Modeling of Pressure Regulating Devices: A Major Problem Yet to be Satisfactorily Solved in Hydraulic Simulation

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Modeling of Pressure Regulating Devices:
The Last Major Problem to be Solved in Hydraulic Simulation

Angus R. Simpson

Abstract

Hydraulic simulation of water distribution systems using computer software appears to have reached a very mature level of practice. There does not appear to be many other improvements that can be made to the basic underlying solution algorithms. While this statement is mostly true, there still remains one area that results in problems when developing simulation models. In discussions with water distribution modeling practitioners, the most commonly mentioned remaining problem is stability of computers programs in the presence of pressure regulating devices. The three most common pressure regulating devices are pressure reducing valves, flow control valves and pressure sustaining valves. The difficulty in computer codes is that the status of the device is not known a priori. Consider a pressure reducing valve (PRV) – it may have one of three states. For the first state, the valve operates normally - such that the valve is in a partially closed or throttling position to maintain the set pressure on the downstream side of the valve. The second state occurs when the pressure downstream of the valve cannot be maintained and drops below the set pressure. In this case the valve moves to a fully open position. For the third state, the PRV acts as check valve. If there is more than one pressure regulating valve in a water distribution system then each device may be in one of three states. In computer codes, a guess is made to the status of each of the pressure regulating devices and the system is solved for to determine the flows and pressures. A check is then made to determine if the guesses of status are consistent with the results. If the assumed status of the device is inconsistent with the results the status is altered and the hydraulic solver is re-run. This paper demonstrates with a simple example that has a combination of a pressure reducing valve and a flow control valve that many commonly available commercial programs and Government programs cannot properly model even the simplest of systems. One symptom of the difficulty with the solution of a water distribution system containing pressure regulating devices is evidenced by the program terminating due to oscillation of the status of these devices. A non-convergence situation occurs. At least in this case the program indicates that there is a difficulty. The more worrying situation is where the program converges in a couple of iterations but the answers that are given are clearly incorrect. For one configuration of the example demonstrated in the paper – this very situation occurs. As an outcome, the

hydraulic modeler may not be certain that the results of computer simulations involving pressure regulating valves are correct. Careful checking of the results needs to occur to make sure results are consistent. For very large networks this checking task may be almost be impossible. It is important that this fundamental error that has been identified in some computer simulation codes is researched. A complete remedy to the problem of incorrect results is not provided in the paper. Further research is needed to develop techniques that provide more robust solutions of systems that contain pressure regulating devices.

Introduction

The modeling of pressure regulating valves in computer hydraulic simulation software for water distribution systems is considered in this paper. The three most commonly encountered pressure regulating devices are (i) pressure reducing valves (PRVs) (ii) flow control valves (FCVs) and (iii) pressure sustaining valves (PSVs). The first two types of valve are considered in this paper. An overview of typical conditions experienced for PRVs and FCVs is given. For a single PRV or FCV is a pipeline, results for simulation using the EPANET hydraulic simulation software are consistent with expectations. Some examples of these single valve operations in a simple pipeline system between two reservoirs are presented. A slightly more complicated configuration is where a FCV/PRV combination are used in series (separated by a reach of pipeline). For particular configurations the results from EPANET (and many other commercially available software programs) were not able to converge on the correct solution, even for this simple network configuration. Details of these examples are provided in this paper.

Operating Modes of Pressure Reducing Valves

Pressure reducing valves are placed in pipelines to perform the following functions:

1. To keep the pressure at the downstream side of the PRV at a constant valve whenever the upstream pressure exceeds the preset value for the PRV (pressure setting). The presence of the PRV will prevent the pressure on the downstream side of the valve from rising to unacceptable levels.
2. To avoid reverse flow when the pressure on the downstream side of the valve exceeds the pressure on the upstream side of the valve.

