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PIPE NETWORKS ANALYSIS USING A NEW TECHNIQUE

تحليل شبكات الأنابيب باستخدام طريقة جديدة

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خلاصة

يهتم هذا البحث باستنتاج طريقة جديدة تقوم علي اساس الربط بين طريقتي Linear theory method و Extended linear graph theory لحل شبكات توزيع المياه ومن ثم إستنتاج كل من الضغوط عند العقد والسريان خلال الأنابيب. تختلف هذه الطريقة عن طرق Linear theory المعتادة في كيفية تكوين المعادلات وأيضا الأسلوب المتبع في الحل. من مميزات هذه الطريقة عدم التقيد بتحقيق مبدأ بقاء الكتلة عند عقد الشبكة وبالتالي فإنها لا تعتمد علي الإشتراطات الإبتدائية للحل (قيم السريان الإبتدائية المفروضة خلال الأنابيب) وبالرغم من ذلك فإن الطريقة محل الإعتبار تصل إلي حل ذي دقة عالية في عدد قليل من المحاولات باستخدام معادلة أسية لتحديث قيم السريان خلال الأنابيب في كل محاولة. تم تطوير هذه الطريقة لتقوم بحل شبكات مياه تحتوي علي مضخات المياه وكذلك ثلاثة أنواع من الصمامات وهي: صمامات تخفيض الضغط (PRVs)، صمامات الحفاظ علي الضغط (PSVs)، صمامات عدم رجوع (CVs). تم عمل برنامج بلغة الفورتران يسمي SFLOW لتطبيق مبادئ الطريقة الجديدة وتم إختباره علي شبكة إفتراضية صغيرة تحتوي علي مضختين للمياه وثلاثة صمامات تخفيض ضغط (PRVs). تمت مقارنة نتائج البرنامج مع نتائج برنامج EPANET علي نفس الشبكة وقد كانت النتائج متساوية تقريبا.

ABSTRACT

This research paper exhibits the use of both Linear Theory Method (LTM) and Extended Linear Graph Theory (ELGT) to derive a new technique which could be used for the analysis of pipe networks. This study differs from other linear theory methods in the system formation of linear equations and solution procedures. The solution algorithm used in this study is independent on initial pipe flows estimation, where a power law equation is used to update the pipe flows in successive iterations. The proposed method has been extended to deal with complex systems including control devices such as pumps, pressure reducing valves (PRVs), pressure sustaining valves (PSVs), and check valves (CVs). A FORTRAN program, named SFLOW, has been written for analyzing pipe networks using this new formation of system of linear equations. To check the reliability of the proposed method, the model has been verified with EPANET algorithm against a hypothetical pipe network.

INTRODUCTION

There are three different systems of equations which can be developed for the solution of the network analysis problems [6]. These systems are:

(1) Q-equations (when the discharges in the pipes of the network are the principal unknowns). These equations resulted by applying both the conservation of energy principle at each loop and the conservation of mass at each junction node,

(2) H-equations (when the HGL elevations or the heads H, at the nodes are the principal unknowns). These equations resulted by applying only the conservation of mass at each junction node, and

(3) ΔQ-equations (when the correction discharges, ΔQ, are the principal unknowns). These equations resulted by the estimation of initial discharge through each pipe which satisfies the continuity at each junction node. Then, replace the initial estimation of discharge in each pipe of the network by this initial discharge plus the sum of all of the initially unknown correction values in discharges that circulate through this pipe. Finally, these equations resulted by applying only the

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conservation of energy at each loop in the network.

Four commonly methods [1] are used for the iterative solution of each of the previous system of equations and thereby for the analysis of water distribution networks. These methods are: (1) the Hardy Cross method, (2) the Newton-Raphson method, (3) the linear theory method, and (4) the Gradient method.

In Hardy Cross method, an initial estimation of flows through pipes are corrected by using flow corrections (ΔQ) corresponding to each loop. Only one correction equation is considered at a time for determining the final value of ΔQ and thereby actual values of flows in all pipes that form the considered loop are computed. This procedure is iteratively performed for adjacent loops to determine ΔQ's corresponding to other loops. Instead of considered only one correction equation at a time and solve it in Hardy Cross method, solving all correction equations simultaneously corresponding to all network loops lead to a rapid convergence in a small number of iterations. Newton-Raphson, linear theory, and gradient methods attempt to solve all the concerned equations simultaneously in an iterative procedure. In the Newton-Raphson method the flows or heads (Q or H) are assumed initially and the corrections (ΔQ or ΔH) are updated successively till these corrections stabilize; while in the linear theory method the assumed flows or heads are successively improved till the difference in their values in two successive iterations becomes negligible [1]. Gradient method and Newton-Raphson method are applied simultaneously to obtain the improved Q and H values, instead of computing corrections to them, in an iterative procedure till there is no observed improvement between two successive iterations [1]. Both the linear theory and gradient methods do not need balancing of node-flow continuity equations at each node to begin the process.

Kesavan and Chandrashekar [5] developed a graph – theoretic models for analyzing of nonlinear pipe networks. Both symbolic formulations procedures and illustrative examples were presented. A comparison was carried out using both SYSTEM program, which applies the principle of the proposed method, and HARDY program, which apply the principles of Hardy-Cross procedure. Nielsen [7] presented a formulation of the flow equations in terms of pipe discharge which was found the better in terms of energy heads. The behavior of both LTM and NRM was compared in the initial phase with large error. An explanation was presented about both the oscillation of LTM when the iteration gets close to the correct solution and the dependency of NRM on the first estimation of pipe flows. Nogueira [8] studied the node method for hydraulic network analysis to overcome the problem of convergence, using hybrid element formulation. They concluded that, the formulation should be incorporated in governing equations when an element with very low resistance is present on the network. Wood and Charles [11] used linear theory method which was modified to account for the nonlinear head loss for solving the flow distribution in hydraulic networks. Their technique has several advantages as follows: convergence to the final solution is very rapid, independent on initial estimates of flow rates, and its validity to apply in both closed and open-closed types of network. Wood and Reyes [12] presented a study to document reliability problems which may occur using the various popular algorithms. They concluded that the best two methods are both S-PATH and LINEAR methods comparable with other ones.

The main objective of this paper is to derive a new technique depending on both LTM and ELGT for analyzing complex pipe networks, which could include pumps, pressure reducing valves (PRVs), pressure sustaining valves (PSVs), and check valves (CVs).

FORMULATION OF EQUATIONS

Formulation of equations is performed on the simple hypothetical network shown in figure (1). The network consists of five pipes and four nodes including a source at node (1). Before starting to show the solution procedures, it should be noted that the pipe network analysis consists mainly of three steps [4]: (1) a constitutive relation; (2) the formulation of system equations; and (3) a solution algorithm.

