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THE STUDY OF UNSTEADY OPERATION MODE OF THE CRUDE OIL TRUNK PIPELINE IN CASE OF A SUDDEN STOP FLOW***

1. INTRODUCTION

Non-stationary processes in pipelines are that processes in which flow characteristics of liquid changing from section to section and changing at each section of the pipeline depending on time. During this phenomenon pressure, velocity, flow rate and temperature flow are changed. Moreover, within unsteady flow all parameters depend on linear pipeline section coordinates x and depend on time t: pressure $P = P(x, t)$, velocity $V = V(x, t)$, volumetric flow rate $Q = Q(x, t)$, temperature $T = T(x, t)$ [1].

Unsteady modes of oil movement in pipelines are primarily associated with different technological operations undertaken during transportation oil [1]. Also, pumping of crude oil over main pipelines is connected with complicated hydrodynamic processes. Most of them deal with the implementation of the different ways of regulating operating modes such as stop and start of the oil pump station, stop and triggering certain pumping units. These situations cause significant changes in the operating modes of pipelines and in some cases can lead to an emergency situation. These changes occurring in the pipeline before that time when new operation mode of transportation will be established, so this unsteady process named as transient processes [2].

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Besides, modern hydraulic systems operate over a broad range of operating regimes. Any change of flow velocity in the system induces a change in pressure. The sudden shut--down of a pump or closure of a valve causes fluid transients which may involve large pressure variations, local cavity formation, distributed cavitations, hydraulic and structural vibrations and excessive mass oscillations. In particular, the occurrence of liquid column separation may have a significant impact on subsequent transients in the system. Large pressures with steep wave fronts may occur when vapor cavities collapse and its practical implications are significant. As an outcome, fluid transients may lead to severe accidents [3].

In additional, in fully filled pipelines may occur a water hammer event when the pressure drops to the vapor pressure at specific locations such as closed ends, high points or knees (changes in pipe slope). A vapor cavity, caused by the inertia of the parting liquid columns, will start to grow. The cavity acts as a vacuum, a low-pressure point, retarding the liquid columns, and finally starts to diminish in size when the liquid columns change flow direction. The collision of two liquid columns, or of one liquid column with a closed end of the pipeline, moving towards the shrinking cavity, may cause a large and nearly instantaneous rise in pressure. The large pressure rise travels through the entire pipeline and forms a severe load for hydraulic machinery, individual pipes and supporting structures. The situation is even worse when in one water hammer event will occur many repetitions of cavity formation and its collapse [3].

2. THEORY OF UNSTEADY FLOW

The equations (1)–(2) are applied to calculate unsteady pipe liquid flow when the pressure is (always and everywhere) greater than the vapor pressure. They comprise the continuity equation and the equation of motion:

$$\frac{\partial H}{\partial t} + \frac{\partial V}{\partial t} - V \cdot \sin\theta + \frac{a^2}{g}\frac{\partial V}{\partial x} = 0 \tag{1}$$

$$g\frac{\partial H}{\partial t} + \frac{\partial H}{\partial t} + V\frac{\partial V}{\partial t} + \frac{f \cdot V|V|}{2D} = 0 \tag{2}$$

where:
  H – piezometric head,
  t – time,
  V – flow velocity,

x – distance along the pipeline,

θ – pipe slope,

a – pressure wave speed,

g – gravitational acceleration,

f – Darcy–Weisbach friction factor,

D – pipe diameter.

For most engineering applications, the convective terms $V(\partial H/\partial x)$, $V(\partial V/\partial x)$ and $V\sin\theta$ are very small compared to the other terms and therefore may be neglected. Research by Streeter and Wylie (1967) led to the direct use of the method of characteristics [3].