The PRV is a valuable and very useful device. A pressure reducing valve is a hydromechanical device that acts as a control valve used in a pipe network. The pressure regulating device (either a PRV or PSV) is usually operated by pressures immediately downstream or upstream of the valve. The PRV is designed to maintain a constant pressure (i.e. a pressure setting or preset pressure) on the downstream side of the valve irrespective of how large the upstream pressure is (Jeppson, 1976). PRVs do not have a defined head loss-discharge relationship. There are three modes of operation for a PRV:

Standard mode (or **active** position of PRV). Flow occurs from the upstream side of the valve to the downstream side through the PRV. In the standard or active mode of PRV operation, the pressure on the downstream side of the valve is equal to the pressure setting for the PRV while the pressure on the upstream side of the valve is greater than the PRV setting pressure. As the pressure increases or decreases on the upstream side of the PRV the downstream pressure is held constant. The actual pressure on the downstream side of the valve is measured on a regular basis and compared with the set point pressure. The PRV valve opens or closes to maintain the constant set pressure on the downstream side of the valve. The valve element's position is adjusted until the head losses within the valve produce the required outlet or set pressure. As a result, the head loss through the PRV is essentially variable and varies as the upstream side pressure varies. The entire pipe network section downstream of the PRV is protected from high pressures.

Open mode (or **inactive** position). In this operating mode, the pressure on the upstream side of the PRV is less than the pressure setting for the PRV and as a result the PRV opens fully with the flow being unrestricted. The pressure on the downstream side is equal to the pressure on the upstream side (and both are less than PRV pressure setting). The PRV acts as a short pipe and water flows unrestricted through the valve. Unlike a fully opened check valve, a fully opened PRV in the inactive position has a very low minor loss coefficient *K.* Only a very small local head loss occurs.

Check valve mode (or **closed** position preventing back flow). In this operating mode, the pressure on the downstream side of the PRV is both greater than the pressure on the upstream side and greater than the set point pressure. The valve closes to attempt to bring the downstream side pressure down to the set pressure. As a result, the PRV shuts fully and acts as a check valve preventing reverse flow through the PRV. For this occurrence the PRV could be eliminated from a hydraulic computer model of the pipe network system.

A second situation can also lead to the PRV acting as a check valve. If the pressure on the downstream side of the PRV increases to be above the set pressure then the PRV closes and acts as a check valve. The pressure on the upstream side of the PRV may be greater than the pressure on the downstream side of the valve. This situation is not possible if the network downstream of the PRV is completely isolated from the network upstream of the PRV.

Modeling of PRVs in Hydraulic Simulation Computer Analysis Software

Consider a pressure reducing valve in the middle of a pipeline (1200 m long, 500 mm diameter, and a Hazen Williams roughness coefficient of C = 100) between two reservoirs as shown in Fig. 1 - the upstream reservoir at 60.0 m and the downstream reservoir at 30.0 m. The water is in the pipeline is assumed to be at 15°C thus the density is $\rho = 999.1$ kg/m^3 and the kinematic viscosity is $\nu = 1.141 \times 10^{-6}$ m^2/s.

Consider three cases:

(1a) The PRV with a set pressure of 60 m – or equal to the level of the upstream reservoir. The PRV should open completely as it attempts to raise the pressure on the downstream side of the valve as high as possible to reach the unattainable level of the set point pressure of 60 m.

(1b) The PRV with a set pressure of 35 m. The PRV set point is between the level of the downstream reservoir of 30 m and the highest possible value of the HGL of 45 m on the downstream side of the PRV. Thus the PRV should operate in standard or active mode and maintain the actual pressure equal to the set pressure of 35 m on the downstream side of the valve.

(1c) The PRV with a set pressure of 20 m – or below the level of the downstream reservoir. The PRV should close completely in an attempt to drop the pressure on the downstream side of the PRV as low as possible to reach the unattainable level of 20 m.

The network shown in Fig. 1 was modeled in EPANET. The node and element numbers are shown. A PRV is represented within a computer hydraulic model of a network like a pipe, with an upstream node and a downstream node.

For Case (1a) the results from EPANET show the PRV to be fully open. The hydraulic grade line is as shown in Fig. 1 as if the PRV does not exist at all. The PRV tries to maintain a pressure of 60 m just downstream of the PRV by opening the valve until it is fully opened. The maximum possible discharge through the pipeline with the PRV fully opened is 613 L/s.

