TRANSIENT ANALYSIS AND SIMULATION OF WATER FLOW IN PIPE NETWORKS

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الملخص

تعتبر مشاكل التدفق العابرة المصاحبة لسريان السوائل في الشبكات الكبيـرة أحـد أهـم المسببات لإرتفاع الضغط وحدوث ظاهرة التكهف والإهتزازات، ويمكنها أن تكون السبب فـي بعض التأثيرات الأخرى التي منها ما هو ضار بمكونات الشبكة. ويعتمد حجـم تـأثير التـدفق العابر عادةً على الشكل العام للشبكة تحت الدراسة وعلـى مكوناتهـا الميكانيكيـة والخـواص الطبيعية للأنابيب والمائع المستخدم.

تقدم هذه الورقة نموذجاً لتحليل ومحاكاة مصادر مختلفة لحالة التدفق العابر في شـبكات أنابيب المياه إعتماداً على طريقة الخصائص. تم إعداد النموذج ليكون سهل الإستخدام في صورة برمجية تم إعدادها بلغة البيسك المرئي (Visual Basic) بحيث يمكنه تشغيلها تحـت تطبيقـات الويندوز.

ABSTRACT

Transient problems associated with liquid flow in large networks are characterized as the main cause of high pressures, cavitation, vibration, and may also create different effects on pipes, harmless in some situations and destructive in others. The size of such effect depends highly on the physical configuration of the system under consideration, the mechanical components in the system and the physical properties of the pipe and flow material.

This work presents, based on the method of characteristics, an Algorithm for analysis and simulation of different sources of transient in practical water pipeline network. The Algorithm is prepared in user-friendly computer package written in Visual Basic and can be operated under Windows Application.

KEYWORDS: Transient flow; Water hammer; Network analysis; Method of characteristics.

INTRODUCTION

Transient flow may be defined as a state in which the flow parameters at any point in the system are time dependent. In other words, it is the transition stage between any two successive steady states of the system. That means, if the steady state operating conditions of a fluid system are changed, either by the user in such away as by changing valve setting or due to pump operation, or inadvertently due to some system failure, the change in the equilibrium flow conditions will be transmitted to the system as pressure waves with a traveling speed at the sonic velocity, and propagating away from the point in the system where the change in the steady flow conditions was imposed. A short time later, the system will attain a new equilibrium condition [1 - 3].

The approach of the analysis of transient flow can be divided into two classes:

1- Surge or rigid column theory in which the rate of change of the flow velocity is assumed to be slow in comparison with the time needed for a pressure wave to pass through the system. This theory ignores elastic properties of the pipe wall.
2- Water hammer theory in which the effect of the elasticity of both fluid and pipe are taken into consideration in the analysis [1 - 3].

Transient flow can be modeled by a set of partial differential equations (continuity and momentum equations). However, the complexity of such equations and the associated boundary conditions makes the analytical solution of theses equations only possible if certain simplifying assumptions are considered, such as, neglecting friction terms from momentum equation and presenting boundary conditions in simple forms. Alternatively, solutions to more practical situations can be achieved by approximate techniques or by numerical methods using digital computers.

The method of characteristics (numerical technique) is highly recognized in solving such governing differential equations. This method of analysis requires the simultaneous solution of the momentum and continuity equation, with the help of the equation of state and other physical property relationships.

This work presents a new computer application (TRANS) that can be utilized in analyzing transient flow problems in pipe networks. The application was developed by the Mechanical Engineering Department of Al-Fateh University, and was structured in Visual Basic language and can be operated under Windows application, [4].

ANALYSIS

Modeling of transient flow problems usually led to the formulation of two quasi-linear hyperbolic partial differential equations. These equations take the form, [1, 2, 5]:

$$\frac{dV}{dt} + \frac{1}{\rho}\frac{\partial P}{\partial x} + g\frac{dz}{dx} + \frac{f}{2D}V|V| = 0 \tag{1}$$

$$a^2\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{dP}{dt} = 0 \tag{2}$$

V: Flow velocity	f: Friction factor
P: Pressure	D: Pipe diameter
ρ: Density	a: Wave velocity

The friction factor f which can be calculated from Colebrook-White formula. The general expression of wave velocity a in pipes, as given by Halliwell [2], takes the form:

$$a = \sqrt{\frac{K.E}{\rho.(E + K.\phi)}} \tag{3}$$

In which

E: Young's modules of elasticity of the conduit walls.

