# Comparing the results of two simulating models of the Water Hammer phenomenon: Bentley Hammer V8i and Greek Legislation

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**SUMMARY**

Hydraulic transients, also known as Water Hammer, are phenomena that can occur among others to irrigation networks and may lead to a system's failure causing destructive results. There are many techniques that can be used during design and devices that can be installed in order to prevent that phenomenon. Understanding the way these phenomena work in the stage of the network's planning will minimize its construction cost and protect it from possible disasters during its operation. The network was modelled using utilized software (Bentley Hammer V8i) in order to calculate maximum and minimum growing pressures along with the network and check its adequacy. In addition to that, the corresponding variables were calculated made on the basis of the theory defined by the applicable Greek legislation (Circular D.22.200 / 30–07–07 of Ministry of Public works entitled "Instructions for the control of tubular studies irrigation networks') as described in its chapter 12. According to the results derived from the simulation of the irrigation network, the developed maximum pressures don't exceed pipes' strength and the minimum don't exceed the vapour pressure. The final stage refers to a comparison among the maximum pressures calculated by the Greek legislature formula and the maximum pressures calculated by the simulation of the software Bentley Hammer. As a result, this comparison proved that in some cases the Greek legislature isn't enough to protect the network when most of the times would lead to oversize it. The statistics of that comparison are proving that the difference of the results between two models, may be crucial factor of the cost and the operation of the pipeline system.

**Keywords:** Water hammer, Hydraulic – transients, Unsteady flow, Water hammer simulation, Bentley Hammer V8i

## 1. INTRODUCTION

Hydraulic shock or water hammer is a temporary phenomenon that is regarded as the result of sudden changes in discharge of a liquid or gas in a closed piping system. In other words, when the liquid (or the gas) is forced to a momentum change (e.g. velocity), pressure waves are transmitting in the pipe system producing high and low pressures (Tzimopoulos, 1982).
During that case study, water is the liquid that is being examined.

## 2. WATER HAMMER

During the normal operation of a pipeline system, there are many factors that may lead to the water hammer phenomenon.

### 2.1. Causes of Water Hammer

The most usual actions that can lead to the phenomenon are (Chaudhry, 2014):

- A rapid opening or sudden closure of pipe's control valves
- Any change in the continuity of the network (i.e. break of a pipe)

- The operation of the pump (sudden shutdown or startup)
- An unexpected increase in the water demand
- Any change of the boundary conditions
- The filling of an empty water system with liquid can trap air

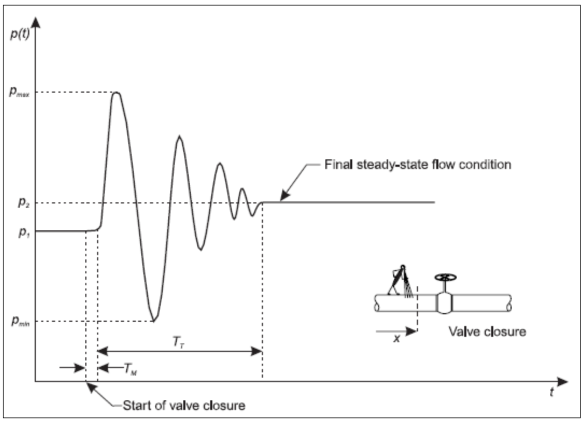


**Figure 2.1:** Water hammer phenomenon that occurred at a point "x" of a specific piping system (Bentley Systems, 2007).

## 2.2. Results of Water Shock

The water shock phenomenon can have many different results in the piping system (Watters, 1984.) (KSB AG., 2006).

