Analysis of Surge in Pipelines Systems by Characteristis Method

M. Salmanzadeh, S. Torfi

***Abstract*—** Transient flows in pipelines mostly occur by closing the valves , turning off or starting up of pump and other any factor which cause flow acceleration or deceleration . Newton was the first one who started researching about the analysis of the transient flow . Then characteristis method for solving equations with partial differential was invented and this method completed more by Streeter at 1950 .The results of characteristis in a simple pipeline are completely correct , since the pipeline can be divided in parts that the characteristis can pass through them . But in a system made of two or more pipelines for computing all the pipelines , definite time interval Δt in order to establishing the boundary conditions in the joint of the pipelines , is considerd . Δt also should satisfy the courant stability condition(C) . If the considered time of Δt was in a state which the pipelines cannot be divided in equal parts through CΔt , then in some intervals , characteristis don't pass through the divided points of these flow in pipes and they pass another points .

***Keywords*—**Surge Analysis , Transient flow , Characteristis Method, Velocity and Pressure Equations .

NOMENCLATURE

a	Wave velocity, m / s
f	Coefficient Darsy Vayzbakh
g = 9.81	Acceleration of gravity, m / s
H	Head or height of fluid, m
p	Pressure, Pa
V	Speed, m / s
ρ	Density, kg / m ^{3}
f	Friction loss

I. INTRODUCTION

TRANSIENT flow in pipelines mainly are created by closing of the valve, a sudden stopping or starting of the pump .For computing hydraulic conditions in these new points , there are two methods :

1- Interpolation method
2- Compounding the characteristis method and the implicit finite difference method

In these method Streeter and Chaudry considered the new points at the end of the pipelines and beside the boundary of the pipelines , in other words the interval linear which isn't equal with the others , is put at the end of the pipeline and because of the importance of the boundaries in the damping flow , they should be regarded with high accuracy . And because these two methods have some errors in computations they affect the results of the computations of these boundary conditions . In the methods which are repnesented in this paper , unequal interval linear is situated in other place of the pipe . For example it is placed befor the end or in the middle of the pipeline . By solving such equations and computer simulation is observed that error in computing the velocity and pressure in the pipelines decreased considerably and the computed simulation are very similar to the practical results .

II. PROCEDURE FOR PAPER SUBMISSION

Both continuity and momentum equation as basic equations in flow are considered transient . The equations that are used for the calculation of the surge in transient currents are explained separately in this section .

$$v\frac{\partial H}{\partial x}+\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial v}{\partial x}-v\sin\theta=0$$

$$\frac{dv}{dt}+v\frac{\partial v}{\partial x}+g\frac{\partial H}{\partial x}+gh_f=0$$

The history of surge analysis indicates the expansion of variety of methods for solving Euler's equation and continuity equation . Variety of these methods depends on numerical analysis and designer innovation capability . Currently, the most common and most accurate method to solve the mentioned equations , is the characteristic method . The characteristic method capability in numerical computer solvability . In this section, first approximate method of parameters solution and then the complete solution will be provided . familiaring with the characteristics method and its simple continuity and momentum equations are simplified here and then can be used . Note that changes of the location *V* and *P* are very small , in every equation that there is variation in comprison with their tine changes time and place parameters , time variation parameter is regarded versus the spatial variation of changes and thus for drawing the equations are written as follows :

$$a^2\frac{\partial V}{\partial s}+\frac{1}{\rho}\frac{\partial p}{\partial t}=0$$

$$\frac{\partial V}{\partial t}+\frac{1}{\rho}\frac{\partial p}{\partial s}+g\frac{dZ}{ds}+\frac{f}{2D}V|V|=0$$

If the linear combination of the above equations is considered and the scale factor λ is linear , we will gets :

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$$\lambda(\frac{\partial V}{\partial t}+\frac{1}{\rho}\frac{\partial p}{\partial s}+g\frac{dZ}{ds}+\frac{f}{2D}V|V|)+a^{2}\frac{\partial V}{\partial s}+\frac{1}{\rho}\frac{\partial p}{\partial t}=0$$

$$\lambda(\frac{\partial V}{\partial t}+\frac{a^{2}}{\lambda}\frac{\partial V}{\partial s})+\frac{1}{\rho}(\frac{\partial p}{\partial t}+\lambda g\frac{\partial p}{\partial t})+\lambda g\frac{dz}{ds}+\frac{\lambda f}{2D}V|V|=0$$

Considering the above equations , only if the equation (5) can be written into complete differential equation :

$$V=\frac{ds}{dt}=\lambda$$

$$V=\frac{ds}{dt}=\lambda$$

$$V=\frac{ds}{dt}=\frac{a^{2}}{\lambda}$$

By equalizing ds/dt in both expressions in above statement , we will have :

$$\lambda=\pm a$$

If $\lambda=+a$ is chosen , equation (5) can be written as follows :

$$\frac{dV}{dt}+\frac{1}{a\rho}\frac{dp}{dt}+ag\frac{dZ}{ds}+\frac{af}{2D}V|V|=0$$

And selecting $\lambda=-a$ equation (5) is written as follows :

$$\frac{dV}{dt}-\frac{1}{a\rho}\frac{dp}{dt}+ag\frac{dZ}{ds}+\frac{af}{2D}V|V|=0$$

Considering the above operations , partial differential equations (3) and (4) differential equations have become complete . Provided that two variables *s* and *t* considered independently . If instead of p , (H-Z) used in which H is considered as height of HGL this relationships will be got :

$$\frac{dV}{dt}+\frac{g}{a}\frac{dH}{dt}+\frac{f}{2D}V|V|=0 \qquad (\frac{ds}{dt}=+a)$$

$$\frac{dV}{dt}-\frac{g}{a}\frac{dH}{dt}+\frac{f}{2D}V|V|=0 \qquad (\frac{ds}{dt}=-a)$$

Because equation (6) and (7) only along the appropriate parameters are used it is better to show used content on chart . To express the content , We used of drawing the characteristics in the system profile s-t and the methods get of to solving the equations (6) and (7) will be shown on a digram .