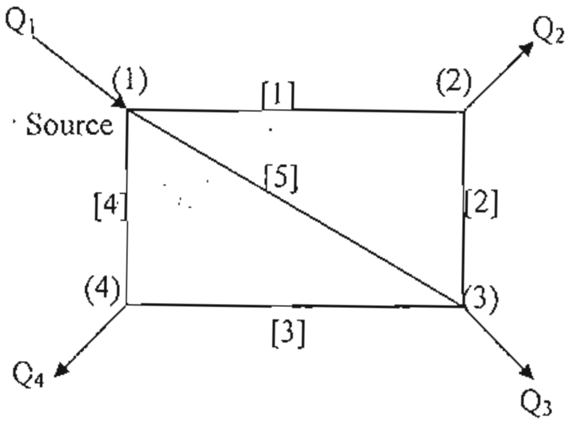


Figure (1): Example network (After Gupta and Prasad [4])

The constitutive relation gives a relation between head loss through each pipe and pipe flow. The deduction of this relation according to Hazen-Williams and Darcy-Weisbach equations is as follows:

Hazen-Williams equation:

This equation is used to calculate the mean velocity through pipes and takes the following form [6]:

$$V=C_k\, C_{HW}\, R^{0.63}\, S^{0.54} \quad (1)$$

in which, V: is the mean velocity through pipe, C_{HW}: is the Hazen-Williams roughness coefficient, S: is the slope of the energy line $(= h_f/L)$, h_f: is the head loss due to friction through pipe, L: is the length of pipe, d: is the diameter of pipe, and C_k: constant, depends on the used units which equal to *1.318* for English System *(ES)* units and equal to *0.849* for *SI* units.

$$q/A = C_k\, C_{HW}\, R^{0.63} (h_f/L)^{0.54} \quad (2)$$

in which, q: is the discharge through pipe, and A: is the cross sectional area of pipe.

$$h_f^{\,0.54} = (L^{0.54}\, q)/(A\, C_k\, C_{HW}\, R^{0.63}) \quad (3)$$

$$h_f = (L\, q^{1.852})/(A C_k C_{HW} R^{0.63})^{1.852} \quad (4)$$

$$h_f = (L\, q^{1.852})/((\pi d^2/4) C_k\, C_{HW}\, (d/4)^{0.63})^{1.852} \quad (5)$$

$$h_f = \frac{(7.88/C_k^{1.852})L}{C_{HW}^{1.852} d^{4.87}} q^{1.852} \quad (6)$$

or $h_f = r_1\, q^{1.852}$,

$$where \quad r_1 = \frac{(7.88/C_k^{1.852})L}{C_{HW}^{1.852} d^{4.87}} \quad (7)$$

Darcy-Weisbach equation:

This equation is used to calculate the frictional head loss through pipes and takes the following form [6]:

$$h_f = f \frac{L}{d} \frac{V^2}{2g} \quad (8)$$

in which, h_f: head loss through pipe, f: friction factor, L: length of pipe, V: mean velocity, d: diameter of pipe, and g: acceleration due to gravity.

$$h_f = \frac{fLq^2}{2gdA^2} \quad (9)$$

$$h_f = \frac{8fLq^2}{\pi^2 g d^5} \quad (10)$$

$$h_f = \frac{fL}{C_k d^5} q^2 \quad (11)$$

in which, C_k: constant, depends on the used units which equal to *39.73* for *ES* units and equal to *12.1* for *SI* units.

Then, $h_f = r_2\, q^2$,

$$where \quad r_2 = \frac{fL}{C_k d^5} \quad (12)$$

From the above derivations, it is seen that the head loss h_f in each pipe in a network can be expressed by an exponential formula in terms of the pipe flow (constitutive relation) which covers both cases, regardless of whether the Hazen-Williams or the Darcy-Weisbach equation is used. This exponential formula takes the following general form:

$$h_f = r\, q^{\alpha} \tag{13}$$

where, values of r and α depend on the used formula.

Formulation of the system equations and solution algorithm are given as follows:

Equation (13) is linearized for pipe i as follows [4].

$$h_{fi} = \left(r_i |q_i|^{\alpha-1}\right) q_i \tag{14}$$

or, rearranging

$$q_i = k_i h_{fi} \tag{15}$$

where $k_i = 1 \Big/ \left(r_i |q_i|^{\alpha-1}\right)$ is called a stiffness factor.

By applying the conservation of mass at each junction node in the simple network, shown in figure (1), the following equations are obtained:

$$q_1 + q_5 + q_4 + Q_1 = 0.0 \quad \text{at node (1)}$$
$$q_1 + q_2 + Q_2 = 0.0 \quad \text{at node (2)}$$
$$q_2 + q_5 + q_3 + Q_3 = 0.0 \quad \text{at node (3)}$$
$$q_3 + q_4 + Q_4 = 0.0 \quad \text{at node (4)} \tag{16}$$

in which, Q_1, Q_2, Q_3, and Q_4 represent nodal flows at nodes 1, 2, 3, and 4 respectively and q_1, q_2, q_3, and q_4 represent pipe flows at pipes 1, 2, 3, and 4 respectively.

By using both equation (15) and equation (16), the following equations are obtained:

$$k_1 h_{f1} + k_5 h_{f5} + k_4 h_{f4} = -Q_1 \quad \text{at node (1)}$$
$$k_1 h_{f1} + k_2 h_{f2} = -Q_2 \quad \text{at node (2)}$$
$$k_2 h_{f2} + k_5 h_{f5} + k_3 h_{f3} = -Q_3 \quad \text{at node (3)}$$
$$k_3 h_{f3} + k_4 h_{f4} = -Q_4 \quad \text{at node (4)} \tag{17}$$

By knowing that the concept of head loss through any pipe is equal to the difference in head between upstream and downstream nodes for this pipe, therefore the above equations take the following form:

$$k_1 (h_1 - h_2) + k_5 (h_1 - h_3) + k_4 (h_1 - h_4) = -Q_1 \quad \text{at node (1)}$$
$$k_1 (h_2 - h_1) + k_2 (h_2 - h_3) = -Q_2 \quad \text{at node (2)}$$
$$k_2 (h_3 - h_2) + k_5 (h_3 - h_1) + k_3 (h_3 - h_4) = -Q_3 \quad \text{at node (3)}$$
$$k_3 (h_4 - h_3) + k_4 (h_4 - h_1) = -Q_4 \quad \text{at node (4)} \tag{18}$$

in which, h_1, h_2, h_3, and h_4 are nodal heads at nodes *1*, *2*, *3*, and *4* respectively.

