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WATER HAMMER IN STEEL TRUNK WATER CONDUITS AND PROTECTION MEASURES (CASE OF THE KAMPIRRAVAT – FERGANA SYSTEM)

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Abstract
Water hammer is analysed in the steel gravity conduit (Kurgantepa – Fergana, 1020×9 mm) and the pumped conduits (Fergana – Pakana and Fergana – Kirguli, 820×8 mm) of the Kampirravat – Fergana water transfer system. The pressure wave celerity is calculated with Joukowsky's formula and compared for different pipe materials. In steel pipes the celerity is 980–1006 m/s, 2.4–2.5 times higher than in glass-fibre reinforced plastic pipes. Rapid valve closure on the Kurgantepa – Fergana conduit raises the pressure by 175 m to a maximum of 336 m, i.e. 1.9 times the allowable value of the pipe. The minimum permissible valve closure times are determined for each section (42–119 s), and 200–240 s is recommended in practice. The filling regime of the conduit and the number of air valves are determined. Protection devices for the pumping stations and temperature compensators for above-ground sections are justified. Steel and GRP pipes are compared in terms of surge head, allowable pressure and resistance to vacuum.

Keywords: Water hammer, wave celerity, steel pipe, valve closure time, relief valve, expansion joint.

Introduction

Water hammer is the wave-like rise and fall of pressure in pressurised pipelines caused by a sudden change in flow velocity; it is one of the main causes of failures in trunk water conduits. The theory of the phenomenon was developed by N.E. Joukowsky in 1898 [1] and later extended by Allievi, Wylie and Streeter, Chaudhry and others [2, 3]. The surge pressure depends on the elasticity of the pipe material, the wall thickness, the flow velocity and the closure rate of valves.

Our field studies on the Khanabad – Andijan trunk main showed that when the flow stops, the pressure in the lower part of the route reaches 1.28 MPa, and the water hammer head may reach 157 m. These values exceed the strength margin of the pipe wall, which has corroded after 32 years of service, and are causing an increase in the number of defects. To prevent this in the new conduits of the Kampirravat – Fergana system, water hammer must be taken into account at the design stage.

In the design, the Kurgantepa – Fergana conduit is to be built of glass-fibre reinforced plastic (GRP) pipes. However, owing to the high cost of these pipes, the need to import them and the lack of experience in installing them at large diameters, building part of the route or the second-

stage sections of steel pipe is also being considered. Since the modulus of elasticity of steel is about 20 times that of GRP, the surge pressure also increases considerably.

The aim of the paper is to determine the water hammer parameters in the steel conduits of the Kampirravat – Fergana system, to justify the permissible valve closure times and to develop protection measures.

Method

The propagation velocity of the pressure wave in a pressurised pipe was determined by Joukowsky's formula:

$$c = \frac{1425}{\sqrt{1+\frac{E_w}{E}\frac{D}{s}}} \quad (1)$$

where E_w= 2060 MPa is the bulk modulus of water; E is the modulus of elasticity of the pipe material ($2.06 \cdot 10^5$ MPa for steel); D is the internal diameter; s is the wall thickness; 1425 m/s is the speed of sound in water. For instantaneous valve closure (faster than the wave reflection time), the pressure rise and the reflection time (surge phase) are:

$$\Delta H = \frac{cv}{g}, \qquad T_r = \frac{2L}{c} \quad (2)$$

where v is the initial flow velocity and L is the distance from the closing valve to the pressure source (a reservoir or PRV). For slow closure (T_c > T_r), the pressure rise is estimated approximately by Michaud's formula:

$$\Delta H_c \approx \Delta H \frac{T_r}{T_c} \quad (3)$$

The minimum permissible valve closure time follows from the condition H_st + ΔH_c ≤ [p]:

$$T_{c.\min} = \frac{T_r \Delta H}{[p]-H_{\text{st}}} \quad (4)$$

The wall thickness required for the pipe to withstand an unprotected surge is:

$$s_{\text{req}} = \frac{\rho g (H_{\text{st}}+\Delta H) D_o}{2[\sigma]\varphi} + c \quad (5)$$

where [σ] = 140 MPa, φ = 0.8 and c = 1 mm. The flow velocities and static heads were taken from the hydraulic analysis of the Kurgantepa – Fergana conduit (recommended pressure regulation regime).

Results

The wave celerities calculated by (1) for different pipes are given in Table 1 and Fig. 1.