For drawing coordinate system s-t the start axis s is placed at the beginning of the upper pipe , and the positive set toward the lower part of the pipe will length L . Figure (1) show coordinate system s-t . Closing the valve , pipe flow instability appears . Waves caused by speed a run through the line given in coordinate system s-t . which is shown with negative slope or characteristic C- is the characteristic equation (7) .

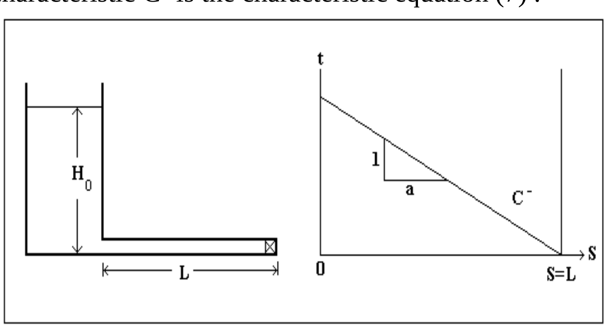


Fig 1 : s-t coordinate system for simple reservoir, valve and pipe system

Multiplying the above relation with (a/g)dt the following relation along the characteristic C- will apply :

$$dH=\frac{a}{g}dV$$

Equation (8) shows that changes in H between two points on the characteristi C- is appropriated with the speed difference between the two points . This result shows the same conclusion is expressed in the previous stagev , also from C- characteristic ds=-adt relation is obtained , indicating that how long time it takes that data reachs from point to point that are in ds distance from each other .

To obtain numerical values of H and V around in different parts of the pipe and at different times , should the initial conditions along the axis s and boundary conditions to different timesin points s=0 and s=L be determined .

To study the method , consider figure (2) that we wanted to obtain H and V values for p point . It is evident that values H and V at p Point are unique , (H and V values don't depend on the which characteristic pass through p point) . It is arguable that two full differential equations along the characteristics C+ and C- that passes p point are true . Therefore the complete differential equations (6) and (7) can be written respectively in the form of finite differences , as follows :

$$\frac{V_p-V_{Le}}{t_p-0}+\frac{g}{a}\frac{H_p-H_{Le}}{t_p-0}+\frac{fV_{Le}|V_{Le}|}{2D}=0$$

$$\frac{V_p-V_{Ri}}{t_p-0}+\frac{g}{a}\frac{H_p-H_{Ri}}{t_p-0}+\frac{fV_{Ri}|V_{Ri}|}{2D}=0$$

Inserting Δt instead t_p-0 of equation (9) and (10) be going as follows :

$$(V_p-V_{Le})+\frac{g}{a}(H_p-H_{Le})+\frac{f\Delta t}{2D}V_{Le}|V_{Le}|=0$$

$$(V_p-V_{Ri})+\frac{g}{a}(H_p-H_{Ri})+\frac{f\Delta t}{2D}V_{Ri}|V_{Ri}|=0$$

For solving characteristic equations using finite difference . Tube should be divided into some tracks . If we divided the plp into N equal parts , the length of each part will be equal to $\Delta s=\frac{L}{N}$. By clearing the value of s , t value from this equality Equation $\Delta s=a\Delta t$ is achieved.Therefore a network of parameters can be plotted which is shown in Figure (3) .

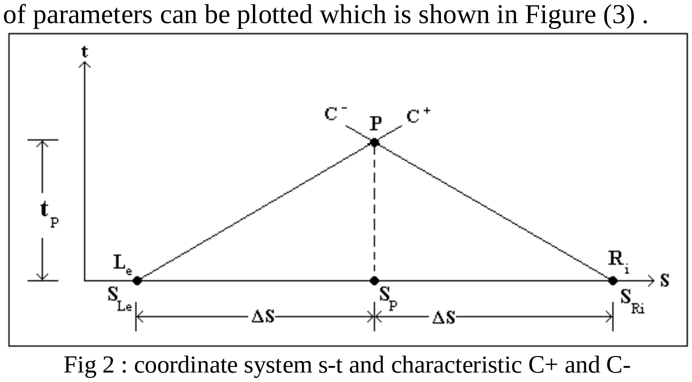


Fig 2 : coordinate system s-t and characteristic C+ and C-

By clearing boundary conditions , the amounts of the speed and head all the net at $t=\Delta t$ are calculated easily values obtained for H and V at the time $t = \Delta t$ are used towrite characteristic equations in next time to obtain H and V at $t = 2\Delta t$ until the .This operation is repeated enough H and V valuse at certain times intervals and at N+1 points of the pipe is calculated .