The above system of linear equations can take the following form:

$$k_1 h_1 - k_1 h_2 + k_5 h_1 - k_5 h_3 + k_4 h_1 - k_4 h_4 = -Q_1 \quad \text{at node (1)}$$
$$k_1 h_2 - k_1 h_1 + k_2 h_2 - k_2 h_3 = -Q_2 \quad \text{at node (2)}$$
$$k_2 h_3 - k_2 h_2 + k_5 h_3 - k_5 h_1 + k_3 h_3 - k_3 h_4 = -Q_3 \quad \text{at node (3)}$$
$$k_3 h_4 - k_3 h_3 + k_4 h_4 - k_4 h_1 = -Q_4 \quad \text{at node (4)} \tag{19}$$

The above equations can be rearranged to take the following form:

$$(k_1 + k_5 + k_4) h_1 - k_1 h_2 - k_5 h_3 - k_4 h_4 = -Q_1 \quad \text{at node (1)}$$
$$-k_1 h_1 + (k_1 + k_2) h_2 - k_2 h_3 = -Q_2 \quad \text{at node (2)}$$
$$-k_5 h_1 - k_2 h_2 + (k_2 + k_5 + k_3) h_3 - k_3 h_4 = -Q_3 \quad \text{at node (3)}$$
$$-k_4 h_1 - k_3 h_3 + (k_3 + k_4) h_4 = -Q_4 \quad \text{at node (4)} \tag{20}$$

The above system of linear equations can put in matrix form as follows:

$$\begin{bmatrix} k_1+k_5+k_4 & -k_1 & -k_5 & -k_4 \\ -k_1 & k_1+k_2 & -k_2 & 0.0 \\ -k_5 & -k_2 & k_2+k_5+k_3 & -k_3 \\ -k_4 & 0.0 & -k_3 & k_3+k_4 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} = - \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{bmatrix} \quad (21)$$

For simplification, the above matrix could be written as:

$$[K]\,[h] = -\,[q] \quad (22)$$

in which, [K]: stiffness matrix, [h]: array of unknown nodal heads, and [q]: array of known nodal flows.

The above system of linear equations can be used to obtain the unknown nodal heads for any pipe network. Stiffness matrix [K] is a symmetric square matrix, i.e. it has number of rows equal to number of columns, equals number of nodes in the under study pipe network. Stiffness matrix can be constituted directly without tracing the above derivation as follows:

Each row (R_i, $i = 1, \ldots\ldots, n$) in the stiffness matrix contains the following entries:

- Its main diagonal element, existed in column (i), contains the summation of all stiffness factors of pipes that connect node which has a number (i) with other nodes.
- Each element in R_i, other than its main diagonal element, contains the stiffness factor with negative sign for a pipe connects node that has number (i) with node that has number equal the number of this column.
- Each element in R_i contains zero entry means that there is no connection pipe between node which has number (i) and the node which has number equal the number of this column.

These steps can be used to obtain the stiffness matrix for any pipe network.

If the head at any node in the network under study is specified, then the above matrix (21) should be rearranged to put the known heads at right hand side and the remaining nodal heads are deduced proportional to the specified head. In this case Eq. (22) may take the following form [4]:

$$[K][h] = -[I][q] \quad (23)$$

in which, [I]: identity matrix of size (n*1), and n: number of nodes.

For example, if the head at node (1) is known, figure (1), then Eq. (21) takes the following form:

$$\begin{bmatrix} 1 & -k_1 & -k_5 & -k_4 \\ 0 & k_1+k_2 & -k_2 & 0.0 \\ 0 & -k_2 & k_2+k_5+k_3 & -k_3 \\ 0 & 0.0 & -k_3 & k_3+k_4 \end{bmatrix} \begin{bmatrix} Q_1 \\ h_2 \\ h_3 \\ h_4 \end{bmatrix} = - \begin{bmatrix} k_1+k_5+k_4 & 0 & 0 & 0 \\ -k_1 & 1 & 0 & 0 \\ -k_5 & 0 & 1 & 0 \\ -k_4 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} h_1 \\ Q_2 \\ Q_3 \\ Q_4 \end{bmatrix} \quad (24)$$

If any node has a known head, an arrangement is performed as made in the above equation. After solving the above system of linear equations and getting the values of nodal heads, values of nodal flows can be obtained using Eq. (15). Head loss (h_f) for any pipe, in Eq. (15), equals to the difference between its upstream and downstream nodal heads.

The system of linear equations, Eq. (24), is solved to get the values of nodal heads by assuming any initial values of pipe flows. To obtain the exact solution, Eq. (24) must be solved through an iterative process. For such an iterative solution, the following function is proposed to update the flow through pipes for the next iterations [4]:

$$q_{wij} = q_{wij-1}^{\beta} * q_{ij}^{1-\beta} \tag{25}$$

in which, q_{wij} : weighted flow through pipe i in iteration j, q_{wij-1} : weighted flow through pipe i in iteration ($j-1$), q_{ij}: flow through pipe i obtained from equation (15) in iteration j, and β : exponent equal to 0.45 [4].

The iteration process can be performed until the relative error, defined below, is reached to an acceptable tolerance.

$$\left(\frac{\sum_{i=1}^{p}\left|q_{ij} - q_{ij-1}\right|}{\sum_{i=1}^{p} q_{ij}}\right) \le tolerance \tag{26}$$

in which, q_{ij}: flow through pipe i in iteration j, q_{ij-1}: flow through pipe i in iteration $(j-1)$, and p: number of pipes through networks.

Modifications of the proposed method to deal with pipe networks including control devices (pumps and valves) are as follows:

(1) Networks including pumps:

To modify the proposed method to cope with pipe networks including pumps, the pump characteristic curve should be represented in the following form [4]:

$$q_p = q_o - \lambda h_p^{\alpha} \tag{27}$$

in which, q_p: flow rate from pump, q_o: maximum flow rate from pump, h_p: pump head corresponding to q_p , and λ and α are constants.