- Pipe's cavitation (trapped air)
- Pipe's suction (negative pressures)
- The downgrading of water's quality (corrosion of the inner walls of pipes)
- Water's leak (at the connection between two pipes)
- Pipe's damage (or even destruction)
- Vibrations to the piping system (due to the waves)

## 2.3. Prevention techniques and protection devices

In order to prevent the phenomenon, there are some techniques that can be used during the design:

- Increase of pipe's diameter to decrease pipe's velocity
- Decrease of pipe's elasticity E
- Optimization of pipe's route to prevent the high static pressure
- Optimization of the number of pumps and use booster bypass layout (Bentley Systems, 2007)
- Use of protection devices (Air chambers, surge tanks and combined devices) (Watters, 1984.) (Tullis, 1989)

Considering that the installation of the devices increases the construction and operational cost, devices are preferred last.

## 2.4. Mathematical Model

During the last century, many methods were developed in order to calculate transient phenomena. The method of characteristics is widely used to solve fluid transient phenomena (Tzimopoulos, 1982). That method transforms the two partial differential equations of motion and continuity into particular total differential equations. Then, that equations can be intergraded to lead to the numerically handled finite difference equations (Wylie, 1978).

Its mathematical model is explained below (Babajimopoulos, 2008) (Wylie, 1978):

*Equation of continuity*

$$\frac{\partial H}{\partial t} + V \cdot \frac{\partial H}{\partial x} + \frac{a^2}{g} \cdot \frac{\partial V}{\partial x} = -V \cdot \sin(a) \qquad (1.1)$$

*Equation of motion*

$$\frac{\partial V}{\partial t} + V \cdot \frac{\partial V}{\partial x} + g \cdot \frac{\partial H}{\partial x} = -\frac{f \cdot V \cdot |V|}{2 \cdot D} \qquad (1.2)$$

where distance X and time are the depended variables and head pressure H(x,t) and velocity V(x,t) are the independents.

Considering that $V = V(x,t)$ and $H = H(x,t)$ are the solutions of the equations (2.4) and (2.5) their differential equations can be expressed:

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial x} \cdot \frac{dx}{dt} \qquad (1.3)$$

and

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \frac{\partial H}{\partial x} \cdot \frac{dx}{dt} \qquad (1.4)$$

At that point, the equation (1.1) is going to be multiplied with an unknown constant λ.

The result will be added to the equation (1.2) and the equation (1.5) derives from the comparison of the previous result with equations (1.3) and (1.4).

$$\frac{\lambda \cdot a^2}{g} = \frac{g}{\lambda} \text{ ή } \lambda = \pm \frac{g}{a} \qquad (1.5)$$

The equation (1.5) can be replaced to the intervening equations of the previous step and using the form of the equations (1.3) and (1.4), the result is two pairs of equation, one pair is $C^+$ and the other is $C^-$:

$$\frac{dV}{dt} + \frac{g}{a} \cdot \frac{dH}{dt} = -\frac{g \cdot V}{a} \cdot sina - \frac{f \cdot V \cdot |V|}{2 \cdot D} \qquad (1.6)$$

$$\frac{dx}{dt} = V + a \qquad (1.7)$$

$C^+$

$$\frac{dV}{dt} - \frac{g}{a} \cdot \frac{dH}{dt} = +\frac{g \cdot V}{a} \cdot sina - \frac{f \cdot V \cdot |V|}{2 \cdot D} \qquad (1.8)$$

$$\frac{dx}{dt} = V - a \qquad (1.9)$$

$C^-$

Expressing the equations on a space – time plane, the equation (1.7) follows a gradient of 1/(V+α) and is valid for the curve $C^+$ when the (1.9) follows a slope of 1/(V–α) and is valid for the curve $C^-$.

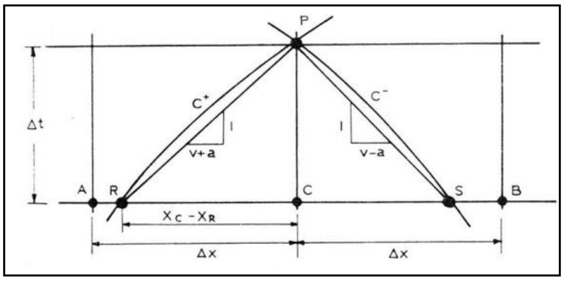


**Figure 2.2:** Characteristic Curves (Babajimopoulos, 2008).

Assuming that there are the known points R and S with known coordinates $(X_R, t_R)$ and $(X_P, t_P)$, and also knowing the values of the depended variables $V_R$, $H_R$, $V_S$ and $H_S$, the derivation of the equations (1.6) – (1.9) will provide results for the point P with a first–order approximation.