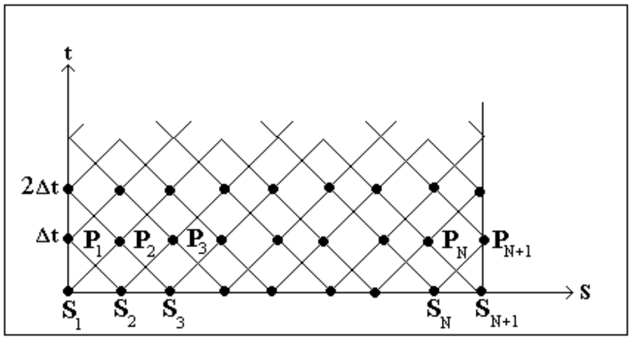


Fig 3 : the specifications for pipe

III. Review of methods for Mesh tube systems and how many intermediate points Interpolation pipeline

1- Series pipes

In unstable state, in all series pipes , flow rate was the same but the flow velocity , pipes diameter , wave velocity and their details are different . In addition , if a pipe in his own way has a different slope this pipe is considered series type pipe . In the system series pipe , method of characteristics to obtain velocity amount and pipe head pressure is used . The only difference is that at the local nodes (intersection of tubes) , there is internal boundary conditions and to complete the solution , these conditions must be specified . To determine the external boundary conditions at both ends of external pipe, the method presented in the previous section is used and to determine the internal boundary conditions , two additional equations moust be used to obtain a combination of them and characteristics equations , four unknowns nodes at the will obtain . For example , if Figure (4) , which shows two series pipes , from sub head loss at of node location isn't regarded , the characteristic equation for point P1 located in the upper tube is equal to :

$$V_{p1} = C_1 - C_2 H_{p1} \qquad : C^+$$

$$C_1 = V_{L1} + \frac{g}{a_1} H_{L1} - \frac{1}{2}\frac{f_1 \Delta t}{D_1} V_{L1}\left|V_{L1}\right| + \frac{g}{a_1}\Delta t V_{L1} \sin\theta_1$$

$$C_2 = \frac{g}{a_1}$$

Also , the characteristic equation for P2 point located in the downstream pipe is equal to:

$$V_{p2} = C_3 + C_4 H_{p2} \qquad : C^-$$

$$C_2 = \frac{g}{a_2}$$

$$C_3 = V_{R2} - \frac{g}{a_2} H_{R2} - \frac{1}{2}\frac{f_2 \Delta t}{D_2} V_{R2}\left|V_{R2}\right| - \frac{g}{a_2}\Delta t V_{R2} \sin\theta_2$$

$$C_4 = \frac{g}{a_2}$$

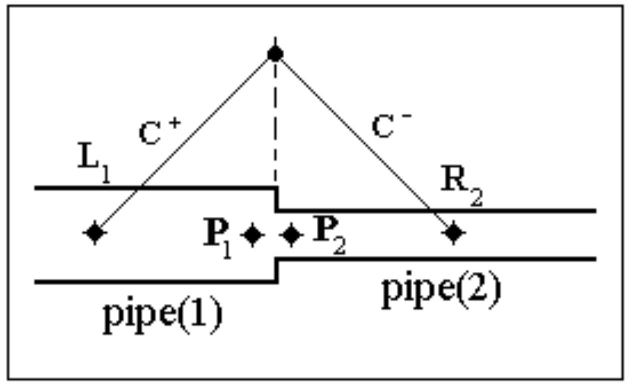


Fig 4 : two series of pipes

Equations (13) and (14) have four unknowns which for determining them we need two other equations . Using the continuity and energy relations the two other equations will be obtained . By applying of continuity equation , the assumption is that point P1 in pipe 1 and point P2 in pipe 2 are so close to each other at local node that no space for fluid mass storage exist . Therefore it can be written :

$$Q_1 = Q_2$$

$$V_{P1} A_1 = V_{P2} A_2$$

With no regard to loss sub head node , the energy relationship can be written as follows :

$$H_{P1} = H_{P2}$$

If the amount of head loss of a sub segment is significant (like crud , decreasing pressure valve , etc.) , the head loss of the segment in the equation should be considered . In solving the system of equations (13), (14), (15) and (16) the head in the node is achieved as follows :

$$H_{P1} = H_{P2} = \frac{C_1 A_1 - C_3 A_2}{C_2 A_1 + C_4 A_2}$$

Then the velocity in pipe 1 and 2 from equations (13) and (14) is obtained .

2 – paraller pipes

It is possible that in a distributed system , a pipe is leading from a pipe that is the main branch . So same equations for completing Numerical Solution resulted from internal boundary condition should be written . Continuity and energy equations usually in local node (intersection pipe) is used and by combination of equations with general equations of parameters method , values of velocity and head pressure in the pipes leading to the node can be obtained and problem in general for the node that N pipe are crossing it can be solved .
Figure (4) shows a node N Pipe leading to it . The direction of the flow like the stedy state flow . Flow direction is effective in determination of efficients of the characteristics equations . The system of characteristics equations for the node shown in figure (4) is as follows :

$$V_{p1} = C_1 \pm C_2 H_{p1}$$

$$V_{p2} = C_3 \pm C_4 H_{p2}$$

$$V_{p_{(N-1)}} = C_{(2N-3)} \pm C_{(2N-2)} H_{p_{(N-1)}}$$

$$V_{p_N} = C_N \pm C_N H_{p_N}$$

In above equations system N equation is included . Values and notations of the coefficients from equations (13) and (14) are determined .

If the flow direction is towards the node (entrance flow) , the pipe is up stream pipe considered and equation (13) is used . If the flow direction is goes outside the node (outlet flow) pipe the is considered downstream pipe and equation (14) is used .

