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A comparative study between one-way-surge tank and air chamber for the protection of pivot irrigation networks

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The severity of water hammer as a result of pump power failure in irrigation pipelines networks requires a dependable protection device to control the minimum head arising in the system. The objective of this paper is to analyze the effect of pump power failure on the pivot irrigation network and to allocate a suitable protection device to be able to control the severity of minimum head. Two protection devices; an air chamber and one-way surge tank, are compared. To achieve this goal, basic partial differential equations based on one-dimensional homogenous flow model are formulated and solved by the method of characteristics. A computer model written in Fortran language is prepared considering several boundary conditions to define the irrigation pipelines networks. An existing irrigation pivot network in Toshka is considered as a case study. Values of minimum and maximum heads before and after pump power failure are illustrated. The effect of using both protection devices is investigated. When every center pivot is considered as an orifice, the results of minimum head values show that using the one-way surge tank as a protection device has more advantages than using an air chamber.

إن ظاهرة الطرق المائى الناتجة عن إنقطاع التيار الكهربى فى شبكات الأنابيب تتطلب وسيلة يعتمد عليها للحد من الضغوط السالبة الناشئة عن توقف عمل المضخات التى تضخ المياه فى الشبكة. الهدف من الدراسة الحالية هو دراسة تأثير إنقطاع التيار الكهربى عن المضخات على شبكة الرى المحورى ومحاولة الوصول إلى طريقة حماية من شأنها تحجيم خطورة الضغوط السالبة المتولدة داخل الشبكة. و تمت المقارنة بين وسيلتين لحماية هذه الشبكات إما بإستخدام حجرة الهواء المضغوط أو بإستخدام صهريج التمُور ذوى الإتجاه الواحد. و لتحقيق هذا الهدف إستخدمت طريقة الميزات العددية لصياغة و حل معادلات السريان المتجانس الاحادية الابعاد التى تمثل ظاهرة الطرق المائى و عمل برنامج بلغة الفورتران يشتمل على عدة شروط حدية لتمثيل هذه الشبكات. و طبقت المعادلات على شبكة رى منفذة بمنطقة توشكى لدراسة تأثير الطرق المائى على الشبكة عند إنقطاع التيار وتأثير وجود وسيلتى الحماية المذكورة كل على حدة على قيم الضغوط القصوى و الدنيا المتولدة داخل الشبكة. أوضحت النتائج على أن إستخدام خزان التمُور ذوى الاتجاه الواحد له تأثير فعال للحد من قيم الضغوط السالبة التى تحدث فى الأنابيب مقارنة باستخدام حجرة الهواء المضغوط و ذلك عند تمثيل كل جهاز رى محورى بالمشروع بفتحة صغيرة.

Keywords: Irrigation networks, Pump power failure, One-way-surge tank, Air chamber, Characteristics method

1. Introduction

It has long been known that the severity of transients in irrigation pipelines networks is underestimated. The use of drip and sprinkler irrigation systems is increasing rapidly. These systems are expensive and require many precautions to work efficiently. Pump power failure is one of the main problems arising in these pipe networks. It may be responsible for pipeline failure due to the highly increase or decrease of pressure head. Computerized transient flow models are used with great success in the analysis of water hammer in topologically simple pipelines systems. There are many well documented results in the literature describing the performance of such models, mostly for various types of pumping plants connected to a series of pipelines. As early as 1937, Schnyder conducted comparisons between computed and observed water hammer pressures in pumping plants. Chaudhry presented test results for hydroelectric power plants (Chaudhry and Portfors [1]), pumping plants (Chaudhry [2]), and makeup cooling-water-supply- lines (Chaudhry, Cass, and Bell [3]), Simpson and Wylie [4]) gave test results for transients water column separation, Hancox and Banerjee [5], presented an implicit finite-difference model and test results for a two-phase flow in nuclear-power-plant piping systems. The main objective of this study is to compare between the use of air chamber and one-way surge tank as a protection device against water hammer, for irrigation pivot networks. An existing project in Toshka is considered as a case study. Every center pivot is represented in the numerical model by either an orifice or a constant head reservoir. The influence of both assumptions on the results has been highlighted.