K: the bulk modules of elasticity of the fluid.

ρ: density of the fluid.

ϕ: is a non-dimensional parameter that depends upon the elastic proper the conduit. Its expression depends on the type of conditions, [2].

THE TRANS APPLICATION

The *TRANS* Application was structured as a tool for analyzing water hammer problems in pipe networks, and can also be used for design and monitoring the operation of pipe networks in order to avoid excessive pressures and cavitation, [4]. The application can be utilized to simulate the following common types of water hammer sources:

- Valve closure at a programmed rate in any number of pipes.
- Valves can be slammed shut at any number of pipes.
- Operation of pressure reducing valves problems.
- Source pump power failure at any pump station.
- Booster pump power failure at any pump station.
- Pressure surge caused by pump start up.
- Sudden change of external flow demand at any node.
- Combination of the above.

The analysis essentially calculates pressure, flows and other associated parameters for a prescribed history of time. This paper outlines the use of the application in simulating the effects caused by one single transient source, while the effect of multiple sources will be discussed in a follow up paper.

NETWORK ANALYSIS AND SIMULATION

A network model is a description of the components of a transport and distribution system. Such a model will contain reservoirs, sources, pipes, pumps and control valves. Additionally, consumer demand is modeled and is assumed to be concentrated at network nodes. The interconnection of the modeled features and their associated hydraulic characteristics (e.g. diameter, length and roughness for a pipe) form the network description.

The network model is, therefore, a geometric layout of nodes and branches. Network data, associated with the model layout, will include static information about such components as reservoir, pipes, pumps, valves, and nodes. Additionally, the runtime is another type of input data to the application, which is necessary to describe some features like operation data of valves and pumps.

Network analysis and simulation is concerned with modeling the hydraulic performance of a network under any type of transient sources. The specification of a standard network analysis is shown in Table (1)

Table 1: Specification of a standard network analysis.

Feature	Data Required	Calculated Parameters
Network	Network Geometry (Connections)	
Pipe	Length, diameter, roughness, Modulus of Elasticity, pipe thickness.	Flow and Head
Node	Head	
Reservoir	Consumption (if present)	Head
Pumps	Lift/flow characteristics	Inlet / outlet heads, and flow.
Control Valve	Direction, setting, relevant characteristics.	Inlet / outlet heads, and flow.

The solution starts by using initial conditions, which constitute the steady state solution of the network, and all other associated data of all elements used in the network. The simulation is then performed along a specified period of time to provide information about network behavior.

THE CASE STUDY

The case study deals with a practical project, which was constructed by the Great Man-made River Water Utilization Authority for Al-Hasaouna and Jfara System. The project is located at a distance of 60 km south of Tripoli, with a total area of 4700 hectare, divided over 700 farms. The water transport and distribution network consists of a main reservoir, valves and a large piping system. The piping system is constructed from Ductile iron pipes (with diameters ranging between 300 mm and 1500 mm), and unplasticized polyvinyl chloride (uPVC) pipes (for diameters smaller than 300 mm). Figure (1) shows a schematic layout of the pipe network of Abu-Aiasha project.

Before the application was used to analyze the case study, it was used to simulate a pipe network presented in the literature [1] in an effort to verify the performance of the Application.

a) Network Description

Water flows from the main project's reservoir, by gravity, into the pipe distribution network starting with node No. 1. To minimize the use of control devices, the project was divided into several sectors with closer levels between the farms of each sector. Gate valves are distributed in the network in order to control the operation of the system. The input parameters of network data are classified as follows [4]:

- Gate Valves (Types I and II) data are listed in Tables (2, 3, 4 and 5).
- Network pipes data are tabulated in Table (6).
- Network nodes data are listed in Tables (7).

Table 2: Loss coefficient for Gate Valve I.

Step No.	%of Opening	Loss Coefficient
0	0	0
1	10	0.0008627
2	20	0.0086775
3	30	.0043238
4	40	.0141243
5	50	.0393701
6	60	.0996016
7	70	.298507
8	80	.63613
9	90	1.0204
10	100	1.38

Table 3: Rate of Closure of Gate Valve I.

Description	Value
Time of Closing first Stage	1 sec
% open at end of first stage	55%
Total Closing Time	60 sec

Table 4: Loss coefficient for Gate Valve II.