In order to simulate pump in the network, it is treated as a special pipe with flow equal to:

$$q' = q_o - q_p = \lambda h_p^{\alpha} \tag{28}$$

This flow (q') occurs in the opposite direction to the actual flow in pipe (q), figure (2.B). Then, Eq. (28) should be rearranged to take the form of Eq. (15), in the following way:

$$q' = \lambda h_p^{\alpha} \tag{29}$$

$$q'^{\frac{1}{\alpha}} = \lambda^{\frac{1}{\alpha}} h_p \tag{30}$$

$$q'^{\frac{1}{\alpha}-1} q' = \lambda^{\frac{1}{\alpha}} h_p \tag{31}$$

$$q'^{\frac{1-\alpha}{\alpha}} q' = \lambda^{\frac{1}{\alpha}} h_p \tag{32}$$

$$q' = \left(\lambda^{\frac{1}{\alpha}} q'^{\frac{\alpha}{1-\alpha}}\right) h_p \tag{33}$$

$$q' = k h_p \text{ , } k = \left(\lambda^{\frac{1}{\alpha}} q'^{\frac{\alpha}{1-\alpha}}\right) \tag{34}$$

Hence, the pump performance is converted to special pipe with stiffness factor $k = \left(\lambda^{\frac{1}{\alpha}} q'^{\frac{\alpha}{1-\alpha}}\right)$, flow q' equal to $(q_o - q_p)$ occurs in the opposite direction for the actual flow in the pipe (q), and head loss equal to pump head h_p. An additional constant consumption with value q_o is added in upstream node of the special pipe (pump location) and constant discharge with value q_o also is added in downstream node of special pipe as shown in figure (2-B). It should be noted that during the solution the flow through the special pipe and nodal inflows and outflows are readjusted to represent the actual flow conditions.

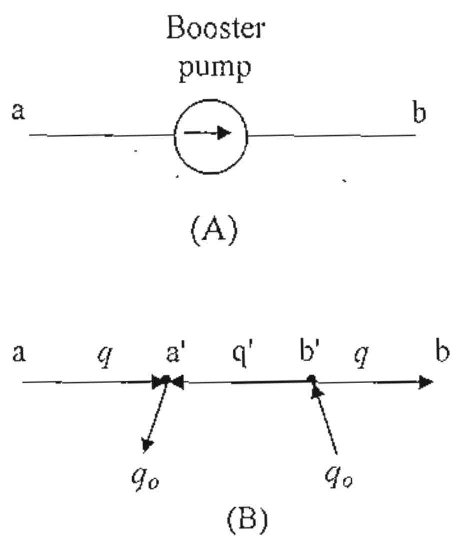


Figure (2): Booster pump; (A) symbol,and (B) model

The following steps exhibit the procedures for determining the values of α and λ:

- Take some points on pump characteristic curve.
- Determine the values of (q_o-q_p) for these points.
- Draw the relationship between h_p on vertical axis and the corresponding values of (q_o-q_p) on horizontal axis.
- Fit a curve between these values of points to get the best power equation in the form of $(y = a\,x^b)$.
- Equation (33) should be rearranged to take the power form as follows:

$$q' = \left(\lambda^{\frac{1}{\alpha}} q'^{\frac{\alpha}{1-\alpha}}\right) h_p \qquad (33)$$

$$h_p = \frac{q'}{\lambda^{1/\alpha} q'^{\alpha/1-\alpha}} \qquad (35)$$

$$h_p = \frac{1}{\lambda^{1/\alpha}} q'^{1-\frac{\alpha}{1-\alpha}} \qquad (36)$$

$$h_p = \frac{1}{\lambda^{1/\alpha}} q'^{\frac{1-2\alpha}{1-\alpha}} \qquad (37)$$

- Calculate the value of α from $b = \frac{1-2\alpha}{1-\alpha}$ and value of λ from $a = \frac{1}{\lambda^{1/\alpha}}$.

After performing the above modifications to convert a pump to a special pipe with stiffness given in Eq. (33), the procedures mentioned previously of analyzing simple networks are carried out.

(2) Networks including check valve:

The function of a check valve is to allow flow of water only occurs in one direction. Consider i is a pipe containing check valve, it is assumed that the pipe is connected between junction node a to b as shown in figure (3). If $H_a > H_b$, the flow will take place and the pipe is considered as an ordinary pipe with stiffness factor $k_i = 1 \big/ \left(r_i |q_i|^{\alpha-1}\right)$, on the other hand if $H_a < H_b$ the valve will be closed. In order to simulate the case of check valve activity put $k_i = 0$ corresponding to this pipe in diagonal matrix of stiffness factor, therefore the flow in this pipe tends to zero.

At each iteration in the solution process, the function of the check valve should be checked, if it operates or not until convergence occurs.

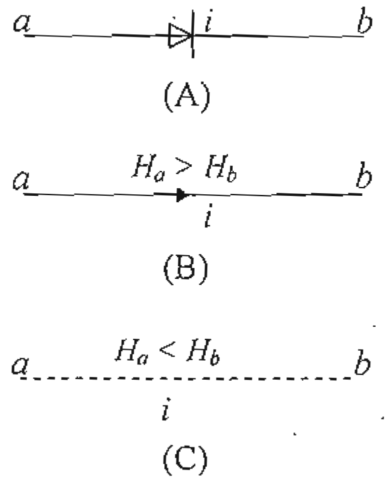


Figure (3): Check valve; (A) symbol, (B) no valve action, and (C) valve action (After Chandrashekar [2])

(3) Networks including pressure reducing valve (PRV):

A pressure Reducing Valve (PRV) is used to maintain a constant pressure at its downstream side, independent on the value of pressure upstream of it [6]. PRV is used in situations where high downstream pressures could cause damage in pipes. Consider i is the pipe containing (PRV) as shown in figure (4) where junction node a is assumed to be the upstream node and b is the downstream node. Let k and k' represent the stiffnesses of the pipe corresponding to the lengths L and L' respectively, and H_e, and H_{set} represent the computed and set values of hydraulic grade line at the location of the valve respectively. Then one of the three possible conditions may occur [2, 4]:

1. $H_e < H_{set}$ and $H_b < H_a$: the PRV has no effect and the simple pipe model may be used with stiffness factor $k_i = 1 \Big/ \left(r_i |q_i|^{\alpha-1} \right)$.

2. $H_e > H_{set}$ and $H_b < H_a$: the PRV is activated which H_e is set equal to H_{set}. To simulate this case in the proposed method, the network should be modified so the upstream portion of the pipe containing the PRV is removed and the PRV is replaced by artificial reservoir with water surface elevation equal to H_{set} and it must be added constant consumption at upstream node of pipe contains PRV equal to the value of flow in downstream portion of PRV as shown in figure (4.C).

3. $H_b > H_a$: the PRV acts as a check valve as in a case of simple check valve.

If one of the possible functions of PRV is known, the same steps of analyzing simple networks are done.

At each iteration in the solution process, the activity of the PRV from the above three functions of valve PRV should be checked until convergence occurs.