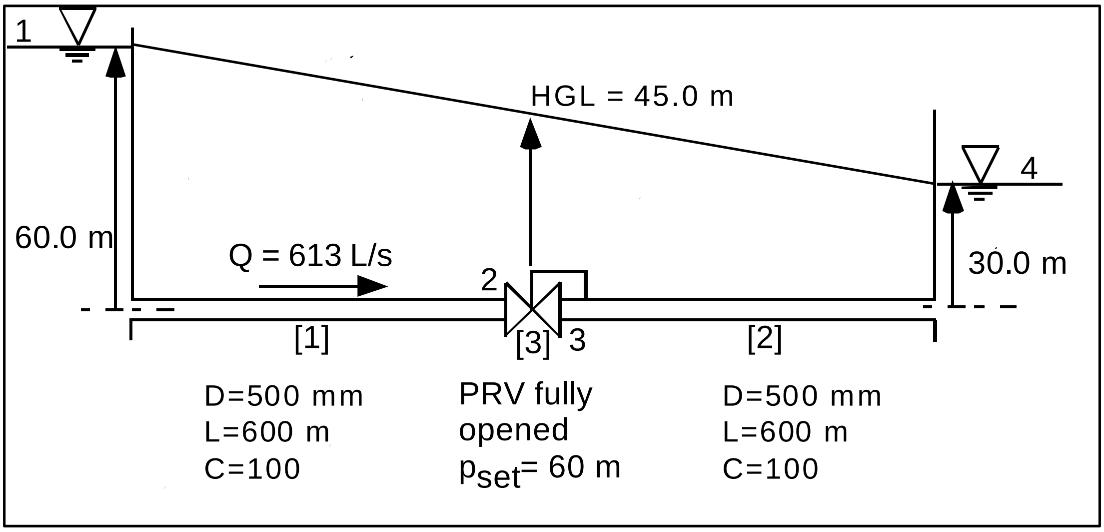

Figure 1. Network 1a - Flow for a PRV setting of 60 m or for the PRV removed

For Case (1b) the EPANET output provides a HGL variation as shown in Fig. 2.

The discharge has been reduced to 338 L/s and the HGL on the downstream side of the PRV is 35.0 metres. The discharge is controlled by the slope of the HGL between the downstream side of the PRV at 35 metres and the downstream reservoir at 30.0 metres.

For Case (1c) where the PRV set point is 20.0 metres the PRV closes completely trying to reduce the HGL on the downstream side of the valve. It is not possible to achieve an HGL of 20.0 metres on the downstream side of the valve and as an outcome the final condition is a no flow condition with the HGL upstream of the PRV horizontal at 60.0 metres and the HGL downstream of the PRV also horizontal at 30.0 metres.

Results for all EPANET runs are summarized in Table 1.

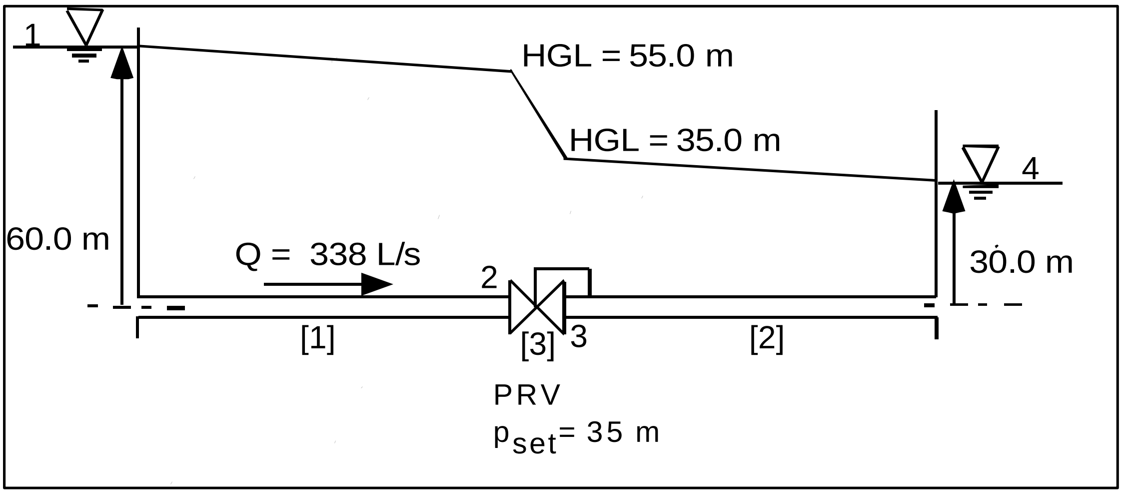

Figure 2. Network 1b - Flow for a PRV setting of 35.0 m or for the PRV in active mode PRV and FCV combinations modeled using EPANET

The modeling of a more complex system is now considered. The pipeline is divided up into three equal sections. Either a PRV or FCV is located at the one-third points as shown in Fig.3. The first case considered is a PRV at link [2] and a FCV valve at link [4]. In this case the set point for the PRV is selected as 60 m and the FCV control discharge is selected as 2000 L/s. Even if the PRV and FCV are removed the maximum possible discharge is only 613 L/s (see Fig. 1). When this configuration was run in EPANET the results, as expected, are as shown in Fig. 3 and in Table 1.