Step No.	%of Opening	Loss Coefficient
0	0	0
1	10	0.0167
2	20	0.0313
3	30	0.0556
4	40	0.1000
5	50	0.1787
6	60	0.3330
7	70	0.625
8	80	1.25
9	90	2.5
10	100	5.27

Table 3: Rate of Closure of Gate Valve I.

Description	Value
Time of Closing first Stage	1 sec
% open at end of first stage	15%

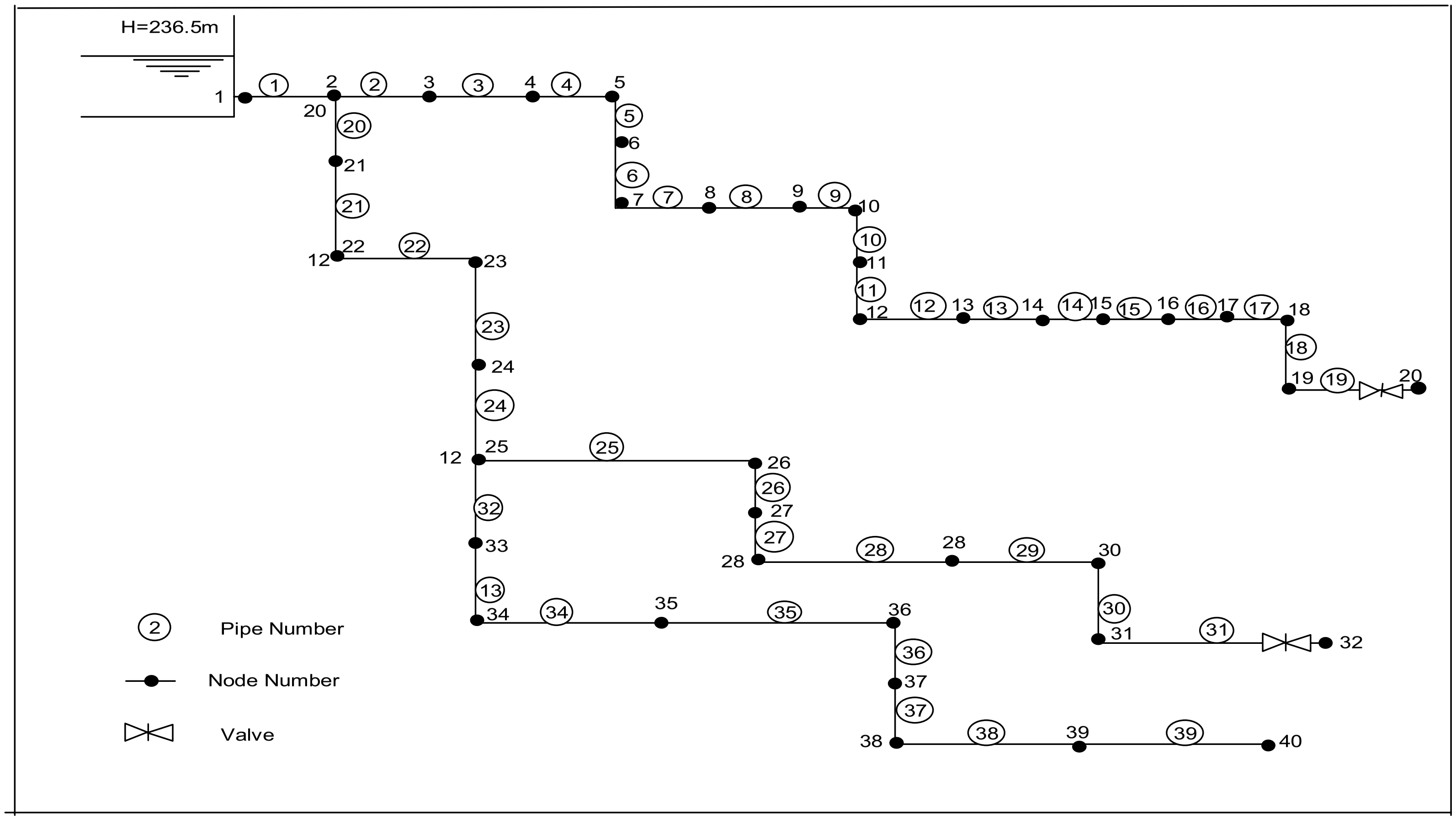

Figure 1: Schematic Diagram of Abu-Aisha Agricultural Project Network.