Table 1 Pressure wave celerity in different pipes

Pipe	D, mm	s, mm	D/s	E, MPa	c, m/s
Steel 1420×12	1396	12.0	116.3	206,000	969
Steel 1020×9	1002	9.0	111.3	206,000	980
Steel 820×8	804	8.0	100.5	206,000	1006
GRP D1000 (s = 18.4 mm)	1000	18.4	54.3	10,000	408
GRP D800 (s = 14.7 mm)	800	14.7	54.4	10,000	408
Polyethylene PE100 D800 (SDR17)	706	47.1	15.0	1,000	252

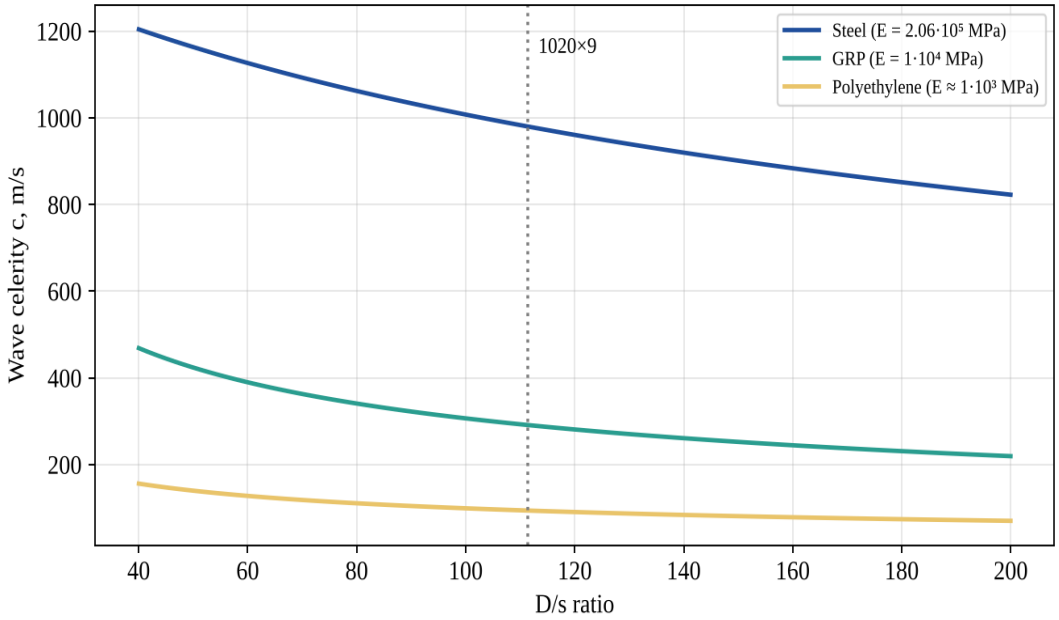


Fig. 1. Wave celerity versus D/s ratio and pipe material

Table 1 and Fig. 1 show that in steel pipes the wave celerity is 980–1006 m/s and depends little on the D/s ratio. In GRP pipes it is 2.4–2.5 times lower, and in polyethylene pipes about 4 times lower. Hence, at the same flow velocity, the surge pressure in steel pipe is more than twice that in GRP pipe.

The water hammer parameters for the conduits of the Kampirravat – Fergana system are given in Table 2.

Table 2 Water hammer parameters in the steel conduits

Conduit	c, m/s	v, m/s	ΔH, m	H_st, m	H_max, m	[p], m	s_req, mm
Kurgantepa – Fergana, 1020×9	980	1.75	175.2	160.5	335.7	179	16.0
Fergana – Pakana, 820×8	1006	0.70	72.2	152.2	224.4	195	9.1
Fergana – Kirguli, 820×8	1006	0.88	89.8	61.3	151.1	195	6.4

Table 2 shows that rapid valve closure on the Kurgantepa – Fergana conduit raises the pressure by 175 m to a maximum of 336 m, which is 1.9 times the allowable pressure of the 1020×9 mm pipe (179 m). Without protection, a wall thickness of 16 mm would be required, increasing steel consumption 1.8-fold. In the pumped conduits the flow velocity is low (0.70–0.88 m/s), but on the Pakana line the pump head is high (152 m), so the maximum pressure reaches 224 m and exceeds the allowable value (195 m); on the Kirguli line water hammer is not dangerous.

The minimum permissible valve closure times obtained from (4) are given in Table 3, and the pressure rise as a function of closure time is shown in Fig. 2.