Also, transient flow occurs when sudden change in flow velocity happens. During the design of the pipeline we must take into account the safety factor against upsurge and down surge pressures. When the cavitations and fluid column separation occur despite the high safety factor of equipment, damage is possible during operation. So water hammer calculation and application of protective equipment is necessary to protect the pipeline. Surge vessel is one of useful equipment that can balance both upsurge and down surge phases. Selection of tank volume and size of connection line is very important due to safe system [4].

More than a century ago Joukowsky mathematically described many of the physical aspects of wave propagation in liquid systems. He also observed and explained column separation. Water hammer numerical models give physically accurate results, especially as to the first pressure rise, when the pressure is above the liquid vapor pressure. The pressure drop is usually quicker in reality due to effects of free air, unsteady friction and structural vibration. Cavitations occurs when the pressure drops to the liquid vapor pressure and the one-phase flow is transformed to two-phase flow. The classical water hammer equations are not valid in regions of cavitations. The first objective of modeling column separation is to predict the pressures that occur when large vapor cavities collapse. The second objective is to predict the timing of the events. A third objective might be to predict the structural response of pipes and supports [3].

The fundamental equation in water hammer theory relates pressure changes ΔP, to velocity changes ΔV, according to:

$$\Delta P = \rho \cdot \Delta v \cdot c \qquad\qquad (3)$$

where:

ρ – the fluid mass density,

c – the speed of sound.

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Korteweg's formula defines c for fluid contained in cylindrical pipes of circular cross-section [5]:

$$c = \sqrt{K^* / \rho}$$ (4)

$$K^* = K / [1 + (DK) / (eE)]$$ (5)

where:

D – the diameter of the pipe,
e – the wall thickness,
E – the modulus of elasticity for the wall,
K – the bulk modulus of the contained fluid.

During the second half of the 19th century and the first quarter of the 20th century, the majority of the publications on water hammer came from Europe. The conception of the theory of surges can, amongst others, be traced to Ménabréa (1858, 1862), Michaud (1878), Von Kries (1883), Frizell (1898), Joukowsky (1900) and Allievi (1902, 1913). Joukowsky performed classic experiments and proposed the law for instantaneous water hammer in a simple pipe system. This law states that the (piezometric) head rise ΔH resulting from a fast ($T_c < 2L/a$) closure of a valve, is given by:

$$\Delta H = \frac{aV_0}{g}$$ (6)

where:

a – pressure wave speed,
V_0 – initial flow velocity,
g – gravitational acceleration,
L – pipe length,
T_c – valve closure time.

The period of pipe, $2L/a$ is defined as the return time for a water hammer wave to travel from a valve at one end of the pipeline to a reservoir at the other end, and back to the valve [3].

The theoretical analyses performed independently by Joukowsky (1900) and Allievi (1902, 1913) formed the basis for classical water-hammer theory.

3. RESULTS OF EXPERIMENTAL INVESTIGATION OF OIL PRESSURE IN THE PIPELINE DURING STOP OF PUMPING UNITS AT OIL PUMPING STATION

Pumping system can never be operated in steady-state condition all the time, since starting up and stopping the pump. The duty conditions of the pump will change. Every change in operating conditions and every disturbance cause pressure and flow variations or, put differently, cause the flow conditions to change with time. Flow conditions of this kind are commonly referred to as unsteady or transient. Referring specifically to pressures, they are sometimes called dynamic pressure changes or pressure transients. The main causes of transient flow conditions are:

a) Pump stop as a result of switching off the power supply or a power failure.
b) Starting or stopping up one or more pumps whilst other pumps are in operation.
c) Closing or opening of shut-off valves in the piping system.
d) Excitation of resonant vibrations by pumps with an unstable H/Q curve (H – pressure differential or head, Q – media flow).

These situations cause significant changes in the operating modes of pipelines which can lead to an emergency situation. Thus, practical implementation of oil pipeline transportation requires scientific and methodological support. The aim is to establish patterns of transient hydrodynamic processes and dynamics of pressure changes at the inlet and outlet of oil pump station caused by stops of pumping units and develops mathematical models for determining the hydrodynamic parameters during non-stationary modes.