2. Governing equations

Two equations are used to model transient flow in closed conduits: the momentum equation and the relation of mass conservation, [e.g., Chaudhry [2], Wylie and Streeter [6]. If x is the distance along the centerline of the conduit, t is time, and partial derivatives are represented as subscripts, these equations can be written as:
Continuity equation:

$$a^2 \frac{\partial v}{\partial x} + \frac{1}{\rho} \frac{dp}{dt} = 0 \ . \tag{1}$$

Momentum equation:

$$\frac{dv}{dt} + \frac{1}{\rho} \frac{\partial p}{\partial x} + g \sin\theta + \frac{f\, v |v|}{2D} = 0 \ , \tag{2}$$

where, $P = P(x,t)$ = pressure head, $v = v(x,t)$ = fluid velocity, D = internal pipe diameter, f = Darcy-Weisbach friction factor, a = wave speed, θ = slope angle of the pipe, and g = acceleration due to gravity. Eqs. (1 and 2) are valid if the flow is one-dimensional, the conduit properties (diameter, wave speed, temperature, etc.) are constant and the friction force can be approximated by the Darcy-Weisbach formula for steady flow. In addition it is usually assumed that the friction factor f is constant during the transient analysis.

The popular Method Of Characteristics (MOC) is a simple and numerically efficient way of solving the unsteady flow equations. In essence, the MOC combines the momentum and continuity expressions to form the following equations in the velocity (v) and piezometric head (h):

$$\frac{dv}{dt} \pm \frac{g}{a} \frac{dh}{dt} \mp \frac{g}{a} v \sin\theta + \frac{f}{2D} v \,|\, v \,| = 0.0 \ . \tag{3}$$

Eq. (3) is valid only along the so called C^+ and C^- characteristic lines defined by $dx/dt = v \pm a$. To satisfy these characteristic relations, the x-t grid is usually chosen to ensure $\Delta t \leq \frac{\Delta x}{\max|a+v|}$, fig. 1. Once the initial and boundary conditions and the space-time grid have been specified, eq. (3) can be integrated along mP and nP in fig. 1. To give the following equations in its final form:

$$C^+ \ : \quad v_p = C_P - C_a h_p \ . \tag{4}$$

$$C^- \ : \quad v_p = C_N + C_a h_p \ , \tag{5}$$

where:

$$C_P = v_m + \frac{g}{a} h_m + \frac{g}{a} \Delta t \, v_m \sin\theta - \frac{f \, \Delta t}{2D} v_m | \, v_m \,| \ ,$$

$$C_N = v_n - \frac{g}{a} h_n - \frac{g}{a} \Delta t \, v_n \sin\theta - \frac{f \, \Delta t}{2D} v_n | \, v_n \,| \ , \text{ and}$$

$$C_a = \frac{g}{a} \ .$$

The unknown values of h_m, v_m, h_n and v_n can be estimated by using linear interpolation with the help of the known values at the grid points R, C, and S.

Once initial and boundary conditions are established, then velocities and heads at all grid points at $t=\Delta t$ can be calculated. Then values at $t=\Delta t$ are used to write new equations to solve for values of (h) and (v) at the next time step where $t=2\Delta t$. This process is repeated continuously ahead in the (x – t) plane until the required time of analysis.

3. Boundary conditions

3.1. Junction of pivot center

The center pivot can be represented as an orifice discharging to the atmosphere and the orifice discharge Q_{pv} is a function of its pressure. The relationship is written in the following form as stated by Hathoot, and Al-Amoud [7]:

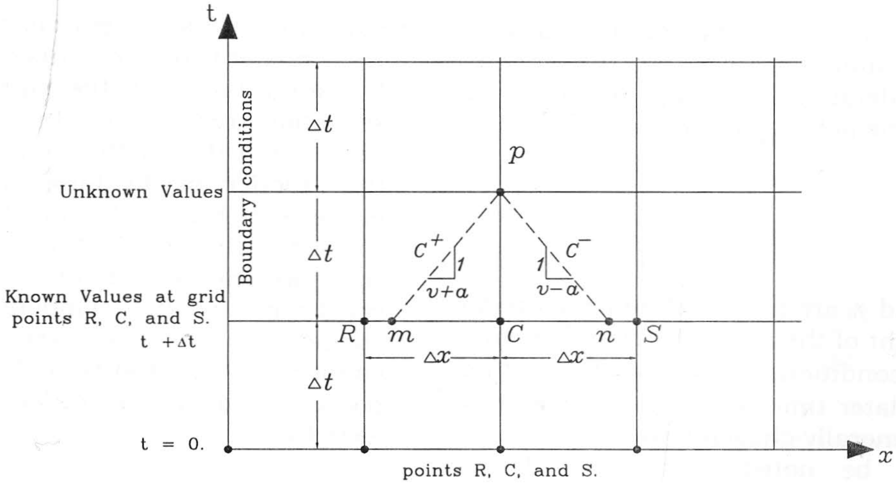

Fig. 1. Interpolation of (*h*) and (*v*) values on the (*x* - *t*) grid.

$$Q_{pv} = C_{pv}\left(H_{pv}\right)^{0.5} , \qquad (6)$$

where H_{pv} = pressure head at the pivot center, and C_{pv} = orifice discharge coefficient.

C_{pv} can be easily calculated at the steady-state condition and its value is kept constant for the rest of the transient analysis.

In the analysis it was assumed that if the head at the center pivot during the transient analysis is less than zero, no air is allowed to enter in the line and the junction will be dealt with as an end junction without any external demand. Also, the center pivot can be represented as a reservoir with constant head.

3.2. Junction of pump

The analysis is concerned with a common pump power failure. The pipeline is provided with a check valve in the pump discharge line, as well as a low-loss bypass line around the pump station. The new rotational speed (N) over a time increment (Δt) can be calculated from the following relation:

$$N_{t+\Delta t} = N_t - \frac{60}{2\pi \; I} T_t \, \Delta t , \qquad (7)$$

where, N_t = rotational speed at time t, T_t = the decelerating torque of the pump at an earlier time interval; I = the total rotational moment of inertia of the rotating parts of the pump. The following assumptions are made when modeling the pump:

- The decelerating torque is constant over the time interval (Δt) and its value is known at the previously instant of time.
- The pump characteristics curves are linearized.
- All the pumps fail simultaneously.
- The head loss across the pump discharge column is neglected
- When the pump head is less than the sump water level then the pump bypass will be opened.
- When the velocity at the pump is negative, then it will be set to zero as the result of the check valve existence.

3.3. Junction of air chamber

The primary purpose of the air chamber is to prevent negative pressure and column separation in the pipeline downstream of the pump station during power failure rundown. The discharge eq. (Watters [8]) for it is:

$$Q_c = C_{out} A_{out} \sqrt{2g(H_c - h_p)} , \qquad (8)$$

where, H_c = the head in the chamber, hp = the transient head in the pipe, C_{out} = the outflow coefficient, A_{out} = the outflow cross-sectional area, Q_c = the discharge from the chamber. During the transient analysis the flow may enter to the chamber, and thus the outflow coefficient is replaced by the inflow coefficient C_{in}.

Another equation is required to describe the thermodynamic process that the air in the chamber undergoes. The most common used equation is the polytropic process:

$$\frac{p}{\gamma^{\eta}}=\frac{p_o}{\gamma_o^{\eta}}\ , \tag{9}$$

where, P_o and γ_o are the absolute pressure and specific weight of the air in the chamber under steady flow conditions, while P and γ are those values at a later time, and η is the polytropic exponent, generally chosen to be 1.2.

It must be noted that flow into the chamber typically is designed to undergo a greater head loss than experienced by an outflow and accordingly, the value of C_{out} is greater than C_{in}.