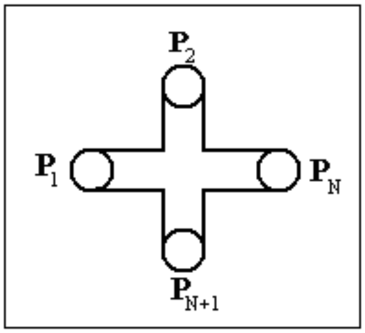


Fig 5 : two series tubes

The assumption in applying the continuity equation is that all parts are so close to each other that in the local node no volume space for fluid mass storage it can be written :

$$Q_1 \pm Q_2 \pm Q_3 \pm \cdots\cdots \pm Q_N = 0$$

In which the Q value is an external flow in node place . Positive sign for the incoming and minus is for outgoing flow is considered . Refraining from sub head loss , the relationship of energy in the node is as follows :

$$H_{P1} = H_{P2} = H_{P3} = \cdots\cdots = H_{PN}$$

$$H_{P1} = H_{P2} = \cdots = \frac{C_1 A_1 \pm C_3 A_2 \pm \cdots \pm C_{2N-1} A_N}{C_2 A_1 + C_4 A_2 + \cdots + C_{2N} A_N}$$

By replacing head pressure of the above equations in speed equations system , the speed amount and the head pressure in the pipes leading to the node at every moment will be counted .

Interpolation of middle points in the nodes

For Interpolation , different methods are presented which are as follows :

(1) Linear Interpolation Method

(A) On the place line includes : Vardy and Hartree methods

(B) on the timeline include : Reachback method and implicit method

(2) Nonlinear Interpolation methods

(A) spline method

(B) Hermite method

IV. Model presented in this article

Consider a pipe with a certain length of 6100 meters , that it should be divided into parts , each one whit length of 1000 meters. This pipe can be of five interval 1000 meters and the other 1100 meters . (Figure 7 points A and B are the boundaries) . The near some few important points in this pipeline at the beginning of the pipe A place (upstream condition boundary) only the line C- exactly passes the point 2 , but in place of B it doesn't happen . line C+ passes through the point L passes instead of point 5 for calculating point L any method that is used , gives some errors . These errors are effective in calculating boundary conditions . On the other hand , boundary in the damping flow have great importance and for having high accuracy , the borders should have high degree of accuracy . What a simple technique if the last piece replaces whit the piece before it Figure (8) is appeared . In the boundary A and B , characteristic lines C+ and C- pass the point 5 and 2 exactly . By simple technique and fixing the other conditions may be the accuracy of the calculation increased .Of course , 1100 meters lenght can be transferred to the middle of the pipeline . This transferring may be increased the accuracy of the calculation . In this paper , all these methods have been observed . On this base three methods can be presented . In these three methods we get used from interpolation and only piece place changes .

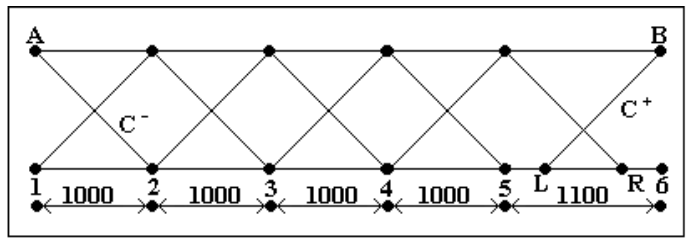


Fig 7 : division of pipeline lenght

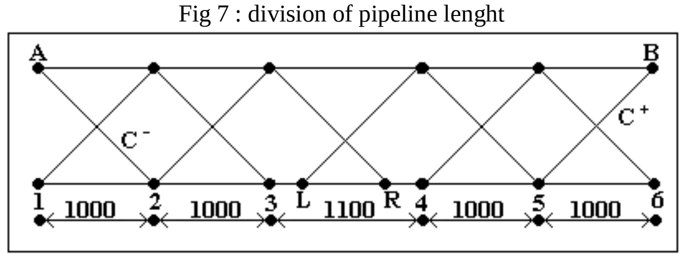


Fig 8 : division of pipeline length

Method A-1

In this method disparate piece with other parts at the end of the pipe is considered . Hydraulic conditions in points R and L are calculated by use of linear interpolation method . Figure (8) .

Method A-2

In this way the desired piece places at before the end part . Hydraulic conditions in points R and L are calculated by use of linear interpolation method . Figure (9) .

Method A-3

In this method the desired piece is placed in the middle of the pipeline . Hydraulic conditions in point R and L are calculated by use of linear interpolation . Figure (10).