When the PRV and the FCV are reversed such that the FCV is at the upstream one-third point, EPANET fails to converge on a solution in 40 iterations. The configuration for this run is shown in Fig. 4. In EPANET, the FCV is initially assumed active while the PRV is assumed to be open mode. In the next iteration the operating modes of the two regulating devices is switched to the opposite mode. Again convergence is not achieved and both regulating devices are switched. Trying a combination of both the

FCV and PRV fully open would have solved the problem and achieved a correct converged solution.

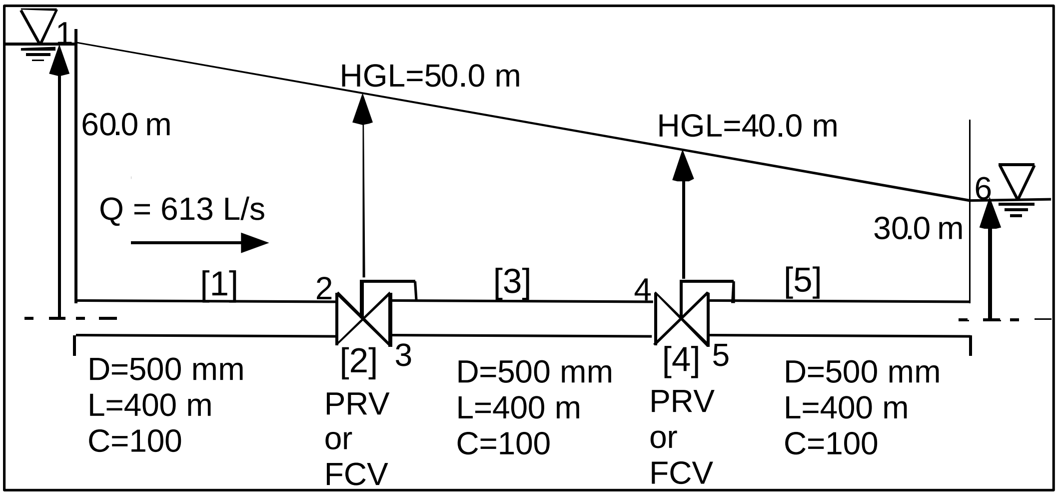

Figure 3. Network 2a - Flow for a PRV and FCV both in inactive mode or both PRV and FCV fully removed

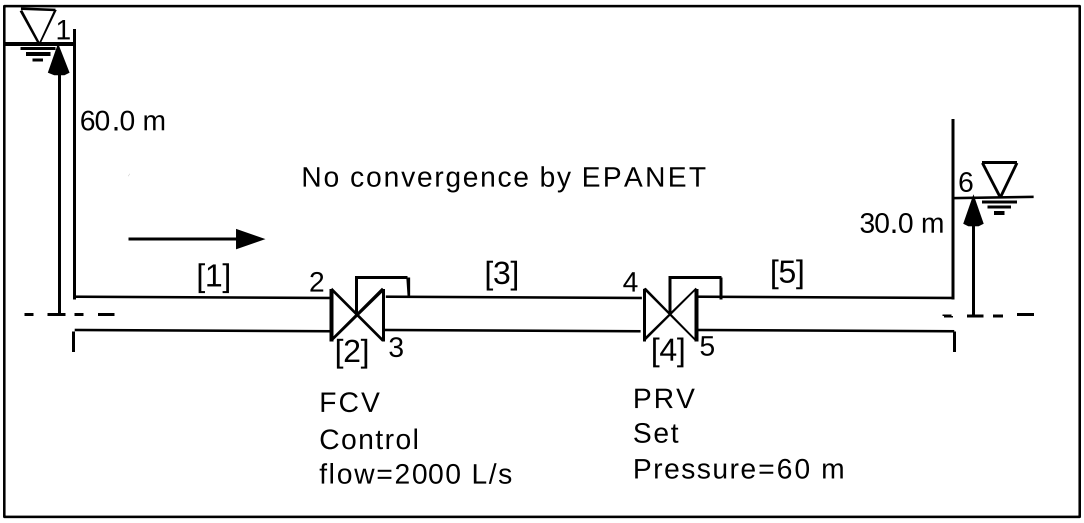

Figure 4. Network 2b – A FCV upstream and PRV downstream does not converge in EPANET (both FCV and PRV should be fully open)