The investigation which was conducted at this paper is based on the handling results of experimental researches performed by using the methods of statistical analysis. The parameters of oil movement in trunk pipeline was measured. In order to develop mathematical models of hydrodynamic processes within abnormal operating modes of oil trunk pipelines exploitation, methods of differential and integral calculus and methods of mathematical modeling which were implemented in computer programs have been used.

Source data for this investigation was received for the section of oil trunk pipeline with nominal diameter of 702 mm and a length of about 400 km. On this pipeline section are situated four oil pump stations which are equipped by modern oil pumping units. Moreover, along this pipeline twelve inspection stations are allocated (Fig. 1). These stations are equipped by modern tools which can control pressure. Inspection station

has possibility to make pressure measurement every second during the fast transition processes. Within that time when industrial experiments were conducted the density of transported oil varies in the range from 866 to 875 kg/m^3 and viscosity of transported oil varies in the range from 16 to 30 cSt.
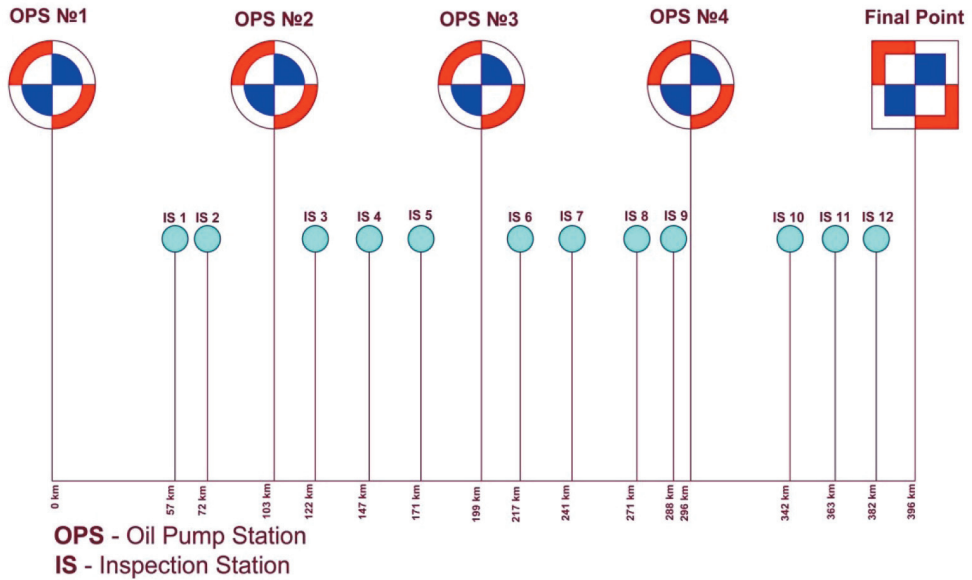

Fig. 1. Location of Oil Pump Stations and Inspection Stations along the pipeline

For obtaining principles of the change in pressure along the pipeline caused by stops of pumping units several experiments were carried. For example, volume flow of oil in the pipeline before stop amounted 2335 m^3/hour. At some point in time, the pumping units at the oil pump stations No. 2 have been disconnected. As a result within a few seconds pressure dramatically increases from 0.55 MPa to 1.45 MPa at the inlet of oil pump station (Fig. 2). After this phenomenon within 20–30 min pressure remained only slightly increased.