*Along the characteristic curve $C^+$:*

$$X_P - X_R = (V_R + a) \cdot (t_P - t_R) \qquad (1.10)$$

$$V_P - V_R + \frac{g}{a} \cdot (H_P - H_R) = -(F_R + G_R) \cdot (t_P - t_R) \qquad (1.11)$$

*Along the characteristic curve $C^-$:*

$$X_P - X_S = (V_S - a) \cdot (t_P - t_S) \qquad (1.12)$$

$$V_P - V_S + \frac{g}{a} \cdot (H_P - H_S) = -(F_S - G_S) \cdot (t_P - t_S) \qquad (1.13)$$

Where:

$$F = \frac{f \cdot V \cdot |V|}{2 \cdot D} \text{ και } G = \frac{g \cdot V}{a} \cdot sina \qquad (1.14)$$

While the terms g, a, f, D are stable

### 2.4.1 Solution using finite differences

Amongst the many methods that have developed in order to solve Characteristic equations (1.10 – 1.13), in that case, the method that uses interpolation in an x–t plan that is covered by an orthogonal grip with side dimensions Δx and Δt. The solution of the equations (1.10) to (1.13) using suitable mathematical transformations, provides the independent variables with a solution at a specific time. Boundary conditions are combined with the characteristic equations using linear interpolation in order to represent boundary nodes.

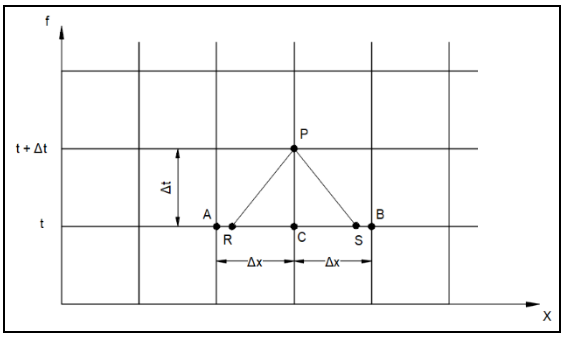


**Figure 2.3:** The orthogonal grip of characteristic equations with interpolation (Wylie, 1978).

At that point, it should be mentioned that the accuracy of the calculations is connected to the Δx length of the grip (Tzimopoulos, 1975). Also, the width of the grip Δt is defined using the conditions Courant – Friedrichs – Levy.

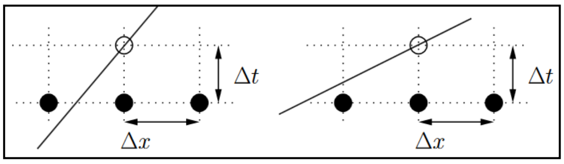


**Figure 2.4:** Graphical representation of condition Courant – Friedrichs – Levy (C.F.L.)

The condition that satisfies the C.F.L. is that the distance that can be covered of the characteristic line at time Δt should be smaller than the Δx length of the cell (Tzimopoulos, 1975). In other words, the formula about that condition is:

$$\Delta t \leq \frac{\Delta x}{|V \pm a|} \quad (1.15)$$

where: Δx: the length of the cell/grip, V: velocity of the fluid (m/s), a: wave speed ($m/s^2$).

## 3. CASE STUDY: THE PRESSURIZED IRRIGATION NETWORK OF LIMNOCHORI

The proposed network has been designed at the Municipality of Amyntaio, which is part of the state of Florina in Northern Greece. It’s worth mentioning the fact that the area of the proposed network is part of “Natura”.