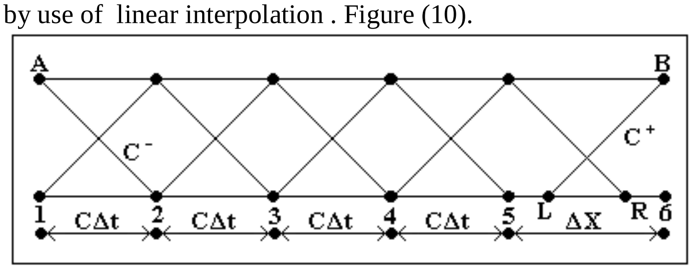


Fig 9 : elements classified A-1 method

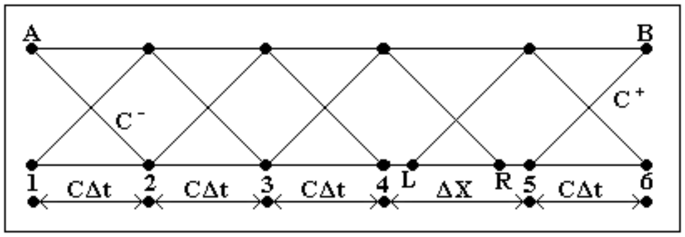


Fig 10 : elements classified A-2 method

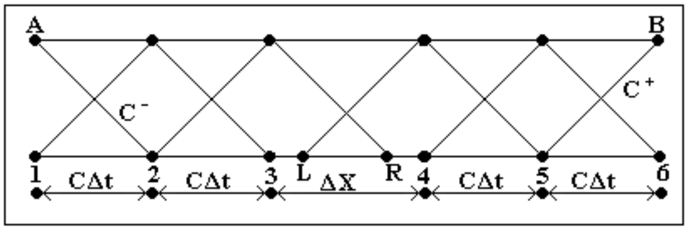


Fig 11 : elements classified A-3 method

V.Combines characteristic method and imprecise method

Consider figue (6) ,There is 6100 meters pipe for calculating it by characteristic method . it should be splited in 1000 meters (CΔt) parts , split into five pieces this splitting includes the pieces of 1000 meters and 1100 meters here . The remaining part in comprision whit an interval is greater than one but for calculation we can divide the pipe to six pieces each piece length 1000 meters and the last one is 100 meters . which is in to the remaining interval is comparison smaller then one . By This division all nodes of this pipeline component except nodes 6 and 7 characteristic method is applicable . Nodes 6 and 7 characteristic method can not be used because of the shortness of the segment . there are four unknown in the length of this segment which are rate and piezometer head points 6 and 7, to calculate such four equations are need . Two equations are obtained from continuity and momentum equations , another equation is dstained from positive characteristic . Point B is at the boundary .An equation at point B is achieved from the boundary condition . So generally there are four equations and four unknowns , so such equation which achieved from boundary condition may itself be a differential equation and solving it simultaneously with three other may be take a lot of time on computer time, and eventually the solution doesn't have high accuracy . So with a technique you can change the place of the 100 meter piece from the boundary to another location . In this case we can use from an equation characteristic by two C+ and C- with the continuity and momentum equations altogether . Both positive and negative features of the equation because of their explicitly , when they will be resolved soon reached convergence and their programming also will be easier .

Method A-4

In this way fragment whit ΔX length is placed in the middle of pipeline . Figure (11)

For this piece we can write the following equations:

1 - positive characteristic equation C+

2 - negative characteristic equation C-

3 - momentum equation

4 - continuity equation

By solving these equations simultaneously rate and piezometer in desired points will be calculated .

Method A-5

In this way fragment whit ΔX length placed before the boundary . Figure (11)

For this piece you can write the following equations :

1 - positive characteristic equation C+

2 - negative characteristic equation C-

3 - momentum equation

4 - continuity equation

By solving these equations simultaneously rate and piezometer in desired points will be calculated .

Method A-6

In this method , desired piece is placed at the boundary . Figure (11)

Governing equations are as follows :

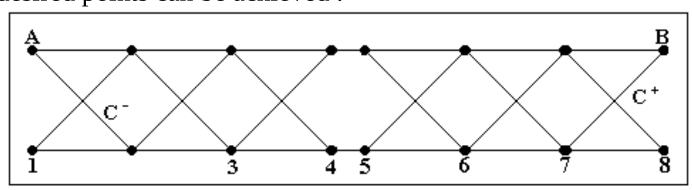
1 - positive characteristic equation C+

2 - momentum equation

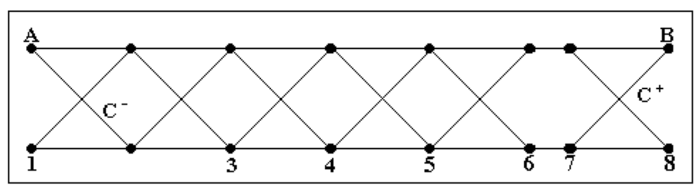
3 - continuity equation

4 – Equation , which is achieved from boundary condition

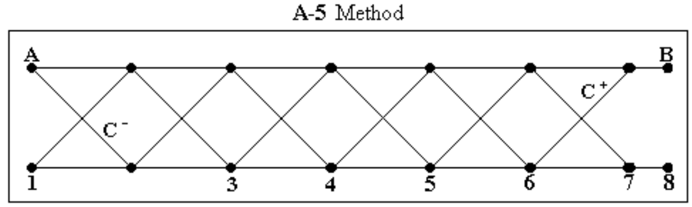
By solving these equations simultaneously flow conditions in desired points can be achieved .



A-4 Method



A-5 Method



A-6 Method

Fig 12 : elements classified

System equations solving method

Methods A-4 and A5 governing equations on the piecewhit length ΔX include :

1 - positive characteristic equation

$$V_{Pi}^{n+1} = C_1 - C_2 H_{Pi}^{n+1} \qquad : C^+$$

2 - negative characteristic equation

$$V_{Pi}^{n+1} = C_3 + C_4 H_{Pi}^{n+1} \qquad : C^-$$

3 - continuity equation

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial X} + \frac{a^2}{g} - V\sin\theta = 0$$

4 - momentum equation

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial X} + g\frac{\partial H}{\partial X} + gS_f = 0$$

Note that S_f is instead of Darcy-Weisbach related .