Moreover, it was analyzed pressure changes along pipeline route for that operational mode. At the Figure 3 is shown pressure change at control point No. 2 which is located between oil pump station No. 2 and No. 1. This control point is located 31 km from place where pressure wave arise. The following figures show the changes in pressure at control point No. 2 and at oil pump station No. 1. At the Figures 2–5 appears the same tendency of pressure changes during the transient processes, but it should be noted if distance from the source of disconnection increased than hydraulic jump goes down.
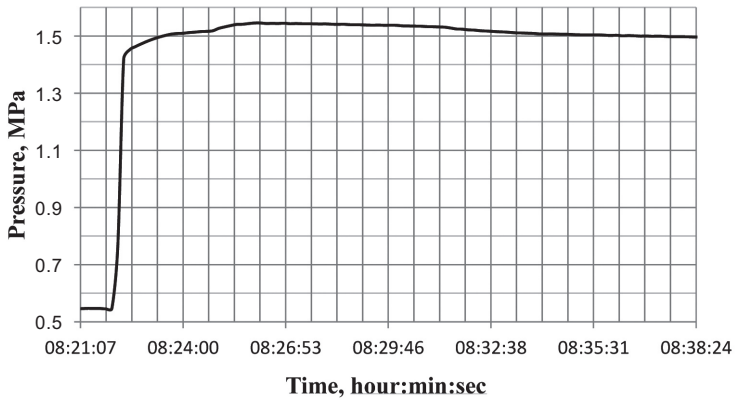
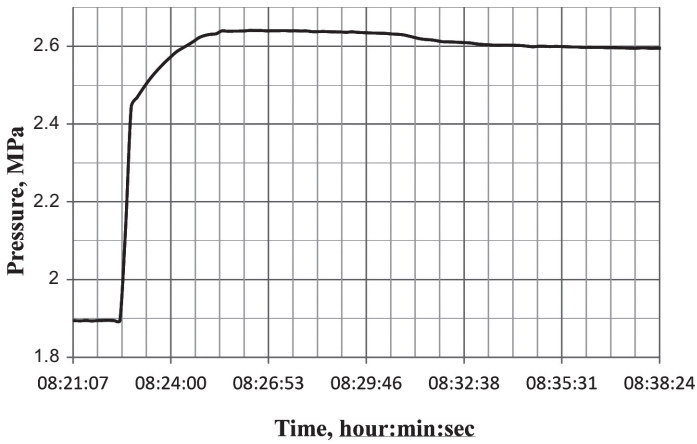**Fig. 2.** Pressure changes at the oil pump station where pumping unit was stopped

Fig. 3. Pressure changes at the distance of 31 km from place where pumping unit was stopped
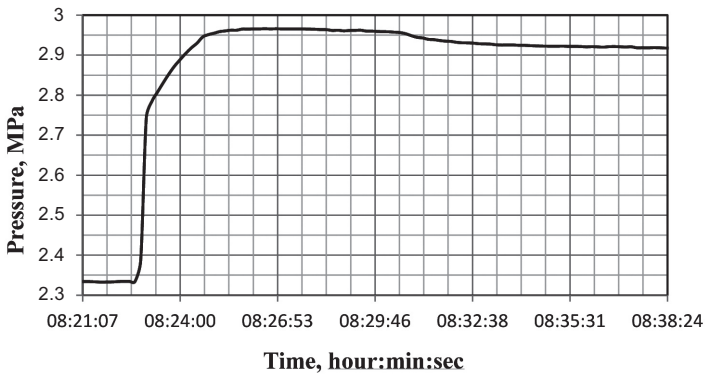

Fig. 4. Pressure changes at the distance of 46 km from place where pumping unit was stopped
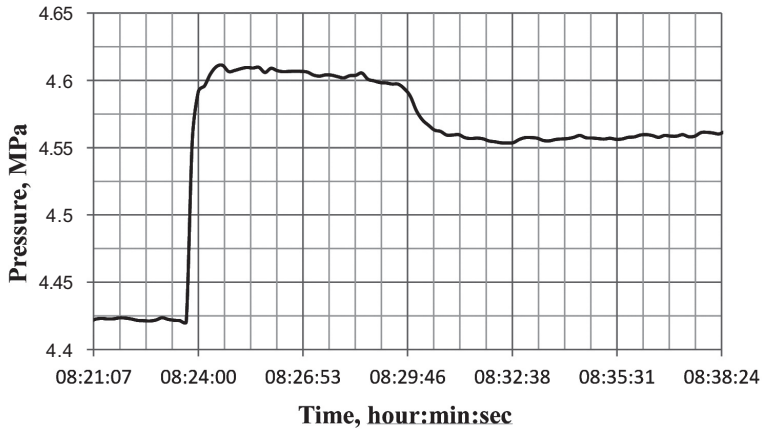
Fig. 5. Pressure changes at the distance of 103 km from place where pumping unit was stopped