Table 6: Case Study Pipe Data.

PIPE				
No.	Type	Dia., mm	Length, m	Flow, L/s
1	DI	1500	230	2700
2	DI	1500	150	1887
3	DI	1200	1850	1481
4	DI	1000	1430	967
5	DI	1000	520	967
6	DI	900	1050	673
7	DI	900	1235	673
8	DI	700	1180	406
9	DI	500	625	271
10	DI	450	515	199
11	DI	350	530	111
12	DI	350	150	111
13	DI	350	370	100
14	DI	300	200	84
15	uPVC	268	215	56
16	uPVC	238	400	40
17	uPVC	192	410	24
18	uPVC	192	150	24
19	uPVC	136	360	12
20	DI	1000	150	812
21	DI	800	1550	705
22	DI	800	625	705
23	DI	800	817	705
24	DI	800	535	553
25	DI	450	1430	223
26	DI	450	510	223
27	DI	350	310	107
28	DI	350	310	107
29	DI	350	615	107
30	uPVC	268	520	72
31	uPVC	268	215	64
32	DI	600	1200	330
33	DI	400	525	163
34	DI	400	600	163
35	DI	400	830	163
36	DI	400	515	147
37	DI	300	490	84
38	DI	300	475	76
39	uPVC	268	345	60

Table 7: Case Study Node Data.

Node No.	Head, m		Demand L/s
	Total	Available	
1	237	46.0	2700.0
2	236	48.5	
3	236	48.5	406.0
4	234	61.6	513.6
5	233	67.4	
6	232	68.3	294.6
7	231	68.9	
8	230	74.2	266.7
9	199	48.0	135.4
10	197	49.4	71.7
11	195	49.5	87.6
12	194	49.5	
13	194	49.5	11.9
14	193	49.5	15.9
15	192	50.0	27.9
16	191	49.8	15.9
17	190	49.6	15.9
18	188	49.8	
19	188	49.4	11.9
20	186	49.8	11.9
21	236	48.4	107.5
22	233	53.6	
23	232	55.9	
24	231	57.7	151.3
25	217	48.3	
26	211	46.2	
27	209	46.3	115.5
28	209	46.3	
29	207	45.2	
30	205	47.8	35.8
31	202	48.0	8.0
32	201	46.3	63.7
33	218	51.7	167.2
34	216	48.3	
35	213	50.4	
36	210	49.4	15.9
37	209	42.2	63.7
38	207	48.7	8.0
39	206	49.2	15.9
40	204	51.3	59.7

b) Results of the Analysis

Samples of the results for the transient behavior of the case study are described below:

- Figure (2) represents head vs. time at downstream end of pipe no. 19 due to valve closure at end of this pipe. The total closing time is considered as 60 and 180 seconds, with valve loss coefficient from Table (2) and valve closing rate from Table (5).
- Figure (3) represents head vs. time at downstream end of pipe no. 19 due to valve closure at end of this pipe. The total closing time is 60 sec, with valve loss coefficient from Table 2. The results are given for both rates of closure as listed in Tables (3) and (5).
- Figure (4) represents head vs. time at downstream end of pipe no. 19 and node no. 12 respectively due to valve closure at downstream end of pipe. no. 19. Results are given for Valve loss coefficient from Table (2) for closing time of 60 seconds.
- Figure (5) represents head vs. time at end of pipe no. 19 due to valve closure at downstream of this pipe. The total closing time is 60 sec. The rates of closure are listed in table 3 and 5 respectively, while valves loss coefficients are listed in Tables (2) and (4) respectively. It is clear that the valve characteristics have real effect on the results.
- Figure (6) represents the effect of total closing time (60 and 180 seconds) on the head at end of pipe no. 31 due to valve closure at downstream end of this pipe. Valve loss coefficient is listed in Table (2) and closing rate is listed in Table (5).

- Figure (7) represents head wave movement along pipe no. 19 at different time steps due to valve closure at end of this pipe. Results are obtained based on valve loss coefficients listed in Table (2) and valve closing rate listed in Table (5).