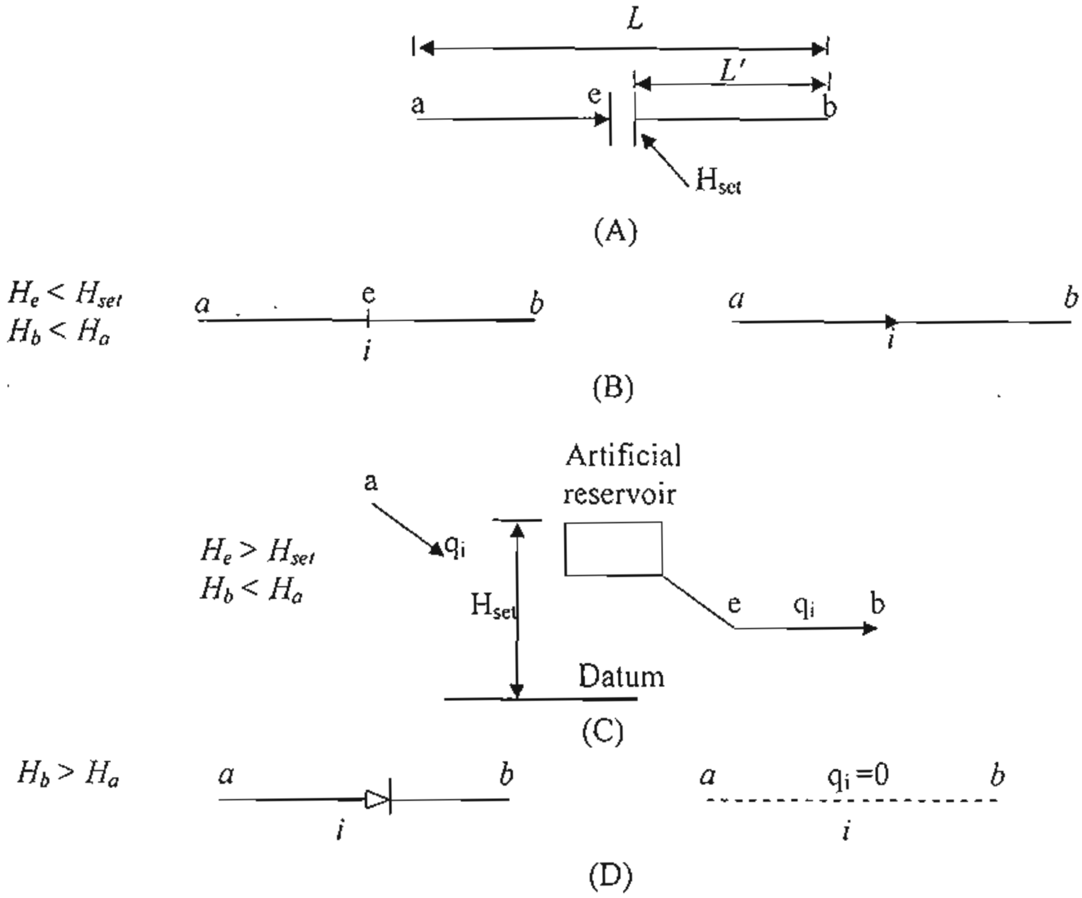


Figure (4): PRV; (A) symbol, (B) as a pipe, (C) as a reservoir pipe, and (D) as a check valve (After Chandrashekar [2])

<u>*(4) Networks including pressure sustaining valve (PSV):*</u>

A Pressure Sustaining Valve (PSV): is used to maintain a constant pressure upstream from it, independent of the value of the downstream pressure [6]. A PSV is used in situations where the pressure would otherwise become too low in the elevated portions of the network. Therefore, unregulated flow may occur.

Consider i is the pipe containing (PSV) as shown in figure (5) where junction node a is assumed to be the upstream node and b is the downstream node. Let k and k' represent the stiffnesses of the pipe corresponding to the lengths L and L' respectively, and H_e, and H_{set} represent the computed and set values of hydraulic grade line respectively at the location of the valve. Then one of the three possible conditions may occur [10]:

1. $H_e > H_{set}$ and $H_b < H_a$: the PSV has no effect and the simple pipe model may be used with stiffness factor $k_i = 1 \Big/ \left(r_i \left| q_i \right|^{\alpha - 1} \right)$.
2. $H_e < H_{set}$ and $H_b < H_a$: the PSV is activated which H_e is set equal to H_{set}. To simulate this case in the proposed method, the network is modified so the downstream portion of the pipe containing the PSV is removed and the PSV is replaced by artificial reservoir with water surface elevation equal to H_{set} and it should be added as a constant discharge at downstream node of pipe contains PSV equal to the value of flow in upstream portion of PSV as shown in figure (5.C).
3. $H_b > H_a$: the PSV acts as a check valve as in the case of simple check valve.

After determination of the specified case from the above three cases of PSV, the same steps of analyzing simple networks are carried out.

At each iteration in the solution process, the activity of the PSV from the above three functions of valve PSV must be checked until convergence occurs.

