required value (e.g., 20 psi [138 kPa]). This can result in a large computational effort and, depending on how fire flow is incremented between each successive run, might only provide an approximate solution. The result of utilizing this approach will often be inefficient performance at a greater cost. Another method that requires less trial-and-error involves adding a pipe of negligible resistance connecting the subject node to a fictitious source node with a hydraulic grade set equal to the required pressure (e.g., 20 psi [138 kPa]). The model then determines the resulting available flow for the pressure specified. The available flow calculated becomes the total water demand at the subject node. Although this procedure provides accurate fire flow calculation, its drawback lies in the need for repetitive changes in the network topology and associated computational overhead required to initialize fire flow analysis for each subject node. The third method is to add an energy equation, in addition to the basic set of continuity and energy equations, between a source node and the subject node (in terms of hydraulic grade line) and determine the demand assigned to that node. The demand calculated becomes the available flow for the specified pressure. This procedure, although explicit, requires major modifications to the hydraulic structure of the computer model and, therefore, may not be amenable for direct implementation by water utility engineers. Furthermore, as demonstrated by Boulos et al.[4,7-10] convergence of the method is mathematically restricted which may render the solution unobtainable. Finally, significant computational times may result since each fire flow assessment necessitates the simultaneous solution of a larger set of quasi-linear equations.

This paper describes an alternative approach that is simple to implement in any existing network solution algorithm. The method is formulated analytically from basic pressure-flow equilibrium relationship and results in an explicit solution for the fire flows. The fire flows are calculated to exactly satisfy the target minimum pressure requirement. The proposed approach is both robust and efficient, and is guaranteed to converge in an expeditious manner. The method is demonstrated by application to a sample network and two actual water distribution systems in California, USA.

2 Methodology

2.1 Network Model

The water distribution network is represented by the node-link system. It is an assemblage of a finite number of links interconnected by nodes in some particular branched or looped configuration. Links are pipes, pumps, regulators, and valves with specified characteristics. The endpoints of each link are nodes with known energy grade (e.g., constant-pressure regions, elevated storage facilities, lakes, rivers, treatment plants, and well fields) or external water consumption (junction node. The location of each fire hydrant is designated as a junction node. Nodes and links are uniquely identified by labels allowing the network topology to be defined. The node-link system must then obey the Euler relation:

$$e = n + l - 1 \tag{1}$$

where e, n, and l designate the number of links, nodes, and loops, respectively. Water flows through the network links and can enter or exit the system at any node.

2.2 Hydraulic Model

Regardless of the network topological configuration, the state of the system is described mathematically by the following set of equations

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Nodal Equations

$$\sum_{j=1}^{n} Q_{i,j} = 0 \; 2 \qquad \forall 3\ i \qquad (2)$$

where $Q_{i,j}$ 4 is the volumetric flow rate in link {i, j} from node i to node j.

Link Equations

$$H_i - H_j = f(Q_{i,j}) \; 5 \qquad \forall 6 \text{ link } \{i, j\} \qquad (3)$$

where H_i 7 and H_j 8 are the heads at nodes i and j, respectively; and $f(.)$ 9 is a functional relation between head loss (or gain) and flow rate.

Equation (2) expresses node flow continuity which asserts that at each node the algebraic sum of inflows (-) or outflows (+) must be zero. Equation (3) represents the mechanical relationship between the energy loss or gain due to flow within a link. This is a nonlinear characteristic function that can vary depending on the approximating flow resistance law selected (e.g., Hazen-Williams, Darcy-Weisbach, Mannings) and the type of link (e.g., pump, valve) used.

The above equations constitute a set of quasilinear algebraic equations over all links and nodes in the network. The simultaneous solution of these equations gives the volumetric flow rate in each link and the hydraulic grade (and pressure) at each node, and may be obtained iteratively using methods as described in Altman and Boulos[11]. The iterations continue until a convergent solution is reached. Convergence of the method is defined as occurring when the relative change in flow rates (or grades) between two successive iterates is less than a specified tolerance (e.g., 10^{-3}).