For expansion $\frac{\partial H}{\partial X}$ and $\frac{\partial V}{\partial X}$ the following three methods are used .

A: Explicit method

B: Crank Nicholson method

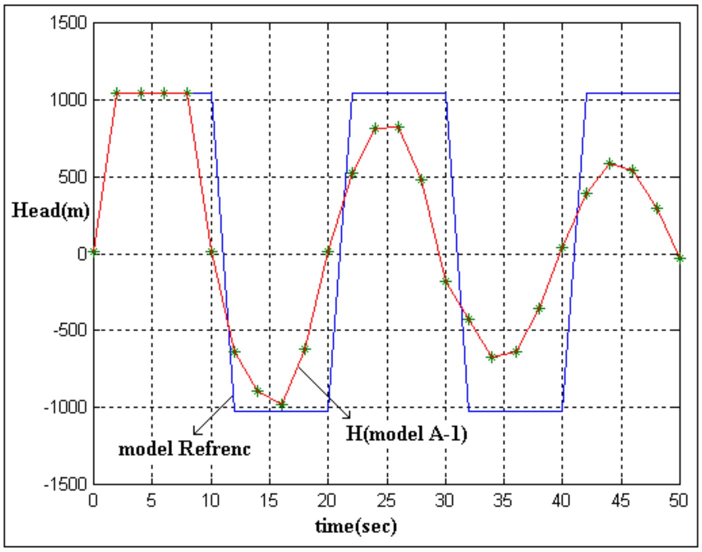
A: implicit method

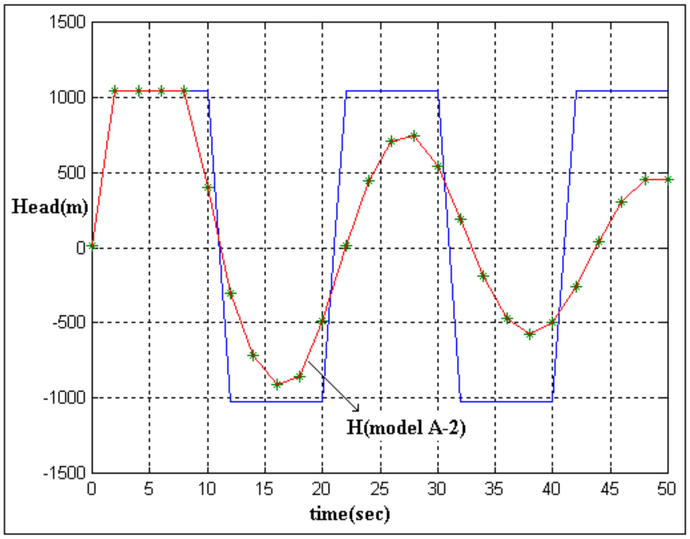
VI. Comparison of Numerical Methods

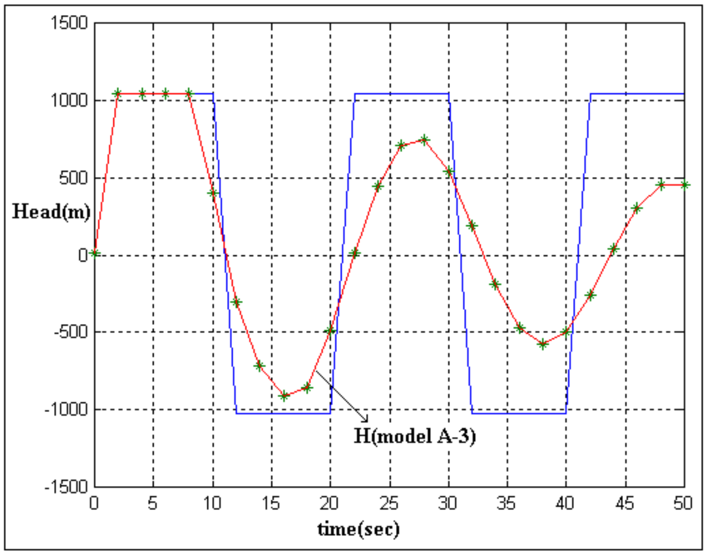
To investigate the accuracy of the proposed methods in the previous section and select the top several methods which have the problem mended analytical solutions were considered . For solving these problems by numerical method a computer program in Fortran language was written that the results of numerical methods are the output of the mentioned program . Then the analytical solutions are campared with numerical methods . Its obvious that a method enjoys superiority that to some extent its results are closer to the results of analytical methods [8], [9] .

Test one: The flow cutout

Consider the last system which consisting of tanks , pipes and valve and consider the pipe without friction and assuming that the fluid is in stable condition , then the valve suddenly decreasing in flow velocity result in increasing of the height of piezometer head to $\frac{C\Delta V}{g}$ in value place is closed . And after passing C/L time (L pipe length and wave speed C) increased pressure in all the pipe is created . for computer solving friction coefficient zero , the wave velocity is 969.264m/s height of the water in the tank 10 meters is considered . This problem has been solved by all methods . In all tests the pipes length 5000 meters has been considered and it is because , of first , enough time exists for the wave and also to solve the pipe with length of 5000 meters exact characteristiclines method is there.