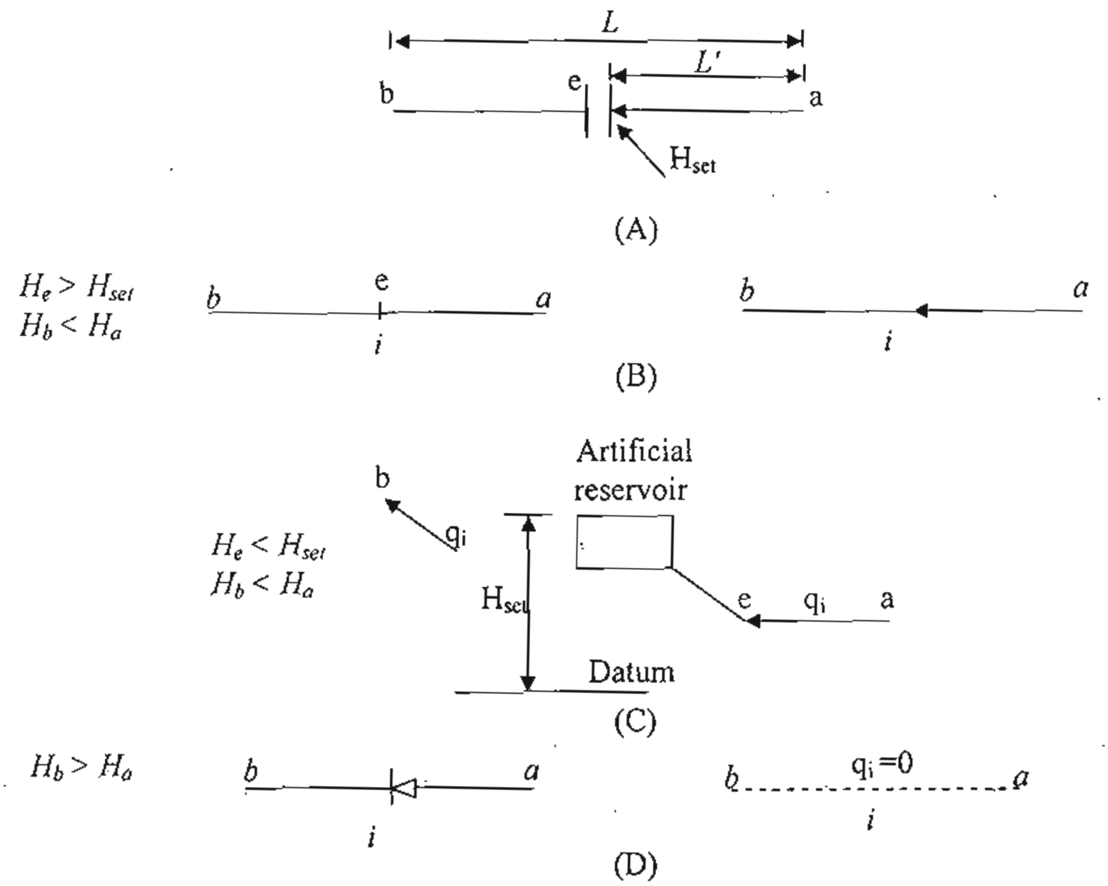


Figure (5): PSV; (A) symbol, (B) as a pipe, (C) as a reservoir pipe, and (D) as a check valve

CODE STRUCTURE

The numerical procedures described previously are programmed in a computer FORTRAN code named SFLOW. This code is compiled by Digital Visual FORTRAN (Ver. 5.0) and is running under Windows XP operating system on a personal computer. SFLOW code consists of a main program and three subroutines. Figure (6) shows the flow chart for the SFLOW code.

CAPABILITIES OF THE SFLOW CODE

The followings are the different capabilities for SFLOW code:

1. The code deals with different units such as International System (*SI*) and English System (*ES*) units.
2. The code is prepared to calculate the head loss using either Hazen-Williams or Darcy-Weisbach equation. In Darcy-Weisbach equation the Darcy coefficient is calculated according to equation of Swamee and Jain [10] which is a modified formula to the Colebrook – White equation (Re > 4000):

$$f_i = \frac{0.25}{\left[\log\left(\frac{\varepsilon_i}{3.7D_i} + \frac{5.74}{\mathrm{Re}_i^{0.9}}\right)\right]^2} \quad (38)$$

where, ε_i = the pipe roughness height, $Re_i = 4Q_i / (\pi D_i \nu)$= Reynolds number, Q_i = flow rate through pipe *i*, D_i = diameter of pipe *i*, and ν= kinematic viscosity of water

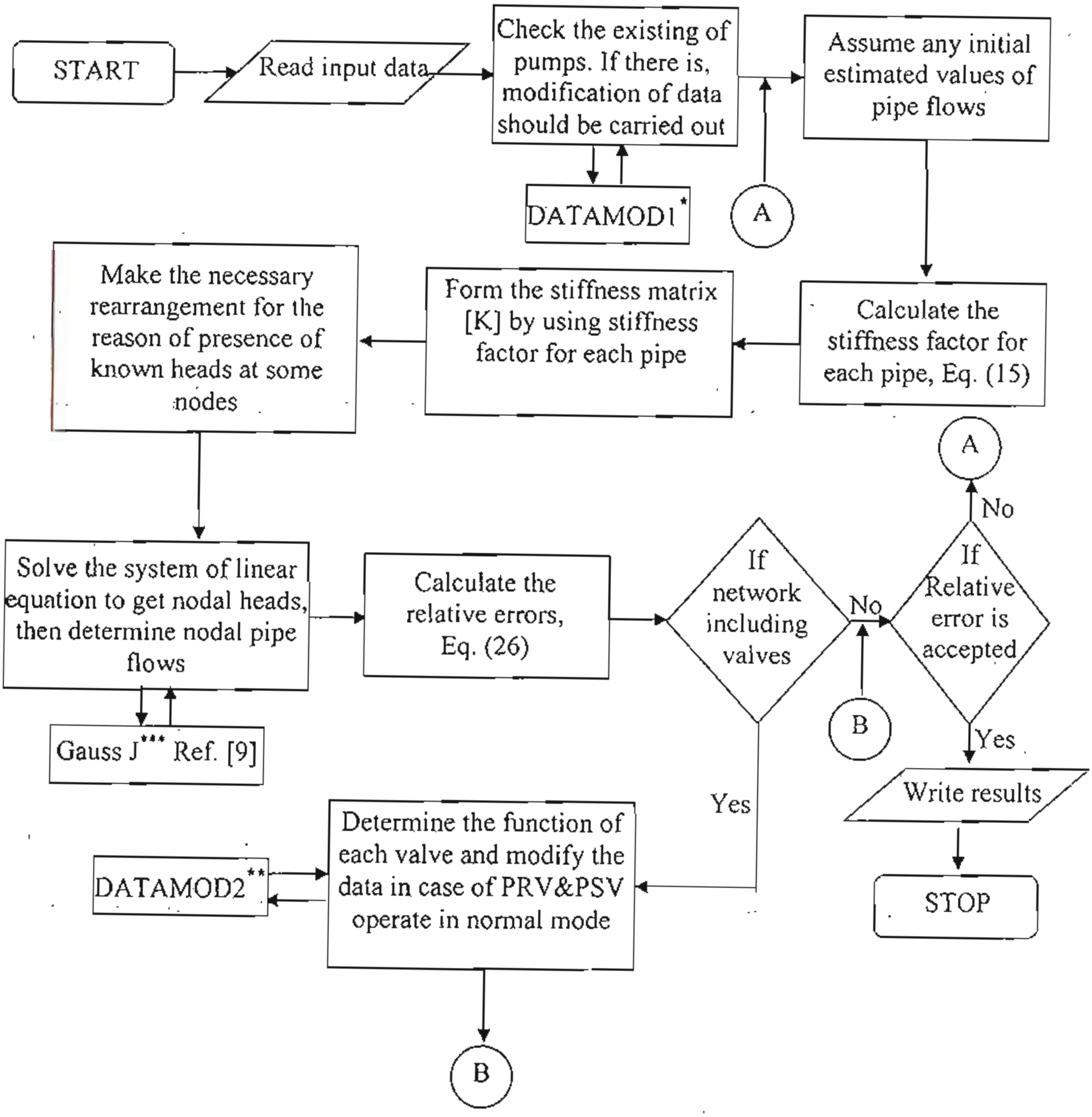
3. The code is prepared to analyze the networks including both booster pumps and source pumps.
4. The code analyzes the networks including some kinds of valves such as CVs or PRVs or PSVs or a combination of these valves.
5. If there are pumps in the network and/or there are PRVs or PSVs work in normal operation, the program is prepared to modify the input data and performs the hydraulic analysis for the network according to these modified data.