Table 3 Minimum permissible valve closure time by section

Section	L, km	H_st, m	v, m/s	T_r, s	ΔH, m	[p] − H_st, m	T_c.min, s
PK 160 – PK 275	11.5	137.1	1.75	23.5	175.2	42.0	98
PK 275 – PK 395+55	13.0	140.5	1.59	26.5	159.3	38.6	109
PK 395+55 – PK 445	5.0	140.5	1.59	10.2	159.3	38.6	42
PK 445 – PK 595	15.0	90.0	1.47	30.6	147.3	89.1	51
PK 595 – Fergana WDS	32.9	96.1	1.47	67.1	147.3	83.0	119

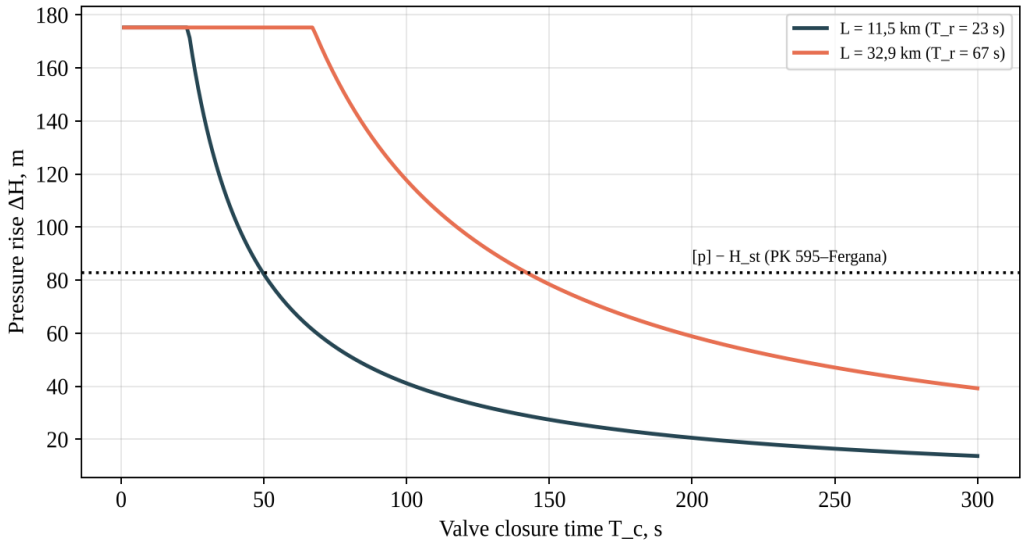


Fig. 2. Pressure rise versus valve closure time (Kurgantepa – Fergana, 1020×9 mm)

Table 3 shows that in the longest section (PK 595 – Fergana, 32.9 km) the reflection time is 67 s and the minimum permissible closure time is 119 s. In the PK 275 – PK 395+55 section, where the static pressure is high, this time reaches 109 s. Taking into account the approximate nature of Michaud's formula and the non-linear closure characteristic of gate valves (most of the pressure rise occurs during the last 10–15 % of the stroke), a closure time of at least 200–240 s is recommended for all section valves. For motorised valves this requirement is met by the choice of the actuator gearbox, and for manual valves by the operating instructions.

Protection Measures

Based on the analysis, the following protection measures are recommended for the steel conduits:

– relief (pressure-release) valves that open automatically on pressure rise, installed upstream of the PRVs and at low points of the route; their opening pressure is 1.1·H_st, and their capacity is 10–15 % of the design flow of the section;

– double-acting air valves (air release and vacuum break) at high points of the route; when the flow is interrupted they admit air, preventing vacuum and the subsequent column-rejoining surge; d = 200 mm valves are provided to release large volumes of air when the pipe is filled;
– slow-closing check valves and air-vessels (surge tanks) on the discharge lines of the pumping stations; for the Pakana line the air-vessel volume is selected so that the pressure drop on power failure does not exceed 0.3·H_p;
– soft start and stop of pump units with variable-frequency drives and power supply of the pumping station from two independent sources;
– connection of pressure and flow sensors to a remote monitoring (SCADA) system with alarms on sudden pressure changes.
In sections laid above ground (on supports), thermal deformation of the steel pipe must also be considered. The thermal elongation is $\Delta x = \alpha \cdot \Delta t \cdot L$, where $\alpha = 1.2 \cdot 10^{-5}$ 1/°C is the linear expansion coefficient of steel and $\Delta t = 34$ °C (water temperature +20 °C, design winter air temperature −14 °C). The results are given in Table 4.

Table 4 Thermal deformations in above-ground sections

Section	L, m	Δt, °C	Δx, mm	Δx/2 per compensator, mm
Fergana – Pakana, K-1	117.0	34	48	24
Fergana – Pakana, K-2 and K-3	154.0	34	63	31
Fergana – Kirguli	140.4	34	57	29

For the calculated deformations (48–63 mm), bellows or lens compensators with a compensating capacity of at least 80 mm are recommended, and anchor supports should be designed for the compensator reaction and friction forces on the supports (safety factor 1.2). In these sections an external paint coating against atmospheric corrosion and thermal insulation against freezing in winter should be applied, and drain fittings should be provided.