Network 2c with the PRV upstream and the FCV downstream is now considered. The PRV set point is selected as 35 m and the FCV control discharge is selected as 500 L/s. The PRV in this case controls the flow while the FCV is fully open as it cannot achieve a flow rate of 500 L/s. The EPANET run converges in 7 iterations to give a discharge of 290 L/s and a HGL as shown in Fig. 5.

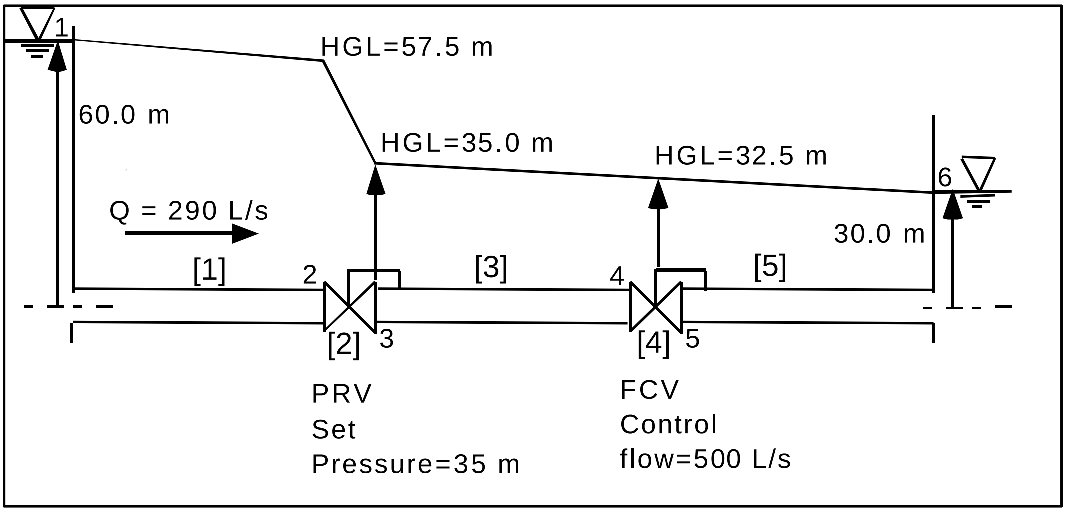

Figure 5. Network 2c – A PRV upstream (set pressure=35.0 m) and an FCV downstream (control flow = 500 L/s)

The PRV and FCV in Fig. 5 are now reversed as shown in Fig. 6. Again as in Fig. 4 EPANET does not converge in 40 iterations. The status of the FCV is assumed to be active and this is not changed. For each successive iteration the status of the PRV is changed from active to open or vice versa. Clearly other combinations of modes of operation for the PRV and FCV should have been tested.