3.4. Junction of one-way-surge tank

In pressured pipelines the one-way surge tank is commonly used because the elevation of Hydraulic Grade Line (HGL) is usually too far above the pipeline. The one-way surge tank is used to prevent downstream low pressures. The energy equation (Watters [8]) is written as:

$$Q_s=C_sA_{pi}\sqrt{2g(H_s+z_s-h)}\ , \tag{10}$$

where, Q_s = discharge from the tank, C_s = the loss constant for the connecting pipe between the surge tank and the pipe, A_{pi} = the cross-sectional area of the connecting pipe, H_s = height of water in the tank, z_s = elevation of the junction of the tank, and h = transient piezometric head at the junction.

The values of C_s can be calculated from the more readily available values for the losses coefficients of the components of the tank connection. For a very well designed connection, C_s could be as large as 0.90. For a poorly designed connection, C_s may be as low as 0.40.

4. Case study

The analyzed network under study is a pivot irrigation network feeding 600 faddans in Toshka by 5 pivots. The network consists of a main pipeline and four branches as shown in fig. 2. Each branch line ends with a pivot. The required discharge for each pivot line is 300 m³/hr. All pipes are UPVC.

4.1. Pump characteristics

A centrifugal pump is installed to feed the pipelines network. The pump characteristics can be summarized in table 1:

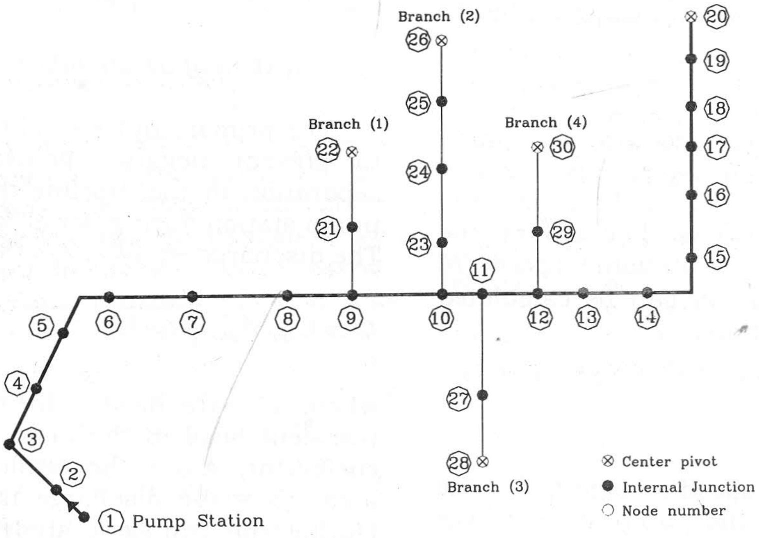

Fig. 2. A sketch of the case study.

Table 1
Data of pump characteristics

Rated speed	1500 rpm
Pump discharge	375 m³/hr
Pump head	78.50 m
No. of pumps on parallel	4
Total inertia	4.0 kg.m²

4.2. Pipeline characteristics

All the UPVC pipes are analyzed as a network. The main pipe starts with node (1) and ends with node (20). The branch pipes data and the nodes elevations are listed in table 2 and table 3, respectively.

Table 2
Data of branch pipes

Branch pipes	1	2	3	4
Inner diameter, (mm)	253.2	321.2	253.2	253.2
Length, (m)	440	1155	440	440
h_o (m) at pivot	56.55	53.58	55.86	51.49

Table 3
Data of pipes, nodes and steady state heads

Pipe	From node	To node	Length (m)
P1	1	2	10
P2	2	3	115
P3	3	4	425
P4	4	5	175
P5	5	6	400
P6	6	7	150
P7	7	8	275
P8	8	9	145
P9	9	10	400
P10	10	11	10
P11	11	12	370
P12	12	13	125
P13	13	14	125
P14	14	15	300
P15	15	16	50
P16	16	17	225
P17	17	18	125
P18	18	19	400
P19	19	20	166.61
P20	9	21	125
P21	21	22	315
P22	10	23	100
P23	23	24	375
P24	24	25	225
P25	25	26	455
P26	11	27	175
P27	27	28	265
P28	12	29	175
P29	29	30	265