APPLICATIONS

The SFLOW code has been tested against EPANET software which applies the principals of gradient method. The two programs were applied on a hypothetical simple water distribution network [6].

Two Pumps – Three PRVs – Three loop network analysis

The pipe network shown in figure (7) consists of 10 pipes, 8 nodes and two constant head reservoirs [5]. Pipe numbers 3 and 10 include pumps with data shown in the figure. Pipes number 4, 5, and 7 include PRVs with data also shown in the figure. All data about the network are presented in table (1) including pipe data and nodal requirements. The level of the water inside the elevated tanks at node (7) is 500 ft, and at node (8) is 400.0 ft. To analyze the network, the pump performance curves should take the form of equation (27). Values of q_o, α, and λ are computed and are found equal to 2.2901 cfs, 0.0567, and 0.865 respectively for pump mounted on pipe number 3 and 7.0759 cfs, 0.189, and 0.5166 respectively for pump mounted on pipe number 10, according to appendix. Results of nodal heads and flow through pipes that obtained from EPANET and SFLOW programs are presented in tables (2) and (3). The results show that the three valves are operating in normal mode. Comparison of results exhibits the superiority of the proposed method for analyzing networks including pumps and PRVs, as mentioned before this method is not based on the initial conditions (pipe flows), as in EPANET program, and the differences between results of both EPANET and SFLOW are very small or not found. This difference could be due to the estimated values of α and λ for every power equation of each pump.



* DATAMOD1 is a subroutine used to modify the input data in case of presence of working pumps

** DATAMOD2 is a subroutine used to modify the input data in case of presence of active PRVs or PSVs

*** Gauss J is a subroutine used to solve a system of linear algebraic equations using Gauss – Jordan elimination method.

Figure (6): Flow chart for the SFLOW code

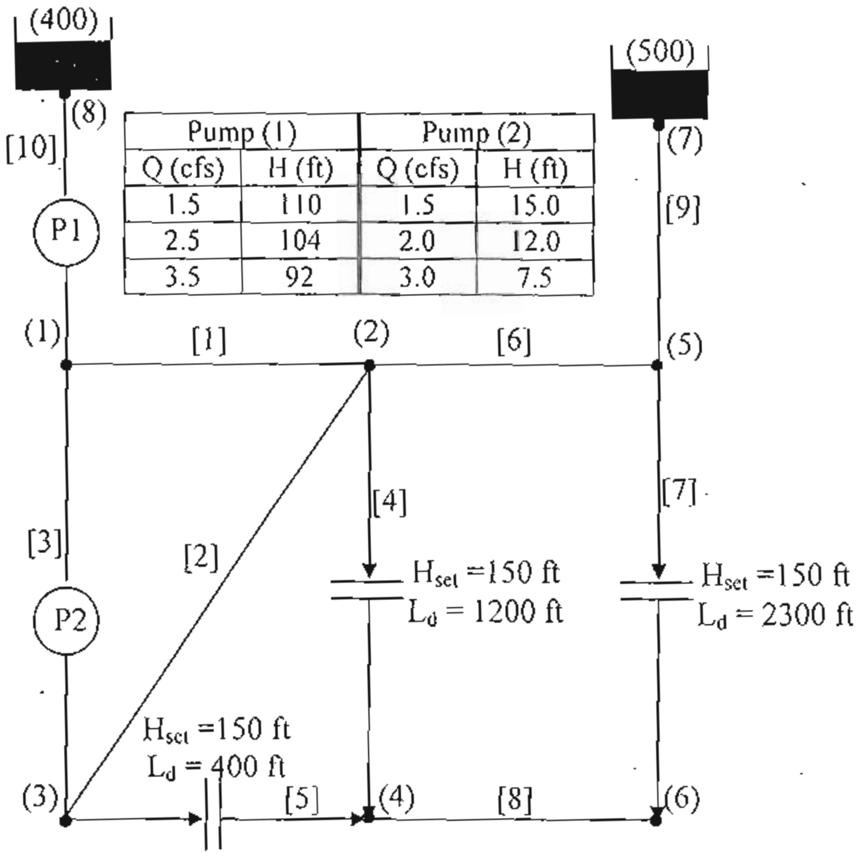


Figure (7): Layout of the network under study (After Larock et al. [6])

Table (1): Pipe data and nodal requirements for case study

Pipe no.	Diameter (in)	Length (ft)	C_{HW} coefficient	Node no.	Demand (cfs)	Level from specified datum (ft)
1	6.0	2000.0	100.0	1	----	400.0
2	6.0	2000.0	100.0	2	3.5	400.0
3	6.0	2500.0	100.0	3	1.0	350.0
4	8.0	1700.0	100.0	4	0.5	60.0
5	6.0	800.0	100.0	5	----	400.0
6	6.0	1000.0	100.0	6	0.5	60.0
7	8.0	3000.0	100.0	7	----	400.0
8	6.0	3300.0	100.0	8	----	400.0
9	10.0	1000.0	100.0			
10	10.0	1000.0	100.0			

Table (2): Comparison between nodal total pressure heads (ft) in EPANET and SFLOW programs

Node No.	EPANET [3]	SFLOW
1	482.32	482.48
2	366.63	366.87
3	367.55	367.82
4	148.95	148.95
5	486.60	486.61
6	147.32	147.34
7	500.00	500.00
8	400.00	400.00

Table (3): Comparison between pipe flows (cfs) in EPANET and SFLOW programs

Pipe No.	EPANET [3]	SFLOW
1	1.50	1.50
2	0.11	0.11
3	1.39	1.39
4	0.33	0.33
5	0.28	0.28
6	2.22	2.22
7	0.39	0.39
8	0.11	0.11
9	2.61	2.61
10	2.89	2.89

CONCLUSIONS

The following conclusions could be drawn from this paper:

- A new technique depends on both LTM and ELGT is derived for analyzing pipe networks.
- Several modifications were added to the derived new technique in order to deal with networks including control devices (pumps, pressure reducing valves, pressure sustaining valves, and check valves).
- A computer program with FORTRAN language named SFLOW has been established to apply the principles of the new technique for analyzing complex network including control devices.
- SFLOW code has many advantages such as: it can deal with different units, different kinds of equation for determining the head losses, and three types of valves (PRVs, PSVs, and CVs).
- The SFLOW code is prepared to determine the function of PRVs or PSVs (operating in normal mode or as a check valve or has no effect) at each iteration until convergence is met. Also in case of there is pumps in the network or valves act in normal operation, the SFLOW program is prepared to modify the input data and performs the hydraulic analysis for the network according to the modified data.