### 3.1. The proposed network for irrigation

The total area was calculated at about 450 ha based on the agrarianism of the cadastre that took place in 1972. An irrigation network was designed for 220 ha, a portion of the previous area. The lake “Zazari” that is near the farmland will be the source of water that is needed of the irrigation network.


**Figure 3.1:** General representation of the irrigation area and network. The proposed irrigation network is

marked by a blue line. (Background: Satellite image by Google Earth).

The proposed irrigation network consists of one (1) main pipeline and ten secondary pipes with total length about 11 km. Each branch node is marked with the letters A, B, C, D, E, F, G, H, Ia and Ib. The proposed pipes are compact and made of polyethylene PE and the installed nozzles are providing a discharge of 7.5 l/sec. Also, the installation of air valves, evacuators and check valves at the beginning of every secondary pipe was necessary to ensure the normal operation of the proposed network.
The installation of a pump near the lake was necessary due to the elevation difference between the lake and the irrigation area. In order to simplify the network modeling, the pump was simulated as a tank. The elevation of the water in the tank equals to the head that the pump would provide.
At each branch junction, are installed two flow control gate valves that will be used in case of maintenance of the network. These control valves are installed after each branch junction, one on the main pipeline and the other on the secondary pipelines. In the case of the secondary pipelines A and B, E and F and H, Ia and Ib is installed for each pair of pipelines one flow control valve because of the small distance between them. Finally, there are six (6) flow control valves, called B, C, D, F, G, H. The hydraulic parameters that used to simulate the air valves and the flow control valves, were selected after bibliographical research (Babajimopoulos, 2008), (Papaevangelou, 2010) and are matched to commercial products.

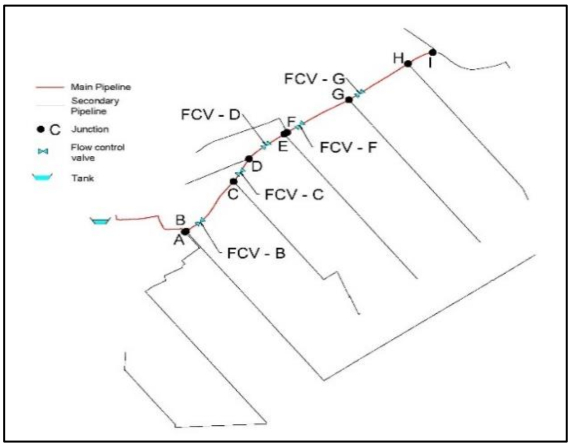


**Figure 3.2:** Graphical representation of the proposed irrigation network. The red line represents the main pipeline and the black ones the secondary pipelines.

### 3.2. Simulation using utilized software

The simulation of the proposed irrigation network was done using the software Bentley Hammer V8i and the excel spreadsheet.

#### 3.2.1 <u>Bentley Hammer V8i</u>

The software Hammer of Bentley Systems Incorporated is specialized in order to calculate water hammer phenomena. The main promises that Bentley Hammer uses are (Bentley Systems, 2016):

- The fluid is homogeneous
- The elasticity of pipeline and fluid follows a linear pattern
- The flow is unidimensional and fluid is incompressible
- The pipe is full of the fluid
- The average velocity is used
- The head loss because of the viscosity is the same during the steady and the unsteady flow

The table below contains the parameters were used as input in order to simulate the irrigation networks and the installed devices.