From the results of the analysis, the following conclusion can be obtained:

1. The total closing time of valves must be large enough to avoid high and low pressures.

2. As the rate of valve closure has an appreciable effect on the transient, different scenarios must be considered in order to obtain an acceptable and practical rate. Generally, it can be summarized that valve characteristic play an important role in the transient analysis, and therefore, care must be taken to include reliable characteristics.

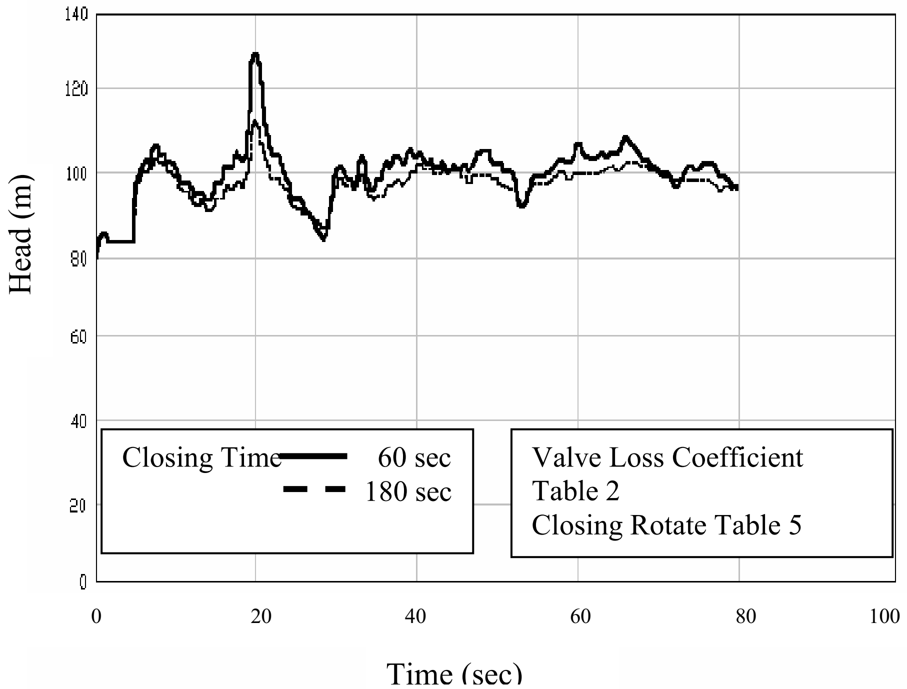

Figure 2: Head vs. time at downstream end of pipe No. 19 due to valve closure at end of the pipe (Effect of closing time).

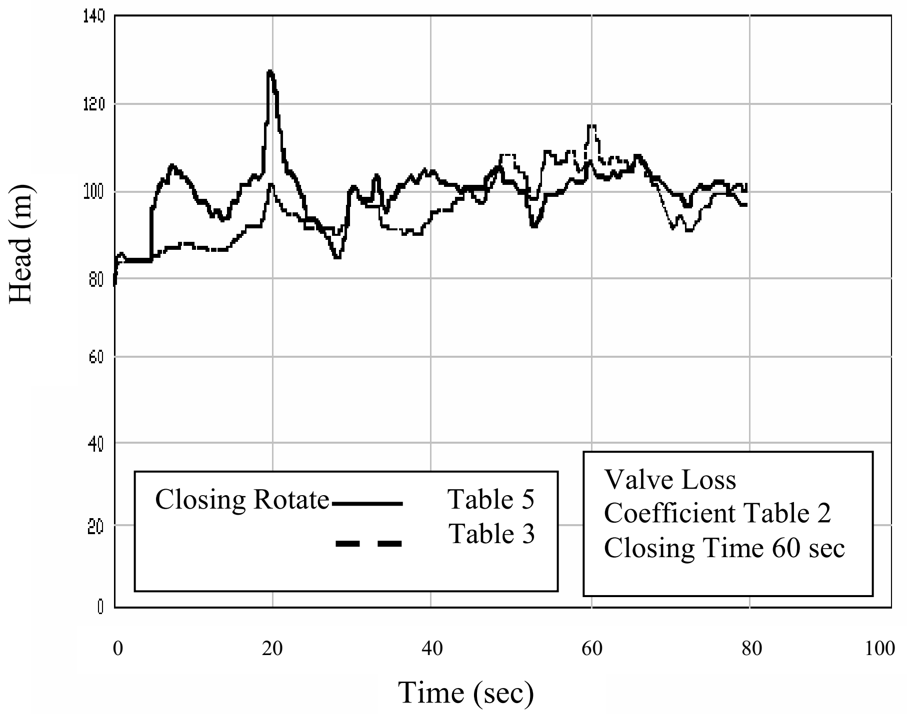

Figure 3: Head vs. time at downstream end of pipe No. 19 due to valve closure at end of the pipe (Effect of closing rate).