2.3 Fire Flow Model

The fire flow model consists essentially of determining for each hydrant location (junction node) in the distribution system the maximum water demand available at any given (fixed) pressure. In a node-link system, the water demand specified at any node of the network is the flow available at that location. The mathematical relationship between water demand and hydraulic head at a node can be approximated by attaching a low resistance pipe from the node to a fictitious reservoir whose water level equals the elevation head at the node. The flow in the pipe to the reservoir equals the demand at the node.

Under this condition and for any junction node designating a hydrant location, the fire flow available Q_a at a target pressure P_a can be computed iteratively from[12]:

$$Q_a = Q_f \left[\frac{P_s - P_a - c\left(P_f - P_a\right)}{P_s - P_f} \right]^{\frac{1}{\sigma}} 10 \qquad (4)$$

where

$$c = (Q_s/Q_f)^{\sigma} 11 \qquad (5)$$

Here, Q_s designates the static demand at the node, P_s is the static pressure, Q_f is the normal fire flow demand, P_f is the pressure at the normal fire demand, and σ is a flow exponent that is dependent on the headloss expression used ($\sigma \varepsilon [1.85, 2.0]$ 12). The above equation represents the exact analytical solution of the basic pressure-flow equilibrium relationship and is applicable to any system of consistent units and for any set of boundary conditions. The iterations continue until the relative change in the available flows between two successive iterates is less than a specified tolerance (e.g., 10^{-4}).

3 Model Application

Justification for the use of any algorithm rests on its ability to efficiently and accurately solve problems by means of a computer implementation. The proposed method has been integrated into H_2ONET[6], a widely used hydraulic and water quality simulation model, and successfully tested on a number of actual water distribution systems of various sizes. The systems range in size from a few nodes to over 15,000 nodes. Convergence of the method is illustrated herein using an example network and two actual water distribution systems.

Example 1

The proposed method is best illustrated using the simple example network shown in Figure 1. A numbering scheme is shown for links and nodes. As can be seen from the figure, this network contains 5 pipes, 3 junction nodes, and two storage nodes. The link and node characteristics are presented in the figure. SI units and the Hazen-Williams headloss expression were utilized for this example. A roughness coefficient of 130 was assigned to all pipes and the exponent σ=1.852. The method was applied to determine the flows available at all three junction nodes to meet a target pressure of 14 m, using an initial fire flow demand of 100 L/s. The convergence tolerance was set to 10^{-4}. The resulting available flows are presented in the figure.

Example 2

The Monte Vista Water District is a retail agency serving the water needs of about 40,000 people in the areas of Montclair, Chino, and portions of the San Bernardino County in Southern California, USA. The service area covers approximately 10 square miles (25.9 square kilometers) with an average daily demand of 10 MGD (37,900 m^3/day) from 12,000 service connections. The historic maximum day peaking factor is 1.75 times the average day demand. Water is supplied from local groundwater and imported water from northern California. The District system has four pressure zones and 173 miles (278.4 km) of pipe from 1 inch (25.4 mm) to 42 inches (1067 mm) in diameter. The network model schematic is depicted in Figure 2 and consists of 2031 pipe sections, 1664 junction nodes, 16 storage nodes, 16 pump stations, and 15 valves. Using an initial fire flow demand of 1,000 gpm (0.0631 m^3/s) and a convergence criterion of 10^{-4}, the resulting available flows at 20 psi (138 kPa) were consistently obtained in less than five iterations.

Example 3

The Goleta Water District is a public water agency serving the water needs of approximately 74,000 people in the south coastal portion of Santa Barbara County in Southern California, USA. The service area covers approximately 50 square miles (129.5 square kilometers) with an average daily demand of 11 MGD (41,700 m3/day) from 14,235 service connections. Water is supplied from local surface water and imported water from northern California. Other sources of supply include groundwater, desalination, and recycled water. The District has eight pressure zones and approximately 200 miles (322 km) of pipe from 1-inch (25.4 mm) to 48-inches (1,219 mm) in diameter. A schematic of the skeletonized network model is shown in Figure 3 and consists of 117 pipes, 115 junction nodes, 5 storage nodes and 7 valves. Using an initial fire flow demand of 1,000 gpm (0.0631 m^3/s) and a convergence criterion of 10^{-4}, the available flows at 20 psi (138 kPa) were computed in less than four iterations for all the network nodes.