**Table 3.1:** Input parameters to Bentley Hammer V8i.

| | | | |
|---|---|---|---|
| **Pipe** | Pipes Material | HDPE 3rd generation | – |
| | Roughness Coefficient **k** | 0.01 | mm |
| | Pipe’s Elasticity **E** | 0.785 | GPa |
| | Factor Poisson **μ** | 0.45 | – |
| **Fluid** | Viscosity **v** | $1.004 \cdot 10^{-6}$ | $m^2/s$ |
| | Acceleration of the gravity **g** | 9.98 | $m/s^2$ |
| | Fluid’s Temperature **T** | 20 | °C |
| | Fluid’s Elasticity factor **K** | 2.188 | GPa |
| **Calculation Method** | Calculation Time step **Δt** | 0.025 | sec |
| | Vaporization pressure | Discrete Vapor Cavity | – |
| | Head loss (steady flow) | Darcy – Weisbach | – |
| | Head loss (transient flow) | Unsteady – Vitkovsky | – |

The modelled irrigation network:

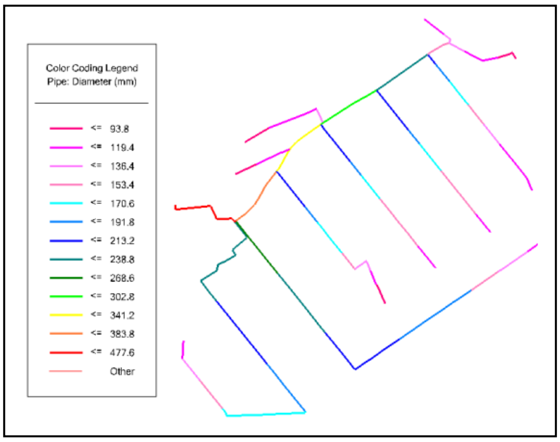


**Figure 3.3:** Graphical illustration of the irrigation network. The different colour of pipes represents the different diameters of the pipes.

### 3.2.2 Simulation using Excel Spreadsheet

The circular letter D.22.200/30 – 07 – 1977 that was published by the Ministry of Public Works (entitled "Instructions for the control of tubular studies irrigation networks) describes the water hammer phenomenon that is caused by valves. The equation (1.6) is the Greek legislation’s proposed formula to calculate the maximum transient pressure that is being developed during the phenomenon.

$$\Delta p = \frac{a \cdot \Delta V}{g} \tag{1.16}$$

Where: Δp: maximum transient pressure (m), a: transmission speed of the elastic wave (m/s), ΔV: change of velocity (m/s) και g: acceleration of gravity ($m^2/s$).

The results of the formula (1.16) for the proposed irrigation network were calculated using an Excel Spreadsheet.

## 4. RESULTS – CONCLUSION

The results of the simulation with the Bentley Hammer and the Excel Spreadsheet were examined in order to check network pipes' adequacy.

### 4.1. Software's simulation results

The scenarios that were simulated in Bentley Hammer are:

- Valve Close within 0 seconds
- Valve Close within 30 seconds
- Valve Close within 45 seconds
- Valve Close within 60 seconds
- Valve Close within 90 seconds

The proposed network consists of pipes 12,5 atm. The maximum transient pressure that developed in each scenario is lower than the maximum pressure that the pipes can bear. Also, the minimum transient pressure is lower than the vaporization pressure for each scenario.

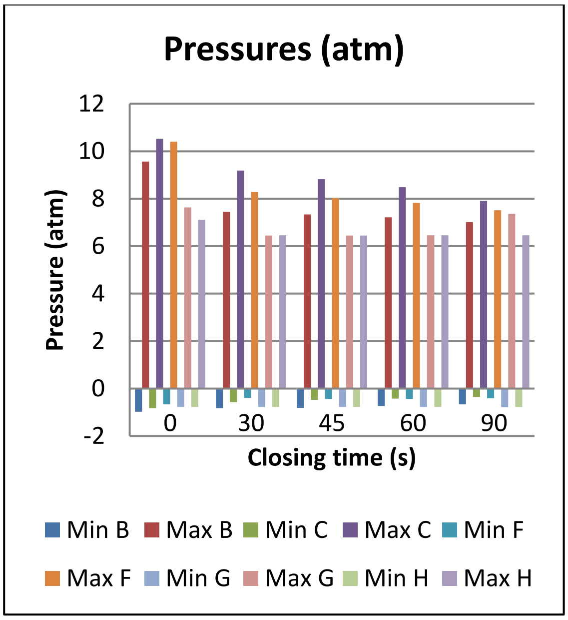


**Figure 4.1:** Developed maximum and minimum transient pressure of the pipes AB – BC – CD – DG – GH during each scenario

At the same time, the maximum and minimum developing pressures for the secondary pipes were calculated, using the worst-case scenario (0 seconds). There is developed pressure that exceeds the adequacy of the pipes. The results are presented in the following diagram.