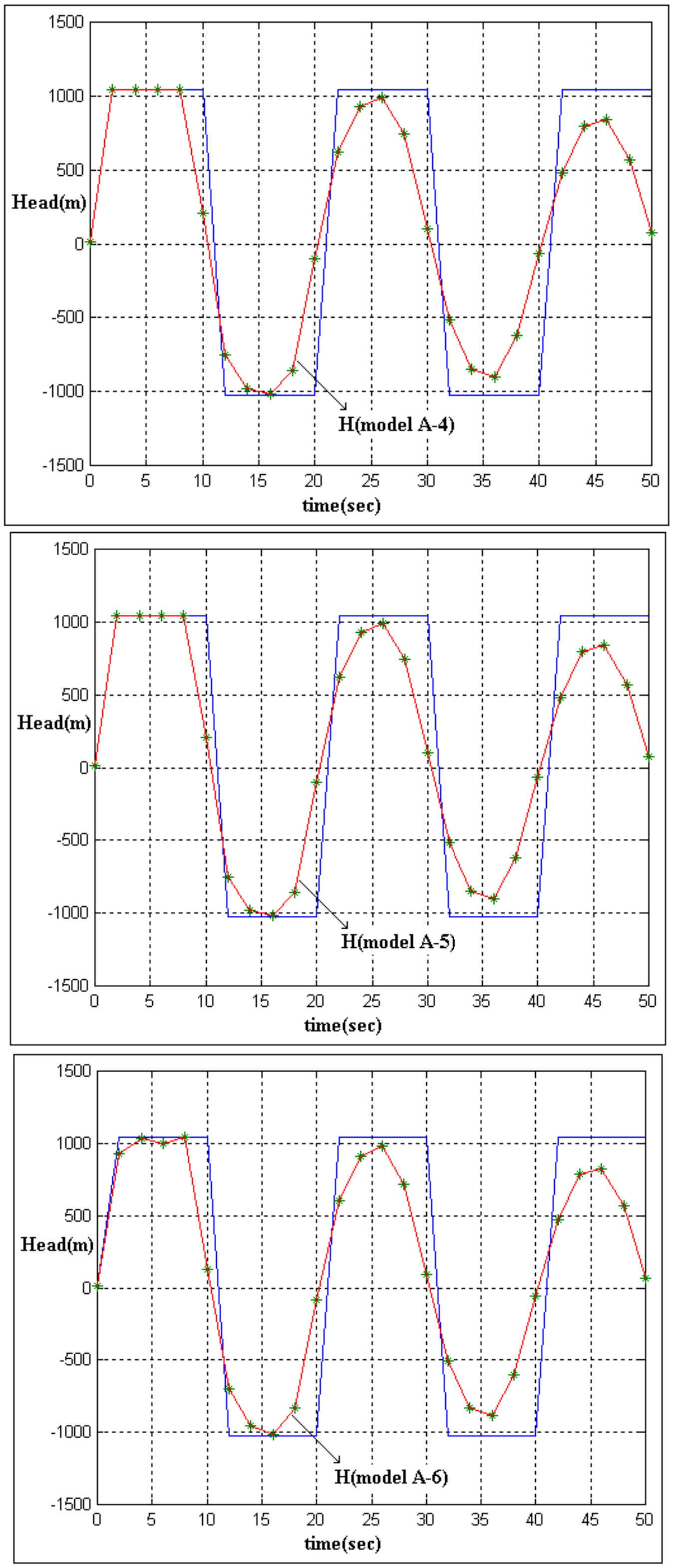
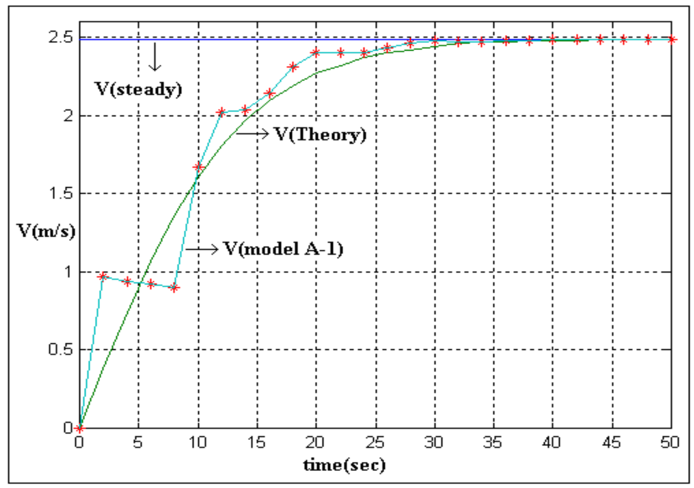
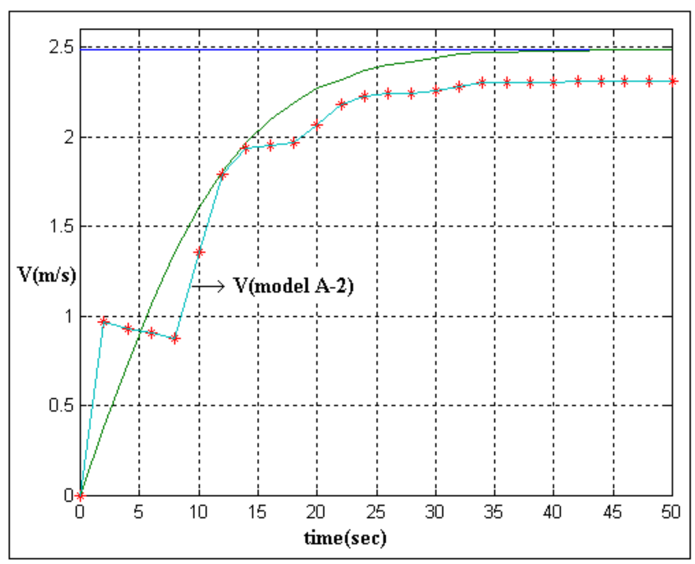