- Application of the SFLOW code on small hypothetical networks shows the superiority of the proposed method for analyzing the networks. This method does not depend on the initial conditions (initial pipe flows), and proves its capability to be applied on real water distribution networks.

REFFERNCES

[1] Bhave, P. R., and Gupta, R., (2006). "Analysis of Water Distribution Networks". Alpha Science International Ltd., Oxford, UK. P.515.

[2] Chandrashekar, M. (1980). "Extended Set of Components in Pipe Networks". Journal of Hydraulic Division, 106(HY1), pp. 133 – 149.

[3] EPANET 2, 2002. http://www.epa.gov/nrmrl/wswrd/epanet.html

[4] Gupta, R., and Prasad, T. D. (2000). "Extended Use of Linear Graph Theory for Analysis of Pipe Networks". Journal of Hydraulic Engineering, 126(1), pp. 56 – 62.

[5] Kesavan, H., and Chandrashekar, M., (1972). "Graph – Theoretic Models for Pipe Network Analysis". Journal of the Hydraulic Division, Vol. 98 (HY2), pp. 345 – 363.

[6] Larock, B. E., Jeppson, R. W., and Watters, G. Z. (2000). "Hydraulics of Pipeline Systems". CRC Press LLC, P. 537.

[7] Nielsen, H. B., (1989), "Method for Analyzing Pipe Networks", Journal of Hydraulic Engineering, Vol. 115(2), pp. 139 – 157.

[8] Nogueira, A., (1993). "Steady – State Fluid Network analysis". Journal of Hydraulic Engineering, Vol. 119(3), pp. 431- 436.

[9] Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P., (1992). "Numerical Recipes in Fortran". American Institute of Physics, P. 957.

[10] Rossman, L. A., EPANET 2, Users Manual. U.S. Environmental Protection Agency, Cincinnati, Ohio, 1993. http://www.epa.gov/nrmrl/wswrd/EN2manual.PDF

[11] Wood, D., and Charles, C., (1972). "Hydraulic Network Analysis Using Linear Theory". Journal of the Hydraulic Division, Vol. 98 (HY7), pp. 1157 – 1171.

[12] Wood, D., and Rayes, A., (1981). "Reliability of Algorithms for Pipe Network Analysis". Journal of the Hydraulic Division, Vol. 107 (HY10), pp. 1145 – 1161.

APPENDIX

DETERMINATION OF PUMP PARAMETERS VALUES

This Appendix concerns with determination of pump parameters (q_o, α, λ) corresponding to pump mounted in pipe number 10, figure (7). These parameters are necessary for hydraulic analysis of networks including pump using the proposed method. The procedures for parameters computation are as follows:

Value of (q_o):

To deduce the value of q_o (maximum flow rate from the pump), EXCEL program is used to find the best fitting of second degree polynomial corresponding to data of pump (1), shown in figure (7). This equation is found to be:

$$h_p = -3.0\, q^2 + 6.0\, q + 107.75 \qquad (A.1)$$

q_o occurs when h_p (pump head) equal to zero. Then, the above equation becomes:

$$-3.0\, q_o^2 + 6.0\, q_o + 107.75 = 0.0 \qquad (A.2)$$

by solving this equation, the value of (q_o) is found equal to *7.08 cfs.*

Value of (α and λ):

The steps previously mentioned are applied for computation the values of (α, λ) as follows:

- Table (A.1) presents the values of h_p, q, and $(q_o\text{-}q)$ for some points on the pump curve, Eq. (A.1).
- Figure (A.1) show the relationship between the values of $(q_o\text{-}q)$ on the horizontal axis and h_p on the vertical axis.
- Using EXCEL program to determine the best fitting power equation corresponding to the curve shown in figure (A-1). This equation is found to be:

$$h_p=32.928(q_o\text{-}q)^{0.7669} \quad \text{(A.3)}$$

- To determine the value of (α):

$$0.7669 = (1\text{-}2\,\alpha)/(1\text{-}\,\alpha) \quad \text{(A.4)}$$

by solving the equation, the value of α is found equal to 0.189.

- To determine the value of (λ):

$$32.928=1/\lambda^{(1/0.189)} \quad \text{(A.5)}$$

by solving this equation the value of λ is found equal to 0.5166.

Table (A.1): Values of h_p, q, and $(q_o\text{-}q)$ for some points on the pump curve, Eq. (A.1)

h_p (ft)	q (cfs)	$(q_o\text{-}q)$ (cfs)
147.66	0.00	7.08
123.00	1.50	5.58
105.70	2.50	4.58
87.49	3.50	3.58
68.03	4.50	2.58
46.67	5.50	1.58
21.57	6.50	0.58
0.00	7.08	0.00

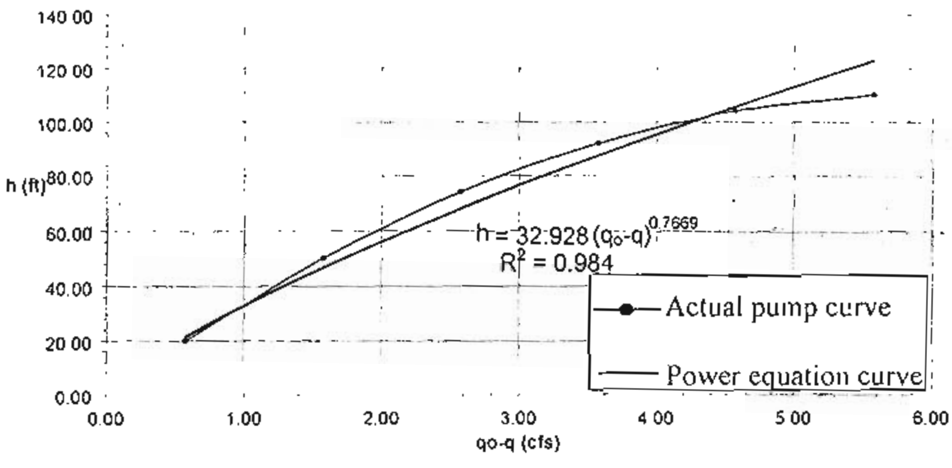


Figure (A.1): Relationship between values of $(q_o\text{-}q)$ and h_p