4 Conclusions

A rigorous model is presented to address the problem of fire flow assessment in water distribution systems. The proposed approach provides a reliable and efficient means of performing explicit fire flow calculations to meet targeted pressure requirements at any location throughout the distribution system and under a wide range of demand loading and operating conditions. Fire flows are assessed on the basis of hydraulic network calculations to exactly meet pressure-flow equilibrium at the subject nodes. The resulting model is both computationally efficient and guaranteed to converge in an expeditious manner. Moreover, the method is simple to understand and can be effectively implemented in any existing hydraulic network analysis model. Such capabilities will greatly enhance the ability of water utilities to effectively utilize hydraulic network modeling to determine system integrity for fire fighting needs and define cost-effective improvements.

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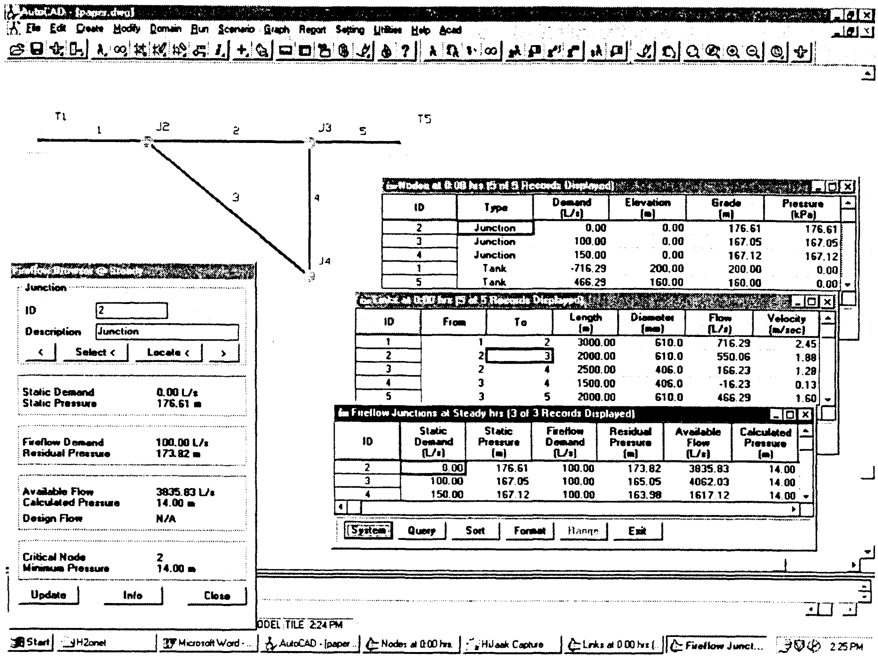