Choice of closure time and filling regime

To show clearly the effect of valve closure time on the maximum pressure, the maximum head at the start of each section was calculated by (3) for various closure times (Table 5, Fig. 3).

Table 5 Maximum head $H_{max} = H_{st} + \Delta H_c$ versus valve closure time, m

Section	T_c = 30 s	T_c = 60 s	T_c = 120 s	T_c = 180 s	T_c = 240 s
PK 160 – PK 275	274	206	171	160	154
PK 275 – PK 395+55	281	211	176	164	158
PK 395+55 – PK 445	195	168	154	150	147
PK 445 – PK 595	237	165	128	115	109
PK 595 – Fergana WDS	243	243	179	151	137

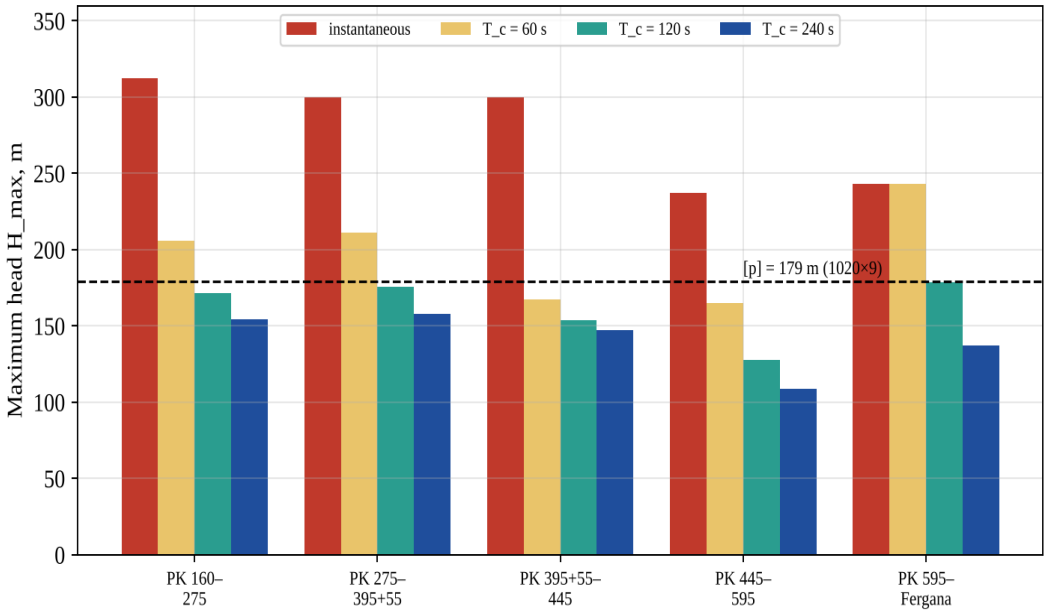


Fig. 3. Maximum head by section versus valve closure time

Table 5 shows that with a closure time of 30 s the maximum pressure exceeds the allowable value (179 m) in all sections, and at 60 s it is safe only in the PK 395+55 – PK 445 section. Increasing the closure time to 120 s gives maximum heads of 128–179 m, still close to the limit in the longest section. At 240 s the head does not exceed 158 m in any section, ensuring a strength margin of more than 15 %. Together with Table 3, this confirms the recommended valve closure time of 200–240 s.

Another dangerous source of water hammer is the filling of the pipeline. When water is admitted too quickly into an empty pipe, air pockets are compressed and then escape rapidly through the air valves, and the water column strikes a closed valve or a bend. The filling velocity should therefore not exceed 0.3 m/s, and air should be released through air valves installed every 0.5–1.0 km and at all high points [3, 9]. The filling parameters by section are given in Table 6.

Table 6 Filling parameters of the conduit sections (v_{fill} = 0.3 m/s)

Section	L, km	d_int, m	Volume, m³	Filling flow, m³/h	Filling time, h	Air valves (≈ every 0.8 km)
Kurgantepa node – PK 160	16.0	1.396	24,490	1,653	14.8	21
PK 160 – PK 275	11.5	1.002	9,068	852	10.6	16
PK 275 – PK 395+55	13.0	1.002	10,251	852	12.0	18
PK 395+55 – PK 445	5.0	1.002	3,943	852	4.6	8
PK 445 – PK 595	15.0	1.002	11,828	852	13.9	20
PK 595 – Fergana WDS	32.9	1.002	25,943	852	30.5	43
Total	93.4		85,523		86.5	126

Table 6 shows that the total volume of the conduit is 85,523 m³, and filling it at a safe velocity takes 86 hours. Filling is therefore carried out section by section, using the downstream PRVs and sectioning valves. After each section is filled, it is checked that air has stopped escaping

from the air valves, and only then is water admitted to the next section. The total number of air valves (about 126) is refined from the longitudinal profile of the route: they are installed at all local high points, at changes of slope and on both sides of the sectioning valves.