Node	Elevation (m)	Steady state head, h_o (m)
1	193.5	78.5
2	192.93	79.03
3	192.93	78.59
4	196.07	73.82
5	200.39	68.82
6	199.66	68.02
7	200.61	66.49
8	203.68	62.36
9	203.67	61.82
10	203.65	60.02
11	203.65	59.87
12	203.75	57.32
13	202.48	58.38
14	202.42	58.22
15	203.79	56.34
16	204.8	55.24
17	204.78	54.88
18	206.65	52.79
19	207.78	50.98
20	208.78	49.69
21	203.87	60.28
22	204.24	56.55
23	203.88	59.47
24	204.64	57.53
25	204.74	56.72
26	206.45	53.58
27	202.87	58.78
28	202.96	55.86
29	203.87	55.33
30	204.88	51.49

4.3. Water hammer analysis

The pump power failure is the major design analysis for the main pipeline. In this analysis, the boundary condition at the center pivot is studied with two different assumptions:-

- assumption {*Reservoir System*}:

Each center pivot is represented by a constant head reservoir.

- assumption {*Orifice System*}:

Each center pivot is represented by an orifice discharging to the atmosphere. The orifice discharge varies with the head.

Both assumptions are analyzed with three different cases, as given in table 4.

4.4. Air chamber specifications

Specifications of air chamber are given in table 5.

4.5. One-way surge tank specifications

Specifications of one-way-surge tank are given in table 6.

Table 4
Cases of analysis

Case 1	Without the use of any protection
Case 2	With air chamber as a protection device, located downstream the pump.
Case 3	With one-way surge tank as a protection device, located downstream the pump.

Table 5
Specifications of air chamber

Initial air volume	6.00 m^3
Outflow discharge coefficient	0.80
Inflow discharge coefficient	0.60
Diameter of the air chamber nozzle	25.0 cm
Polytropic process exponent	1.20

Table 6
Specifications of one-way-surge tank

Initial height of water surface above pipe	12.0 m
Diameter of tank	1.80 m
Diameter of connection to the pipeline	25.0 cm
Discharge coefficient for surge tank	0.80

5. Results

The simulation time for the analysis due to pump power failure is 200 seconds, with time interval of 0.003 sec. The results are summarized in table 7, from the results:

- The orifice assumption confirms that the maximum head will not exceed the steady-state condition.
- Comparing the first two cases for the reservoir assumption, it is found that the existence of air chamber (case 2) has deleted the negative head in the entire pipeline.
- Comparing the cases of protection when using the reservoir assumption, it is shown that the use of air chamber gives safer values than the use of the one-way-surge tank either for the maximum or minimum head values.
- Comparing the cases of protection for the orifice assumption, it is shown that the use of the one-way-surge tank gives safer values than the use of the air chamber for minimum head value.
- Further increase in the initial size of the air volume in the chamber will not decrease the minimum head value than (≈-5.8 m).

Figs. 3 through 6 show the envelope of maximum and minimum head values along the main pipeline due to pump power failure for the considered different cases.

Table 7
Results of power failure

Assumption	Case	Maximum head (m)		Minimum head (m)	
		value (m)	h/h_o	value (m)	h/h_o
Reservoir	1	124.1	1.57	-3.82	-0.06
	2	94.6	1.2	35.82	0.52
	3	118.5	1.5	-2.61	-0.04
Orifice	1	79.0	1.0	-29.4	-0.59
	2	79.0	1.0	-5.84	0 12
	3	79.0	1.0	-4.18	-0.08