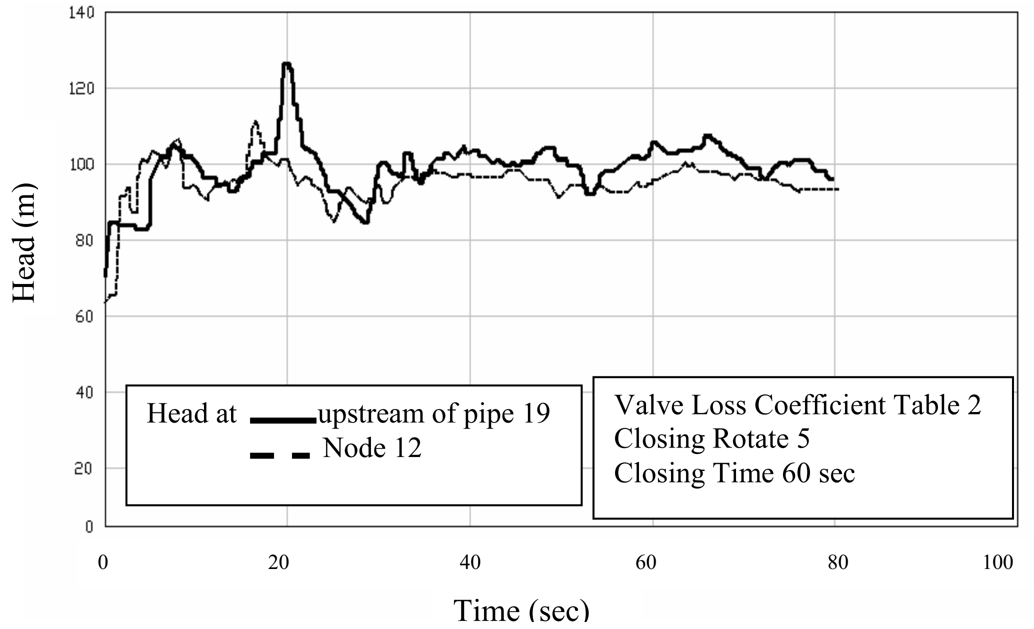

Figure 4: Head vs. time at downstream end of pipe No. 19 and node No. 12 due to valve closure at end of pipe No. 19.