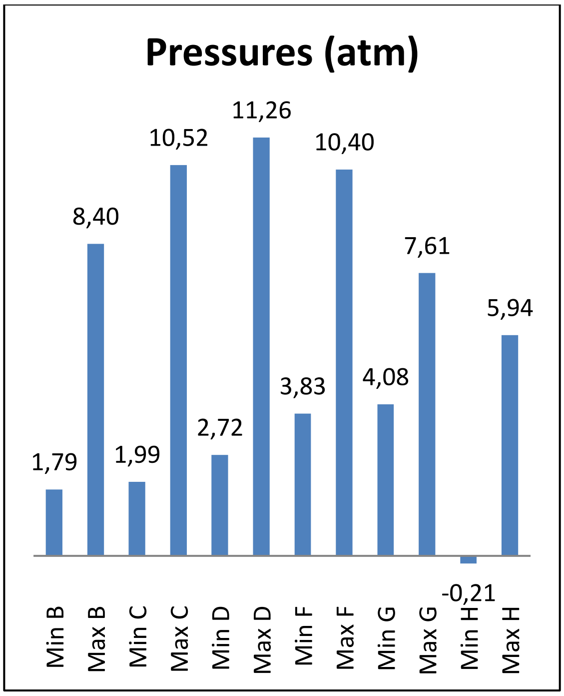


**Figure 4.2:** Maximum and minimum transient pressures that were developed during the sudden valve close scenario

### 4.2. Results based on Greek legislation

Using the formula (1.6), maximum transient pressure was calculated for each pipe. That pressure Δp was added to the static pressure of the pipe and the result represents the maximum pressure that could be developed during the water hammer phenomenon.
In that case, also, the calculated pressures aren't exceeding the maximum pressures that the proposed pipes can stand.

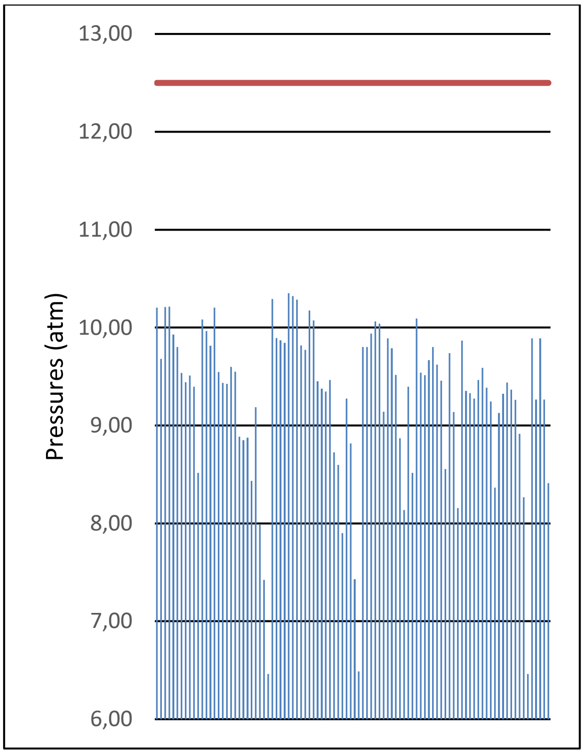


**Figure 4.3:** Maximum transient pressures by the Greek legislation (blue represents calculated values and red represents pipes' pressure nominal)

### 4.3. A comparison of the results of the two methods

Examining the results (Figure 4.4), it can be seen than in most of the cases, the pressure of formula (1.6) is higher than the maximum pressure calculated by Bentley Hammer. Although, in two pipes (of the secondary pipeline), software's pressure exceeds the pressure that was calculated by the Excel.