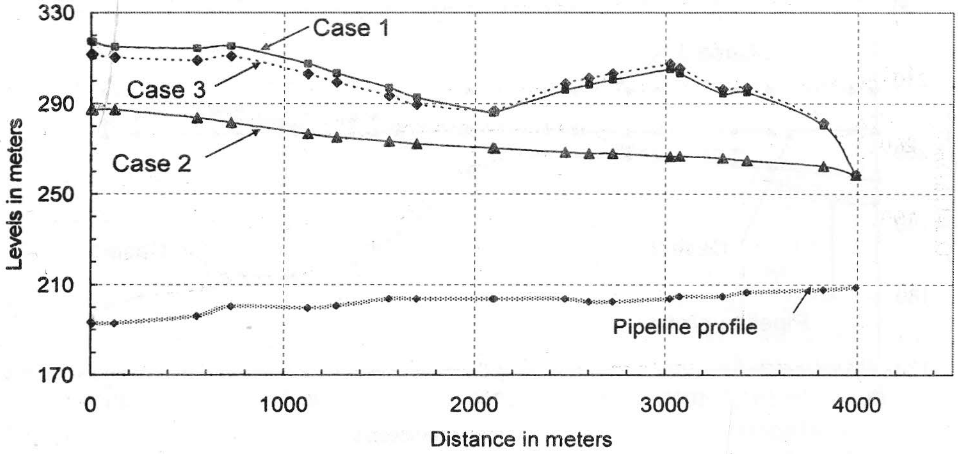

Fig. 3. Maximum pressure along the main pipeline for different cases (reservoir assumption).

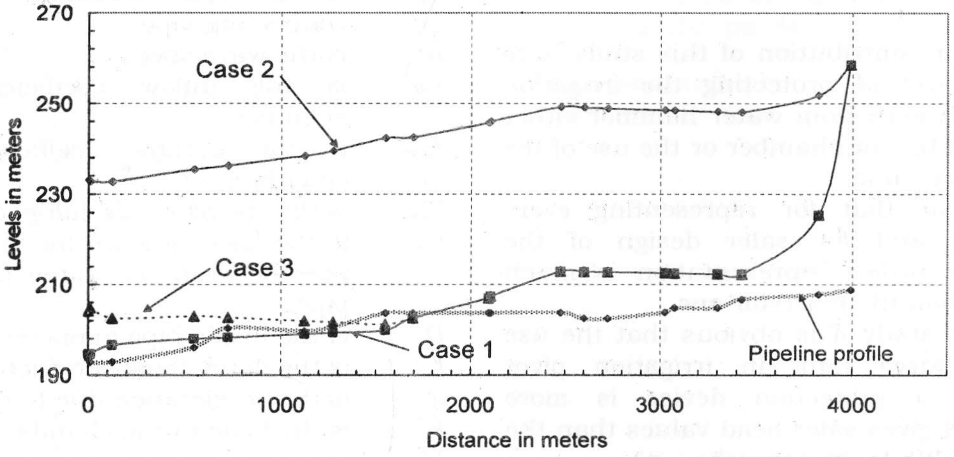

Fig. 4. Minimum pressure along the main pipeline for different cases (reservoir assumption).

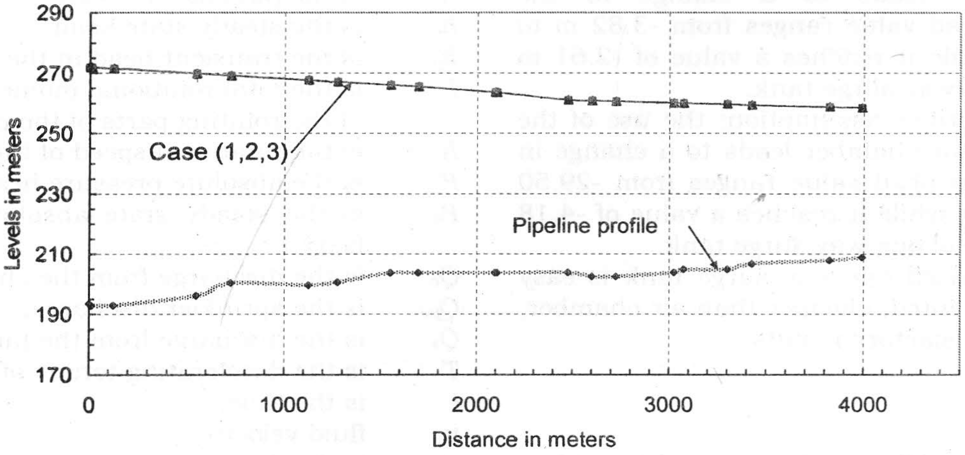

Fig. 5. Maximum pressure along the main pipeline for different cases (orifice assumption).