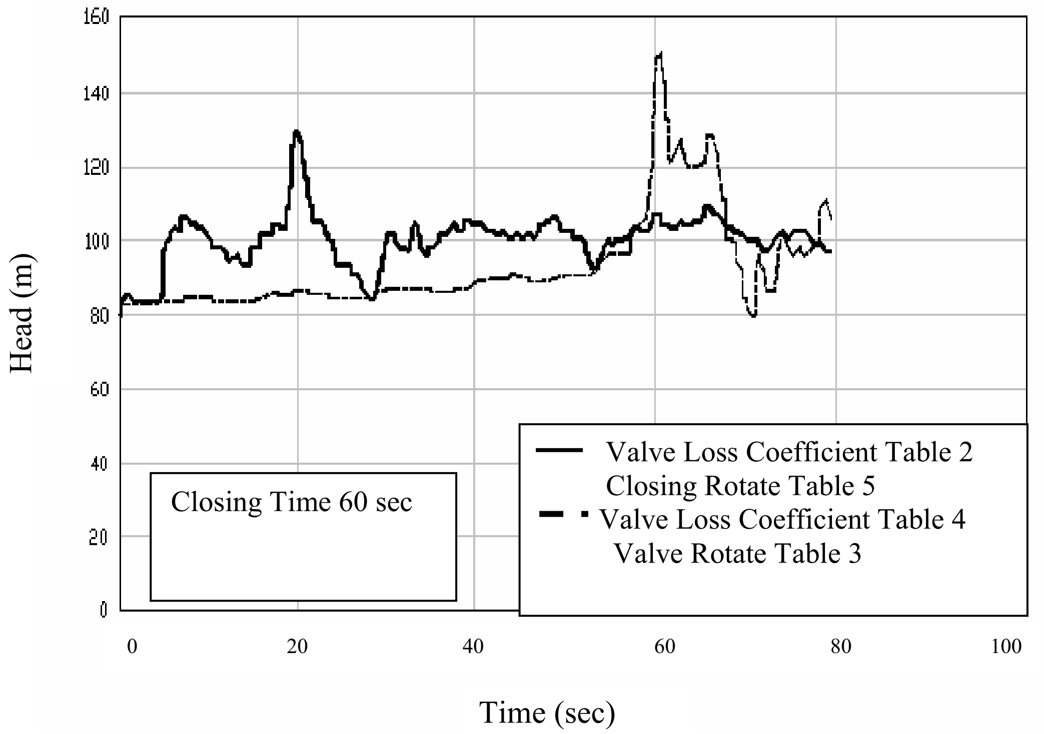

Figure 5: Head vs. time at downstream end of pipe No. 19 due to valve closure at end of pipe No. 19 (Effect of Valve Type).

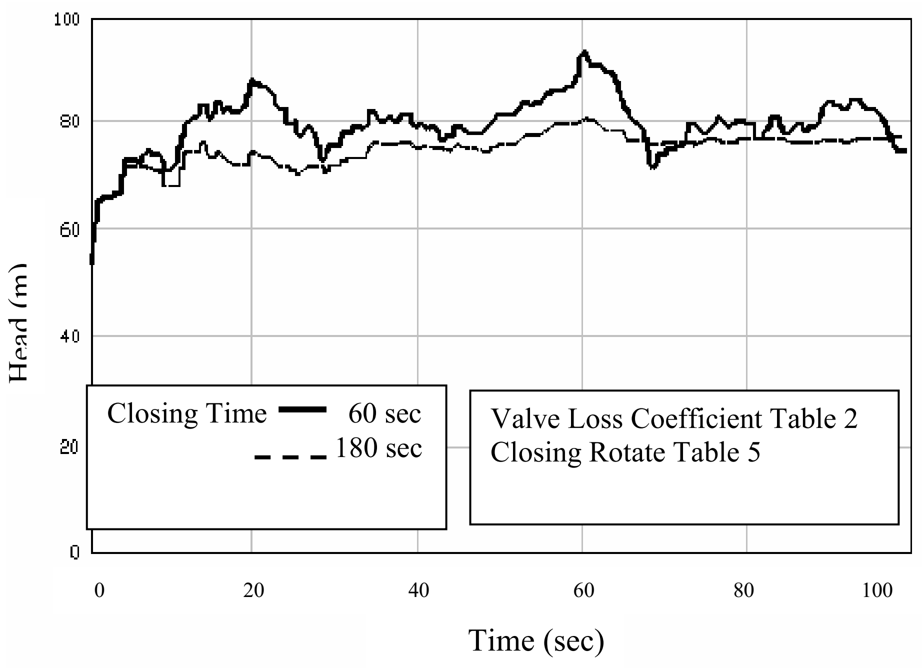

Figure 6: Head vs. time at downstream end of pipe No. 31 due to valve closure at end of the pipe (Effect of Closing Time).