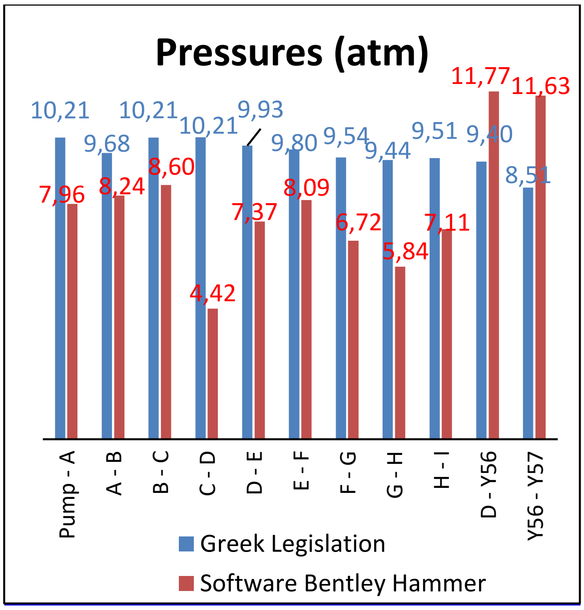


**Figure 4.4:** Comparison of the maximum pressures developed by the software (red) and the Greek legislation (blue)

At that point, a comparison between the results of the sudden closure scenario for each valve and the results of the Excel was made. There were eleven (11) times that the results from the software exceeded the results calculated by Excel. In particular that happens at six (6) different pipes (Y17 – Y18, Y41 – Y42, Y53 – Y54, Y54 – Y55, D – Y56, Y73 – Y74). Twice (2) in pipeline B, four (4) in pipelines C and D and one (1) time in pipeline F. Furthermore, the pressures of pipe Y17 – Y18 and Y41 – Y42 using the software are higher than the ones calculated with excel in three (3) scenarios, when a similar situation for the pipe Y54 – Y55 is happening in two (2) scenarios and for the rest of the pipes only one (1) scenario.

Table 4.1 represents the statistics of the results of maximum transient pressures during the sudden closure of each valve and the results that were calculated using formula (1.6).

**Table 4.1:** Maximum transient pressure statistics

| t = 0 sec | Mean | Max | Min | St. Dev | n |
|---|---|---|---|---|---|
| (-) | (atm) | (atm) | (atm) | (atm) | (atm) |
| Excel Spreadsheet | 9.311 | 10.351 | 6.462 | 0.828 | 90 |
| Valve Closure B (Hammer) | 6.343 | 8.330 | 4.480 | 1.377 | 86 |
| Valve Closure Γ (Hammer) | 6.603 | 9.940 | 4.480 | 1.428 | 86 |
| Valve Closure Δ (Hammer) | 6.644 | 9.880 | 4.480 | 1.426 | 86 |
| Valve Closure Z (Hammer) | 6.300 | 8.780 | 4.480 | 0.958 | 86 |
| Valve Closure H (Hammer) | 5.903 | 6.910 | 4.480 | 0.570 | 86 |
| Valve Closure Θ (Hammer) | 5.433 | 5.940 | 4.460 | 0.313 | 86 |

The following table contains the statistics of the difference between the maximum transient pressures calculated by the two methods for the eleven (11) times that mentioned before.

**Table 4.2:** Statistics of the difference between maximum transient pressures.

| Mean | Max | Min | St. Dev | n |
|---|---|---|---|---|
| (atm) | (atm) | (atm) | (atm) | (atm) |
| 0.670 | 1.804 | 0.148 | 0.590 | 11 |

The maximum difference of calculated transient pressure between the two methods is 1.8 atm. Considering that this value is big enough to lead a designer to change pipes' pressure nominal, the difference is regarded as important.

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