Figure 1: Example pipe distribution network

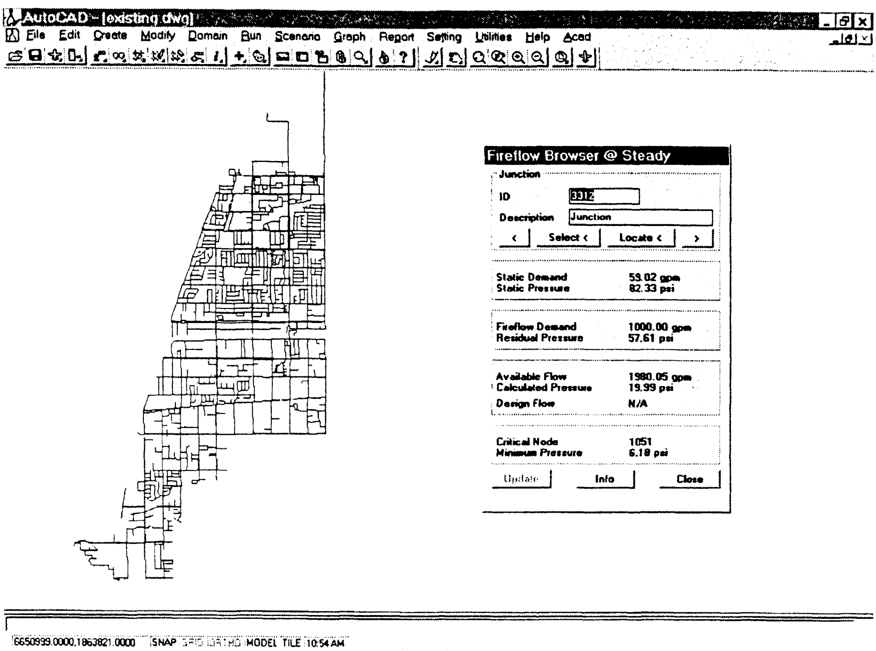
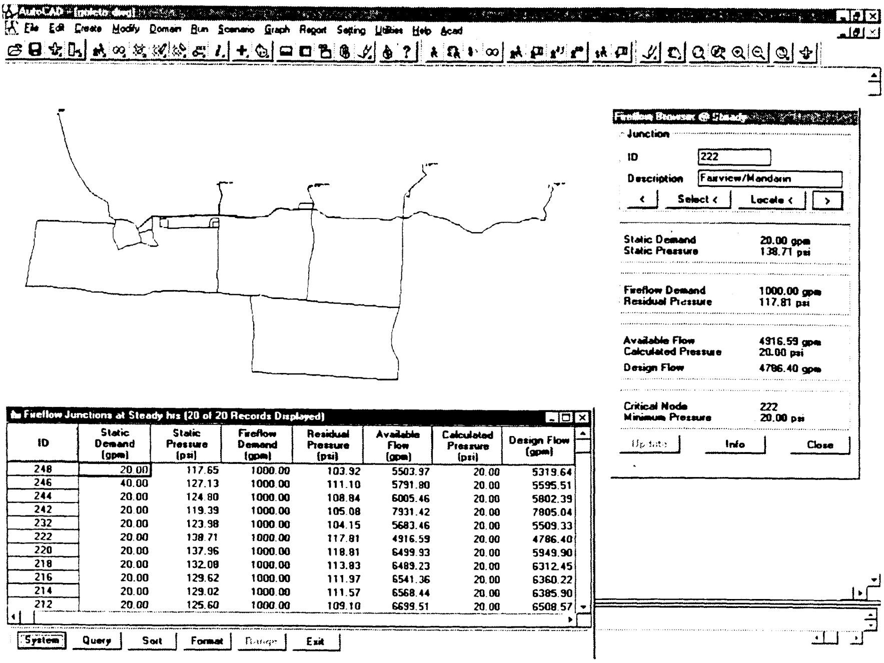


Figure 2: Schematic of the Monte Vista water network model



ID	Static Demand (gpm)	Static Pressure (psi)	Fireflow Demand (gpm)	Residual Pressure (psi)	Available Flow (gpm)	Calculated Pressure (psi)	Design Flow (gpm)
248	20.00	117.65	1000.00	103.92	5503.97	20.00	5319.64
246	40.00	127.13	1000.00	111.10	5791.80	20.00	5595.51
244	20.00	124.80	1000.00	108.84	6005.46	20.00	5802.39
242	20.00	119.39	1000.00	105.08	7931.42	20.00	7805.04
232	20.00	123.98	1000.00	104.15	5683.46	20.00	5509.33
222	20.00	138.71	1000.00	117.81	4916.59	20.00	4786.40
220	20.00	137.96	1000.00	118.81	6499.93	20.00	5949.90
218	20.00	132.08	1000.00	113.83	6489.23	20.00	6312.45
216	20.00	129.62	1000.00	111.97	6541.36	20.00	6360.22
214	20.00	129.02	1000.00	111.57	6568.44	20.00	6385.90
212	20.00	125.60	1000.00	109.10	6699.51	20.00	6508.57

Figure 3: Schematic of the Goleta (skeletonized) water network model