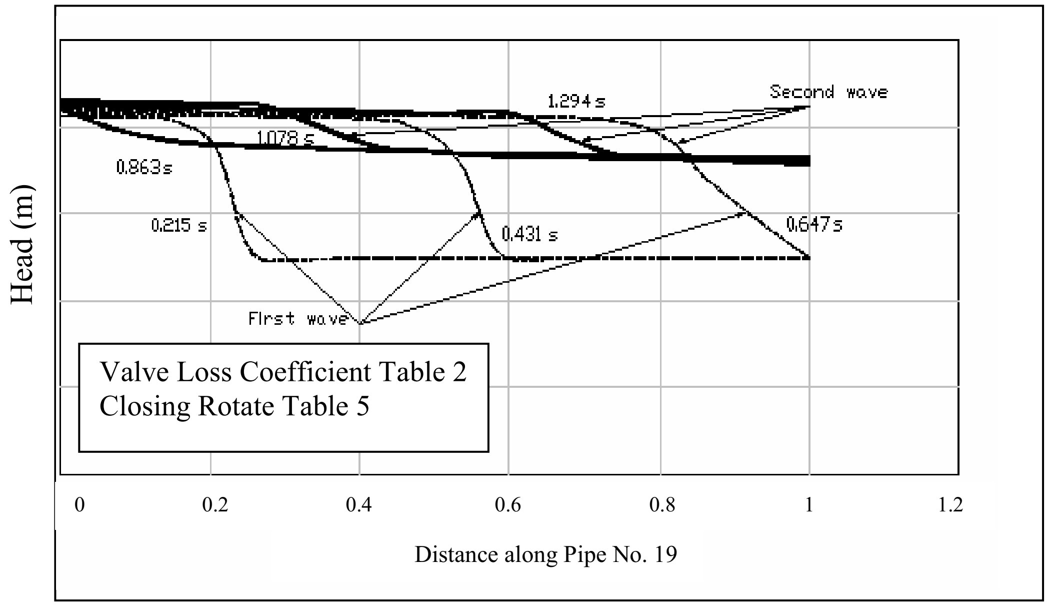

Figure 7: Wave movement along pipe no. 19 due to valve closure at end of the pipe.

Based on the above, the results of the analysis can be summarized in Table (8) below.

Table 8: Summery of the results.

Transient Effect (% of static)	Description
28	Valve loss coefficients listed in Table (2) and closing rate as in the Table (5) with closing time of 180 second.
16	Valve loss coefficients listed in Table (2) and closing rate as in the Table (5) with closing time of 60 second.
18	Valve loss coefficients listed in Table (2) and closing rate as in the Table (3) with closing time of 60 second.
50	Valve loss coefficients listed in Table (4) and closing rate as in the Table (3) with closing time of 60 second.

CONCLUSIONS

The specific conclusion drawn from this work can be summarized as follows:

i- The method of characteristics has become quite popular and is extensively used. This method has proven to be superior to other methods in several aspects, such as correct simulation of steep wave fronts, illustration of wave propagation, incorporation of friction and convective terms, ease of programming, and efficiency of computation. The method was found to be capable of easily modeling variety of boundary conditions and conduits. Therefore, the method is particularly suitable for analysis of systems having complex boundary conditions. The main disadvantage of the method is that the stability conditions restricting the size of the time step.

ii- During the course of the present study, several types of boundary conditions are handled, however, other boundary conditions still require analysis and modeling.

iii- In the current work, a computer program was prepared for the analyze of water hammer problems in pipe networks. The program is incorporated in a package that can be considered as a vital tool for the proper design of pipe networks. It can be utilized in the simulation of wide range of pipe network configurations. The computer program performs transient analysis of a variety of water transport and distribution networks and handles many types of boundary conditions

iv- The computer package was designed and developed by using Visual Basic language, with the facility of operating it as Windows application (full friendly user).

v- One of the important contributions in this work is modeling and programming the simultaneous effect of more than one transient source if applied at the same time.

vi- The characteristics of valves and pumps play an important role in the transient behavior of network system, therefore, care must be given to include need data in the analysis. Such data is found to be very scare in the literature.

vii- Selective of proper network configuration requires previous experience which will help in selecting the network elements and their locations. This selection has great influence on the system transient, therefore, care must be taken in this respect.

viii- During investigation of the computer program, the operation condition of valves must be chosen to avoid high pressures in one side, and to prevent occurrence liquid column separation in the other side.

ix- It is quite clear that omitting friction from the analysis may lead to an increase in the transient effect estimation. Thus the contribution of the friction terms is very important in the analysis, and must be included in the analysis to avoid over sizing problems.

RECOMMENDATIONS

Based on the above mentioned conditions, and taking its consideration the results obtained during the analysis of the case studies, the following recommendations can be drawn:

i- Other practical situations need to be modeled using the relevant boundary conditions. The following situations are example:

- The simulation of surge tanks and air vent valves operation.
- The simulation of air chambers operation.
- Inclusion of the effect of column separation.
- Modeling other configuration of pumps and valves.

ii- Coupling the package development in this work with a steady state flow analysis program, so that, the user will only enter the physical priorities of the network and, therefore, avoid performing the two tasks separately, thus saving time and ensuring accuracy.

iii-Input/output procedure represents the communicate element with package, therefore enhancing it will contribute to the flexibility of the package. In this respect, graphical introduction of the network configuration will certainly minimizing the possibility of erroneous data in one hand, and plays the role of checking the data when transferring it into tabular form on the other hand.

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