The transient on power failure is particularly important for the pumping stations. When the pump stops on the Fergana – Pakana line, the pressure at the station outlet drops by approximately $\Delta H = \frac{c \cdot v}{g}$ = 72 m, i.e. from 152 m to 80 m. Since the static lift is 140.7 m, the pressure in the upper part of the route may fall below atmospheric, creating a risk of column separation and a subsequent rejoining surge, which can significantly exceed the initial pressure. An air-vessel and a slow-closing check valve are therefore mandatory on the Pakana line, while on the Kirguli line ($H_p = 61\ m$) a slow-closing check valve and air valves are sufficient.

Comparison of steel and GRP pipes

Since the design adopts GRP pipes for the Kurgantepa – Fergana conduit, the surge parameters of the two materials were compared for the same flow velocities and static heads (Table 7). For GRP, D = 1000 mm with s = 18.4 mm and D = 800 mm with s = 14.7 mm were taken (E = $1 \cdot 10^4$ MPa).

Table 7 Water hammer in steel and GRP pipes for instantaneous valve closure

Conduit	c, m/s (steel)	ΔH, m (steel)	H_max, m (steel)	c, m/s (GRP)	ΔH, m (GRP)	H_max, m (GRP)
Kurgantepa – Fergana	980	175	336	408	73	233
Fergana – Pakana	1006	72	224	408	29	181
Fergana – Kirguli	1006	90	151	408	36	98

Table 7 shows that in GRP pipe the surge head is 2.4–2.5 times lower than in steel pipe: on the Kurgantepa – Fergana conduit it is 73 m instead of 175 m. However, this advantage is partly offset by two factors. First, the allowable pressure of GRP pipes is limited by their nominal pressure class (PN10–PN16, i.e. 100–160 m), so the maximum head with instantaneous closure (233 m) also exceeds the allowable value. Second, for slow closure ($T_c > T_r$) Michaud's formula gives $\Delta H_c = \Delta H \cdot T_r/T_c = 2L \cdot v/(g \cdot T_c)$, which does not depend on the wave celerity. With the recommended closure times of 200–240 s the surge head is therefore practically the same for steel and GRP pipes, and the advantage of GRP appears only for fast closures or pump trips. In addition, the reflection time in GRP pipe is longer (for the PK 595 – Fergana section T_r = 161 s instead of 67 s), so the range of closure times that count as «fast» is wider.

An important difference is the behaviour under vacuum. When the column separates after a pump trip or a rapid closure, the pressure in the upper parts of the route can fall to the vapour pressure. Steel pipe with D/s ≈ 110 withstands full vacuum, whereas GRP pipes with a stiffness class of SN 5000–10 000 may buckle if they are not adequately supported by the backfill. For GRP pipes, therefore, air valves at all high points and careful control of the compaction of the pipe bedding are even more important. Regardless of the material, the protection measures

recommended above (closure time ≥ 200–240 s, relief valves, air valves and air-vessels at the pumping stations) remain necessary; for steel pipe they are decisive, since without them the pipe wall would have to be almost twice as thick.

Conclusions

1. In steel pipes the wave celerity is 980–1006 m/s, 2.4–2.5 times higher than in GRP pipes; therefore, when the pipe material is changed, the water hammer protection must be recalculated.
2. In GRP pipe the surge head is 2.4–2.5 times lower (73 m instead of 175 m on the Kurgantepa – Fergana conduit), but because of the lower pressure class and vacuum sensitivity of GRP, protection against water hammer is required for both materials.
3. On the Kurgantepa – Fergana steel conduit (1020×9 mm), rapid valve closure raises the pressure by 175 m to a maximum of 336 m, which is 1.9 times the allowable pressure of the pipe.
4. The minimum permissible valve closure times by section are 42–119 s; in practice 200–240 s is recommended for all valves.
5. With a filling velocity of no more than 0.3 m/s, filling the conduit takes 86 hours and should be done section by section.
6. Relief valves, double-acting air valves, slow-closing check valves and air-vessels at the pumping stations, and compensators with a capacity of at least 80 mm in above-ground sections should be installed.

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