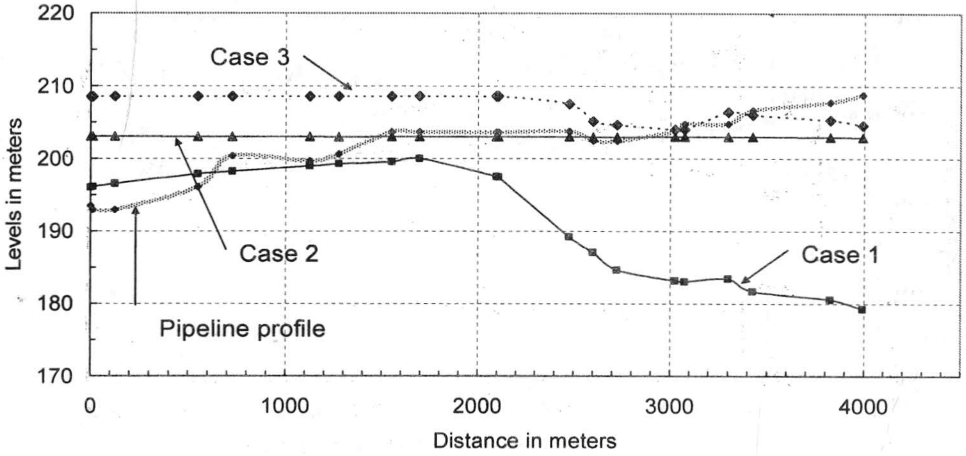

Fig .6. Minimum pressure along the main pipeline for different cases (orifice assumption).

6. Conclusions

1. The major contribution of this study is to show the effect of protecting the irrigation pipelines networks from water hammer either by the use of the air chamber or the use of the one-way-surge tank.
2. It is clear that for representing every center pivot and for safer design of the network, the orifice representation is much convenient than the reservoir one.
3. From the study it is obvious that the use of one-way-surge tank in irrigation pivot network as a protection device is more desirable and gives safer head values than the air chamber. While, in networks with reservoir ends the opposite is correct.
4. For the reservoir assumption; the use of air chamber leads to a change in the minimum head value ranges from -3.82 m to 35.82 m, while it reaches a value of -2.61 m by using one-way surge tank.
5. For the orifice assumption; the use of the same above air chamber leads to a change in the minimum head value ranges from -29.50 m to -5.84 m while it reaches a value of -4.18 m by the use of one-way surge tank.
6. The proposed one-way surge tank is easy to be implemented, cheaper than air chamber, and gives satisfactory results.

Notations:

A_{out}	is the outflow cross sectional area of the air chamber,
A_{pi}	is the cross-sectional area of the connecting pipe,
a	is the wave speed,
C_{in}	is the inflow coefficient for the chamber,
C_{out}	is the outflow coefficient for the chamber,
C_{pv}	is the sprinkler discharge coefficient,
C_s	is the loss constant for the connecting pipe between the surge tank and the pipe,
D	is the inside pipe diameter,
f	is the darcy weisbach friction factor,
g	is the acceleration due to gravity,
H_c	is the head in the chamber,
H_{pv}	is the pressure head at the sprinkler inlet,
H_s	is the height of water in the tank,
h	is the piezometric head,
h_o	is the steady state head,
h_p	is the transient head in the pipe,
I	is the total rotational moment of inertia of the rotating parts of the pump,
N	is the rotational speed of the pump,
P	is the absolute pressure head,
P_o	is the steady state absolute pressure head,
Q_c	is the discharge from the chamber,
Q_{pv}	is the sprinkler discharge,
Q_s	is the discharge from the tank,
T	is the decelerating torque of the pump,
t	is the time,
v	fluid velocity,
x	is the distance,

z_s	is the elevation of the junction of the tank,
γ	is the unit weight of the liquid,
γ_o	is the unit weight of the liquid at steady state,
Δt	is the time interval,
Δx	is the distance interval,
η	is the polytropic exponent for air chamber equation, and
θ	is the slope angle of the pipe.

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