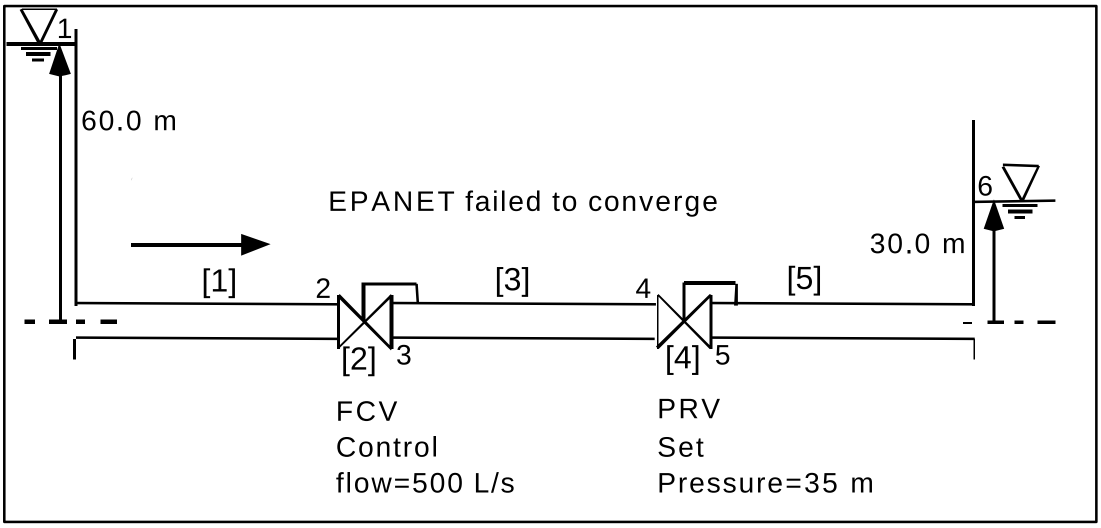

Figure 6. Network 2d – An FCV upstream (control flow = 500 L/s) and a PRV downstream (set pressure=35.0 m) does not converge in EPANET

Table 1. Summary of results

Net-work	PRV	At Link	Set Press. (m)	FCV	At Link	FCV Flow (L/s)	Actual Flow (L/s)	See Fig. No.	EPA-NET Soln?
1a	Yes	[2]	60.0	No	-	-	613	1	Yes
1b	Yes	[2]	35.0	No	-	-	338	2	Yes
1c	Yes	[2]	20.0	No	-	-	0	-	Yes
2a	Yes	[2]	60.0	Yes	[4]	2000	613	3	Yes
2b	Yes	[4]	60.0	Yes	[2]	2000	None	4	No*
2c	Yes	[2]	35.0	Yes	[4]	500	290	5	Yes
2d	Yes	[4]	500	Yes	[2]	35.0	None	6	No*

* Failed to converge in 40 iterations

PRV and FCV combinations modeled using commercial software

A number of commercially available hydraulic simulation software for modelling water distribution systems do not correctly model handle a FCV and PRV in series as illustrated for Network 2 above. Many commercial software packages are based on EPANET as the underlying solver. Unless modifications have been made to the EPANET solver in these programs results obtained from these programs would be expected to be similar to results presented in the section above. One commercial software program successfully solved for all of the various configurations of Network 2.

One commonly used commercial program could not solve Network 2c correctly. It failed to converge within 100 iterations. This same program, however, provided a converged solution for Network 2d for a discharge of 500 L/s – the FCV control discharge value. The results were incorrect with the HGL actually increasing along the pipeline. On the downstream side of the FCV the HGL has increased from 28.2 to 36.84 m. The discharge computed by EPANET in Table 1 is 290 L/s. The HGL values computed by the program are clearly incorrect as shown in Table 2.

Table 2. Incorrect HGL values compared to EPANET values

Solver	Net-work	Node [1]	Node [2]	Node [3]	Node [4]	Node [5]	Node [6]	Computed Flow (L/s)
EPANET	2c	60.0	57.5	35.0	32.50	32.50	30.0	290

Commerc-ial Solver	2c	60.0	53.16	35.04	28.2	36.84	30.0	500

It is not comforting that incorrect results occur when a hydraulic solver claims to have found a converged solution, especially, in the analysis of such a simple network. When large networks contain many pressure regulating devices it would be possible that a user may not notice inconsistencies in the results if the results are indeed incorrect.

Summary and Conclusions

This paper has investigated the ability of EPANET and some other commercial software for simulating water distribution systems to model systems that contain both pressure reducing valves (PRVs) and flow control valves (FCVs). The development of solution algorithms for hydraulic simulation of water distribution systems is relatively mature yet the modeling of pressure regulating devices still presents users with significant problems. A very simple network is used in this paper to illustrate that commonly used hydraulic simulation software, such as EPANET, cannot adequately simulate an FCV and PRV (separated by a section of pipeline) in a single pipeline between two reservoirs. A detailed description of seven different network configurations is given. In one case, the results from a commercially available simulation program that claimed to have converged for Network 2d were clearly incorrect. The occurrence of incorrect but converged results is clearly of concern, especially for larger networks. It may be impossible to detect the occurrence of these inconsistencies if they occur. One amendment to current solution algorithms appears to be to check all the combinations of the operating status of the pressure regulating devices in the network. This may be difficult for large systems. Clearly, more research work is needed to develop improved algorithms for solving systems with multiple pressure regulating devices.

References

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