Fig 12. Graphs comparing the change in back pressure valve in the calculation methods presented theory and mode

Test two: The flow establishment

Consider a system consisting of a pipe, which initially had been attached to a tank at the bottom this pipe is connected to a valve. Pipe friction coefficient f=0.012 the height of water in the reservoir is 10m if the explained system is closed and the valve suddenly opened the fluid velocity gradually increased from stasis to be near steady state . Because every moment of time fluid movement speed is different the fluid movement will be accelerated, indicating that the fluid flow is damped. The mentioned problem with all forms of explanation has been analyzed and the results were plotted. On the figures time on the horizontal axis and velocity on the vertical axis has been considered. It is obvious from the figures that with time increasing fluid velocity rapidly approaches steady and it reached the steady velocity [10]. It this test all methods are sufficiently accurate. At the beginning of solving the problem Q=0.9628m3/s and H=10m assumed. It is the obvious a method is more accurate that its results will be closer to the reference values [11].





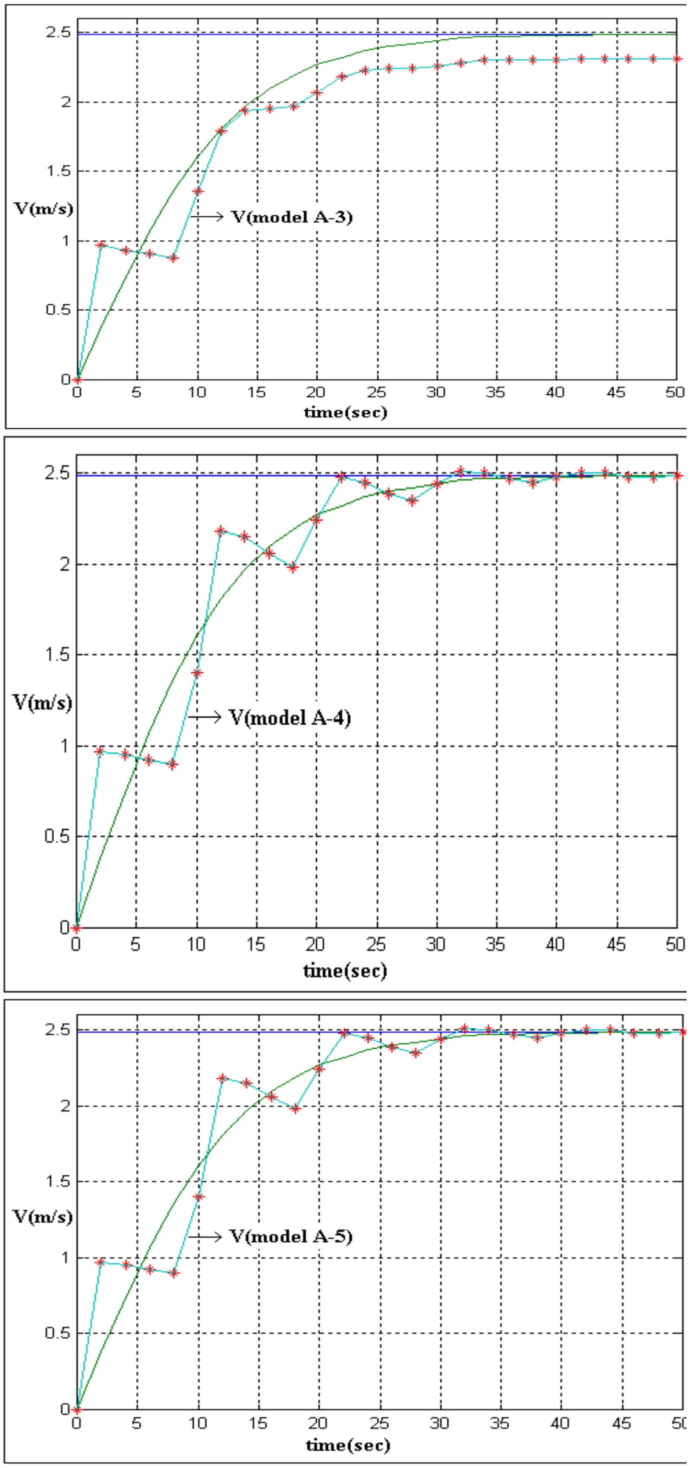


Figure 13. Graphs comparing the theory and quickly speed stable and fast calculation methods presented in

VII. Conclusions and Suggesting of the Best Way

In tests 1 and 2 and 3 all the methods had acceptable accuracy . But in test 4 it seems that the methods A-4 and A-5 and A-6 have more accuracy than other methods . On the other hand for the programming method A-6 is very massive and increase the time of calculation . Thus from the above methods A-4 and A-5 are more accurate than other methods and they are less time consuming and massive . Thus, methods A-4 and A-5 seems better . These two methods of calculation in tests carried out the same accuracy and for programming both methods are recommended . (Unless in the future with strong evidence and convinced a difference between these two methods will be distinguished and one preferred over the other).

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