After hydraulic jump the oil pressure in the pipeline for 25–30 minutes slowly grew and has stabilized on the value that corresponds to the new non-stationary operational mode of the trunk pipeline. The tendency of increasing pressure kept on the entire length of the pipeline. Moreover, if pumping units at the oil pump stations have been disconnected, as a result within a few seconds pressure dramatically increases at each point of pipeline route.

The mathematical modeling of obtained results was showed that dependence between hydraulic jump and place where pumping unit was disconnected can be described by an exponential equation (7).

$$\Delta P = \Delta P_n \exp(-K_z x) \tag{7}$$

where:

ΔP_n – hydraulic jump at the entrance of oil pump station,

K_z – wave damping factor,

x – length from the place where stop occurs [1].

According to experimental data that are given in the previous line graphs dependence between hydraulic jump and distance on the pipeline route during transient processes was received. Besides, it was received mathematical model (8) which describe pressure changes according to given data. Also, it was received exponential dependence for this case (Fig. 6).

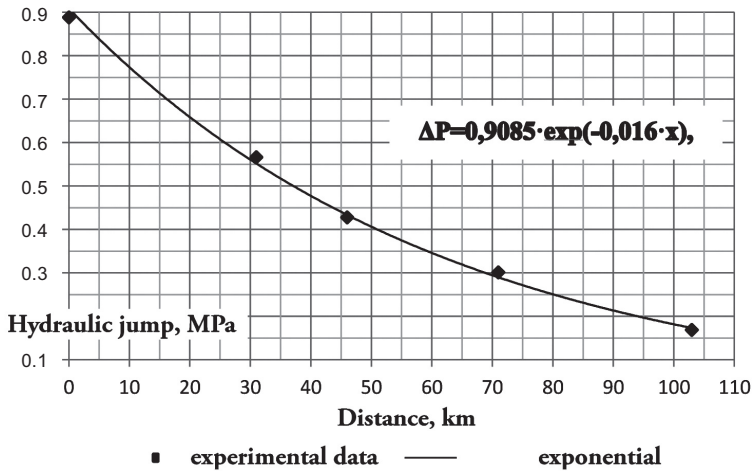$$\Delta P = 0.9085 \cdot \exp(-0.016 \cdot x) \tag{8}$$

Fig. 6. The dependence between abrupt increase of oil pressure and distance

Similarly, results of industrial experiments for other eleven operation modes of given pipeline was processed and analyzed. Also, for each experiment were received exponential models presented at the table (Tab. 1). At the second and the third is existed hydraulic jump at the entrance of oil pump station and wave damping factor in accordance. At the next columns are presented flow parameters and properties of the fluid. At the last columns is operational scheme of pumping units.

Table 1 allows making conclusion that in case of stop one pumping unit hydraulic jump at the inlet is different for each case and this hydraulic jump depend on operation scheme of trunk pipeline, flow parameters and properties of the fluid. Moreover, at each section of pipeline which are located before that place where stop occurs, transition process is not completed practically instantaneous during that moment when pressure increase. After hydraulic jump the oil pressure in the pipeline for 25–30 minutes slowly grew and has stabilized on the value that corresponds to the new non-stationary operational mode of the trunk pipeline. Also, it was received mathematical models, as equation (6) for each experiment that is shown in Table 1. These mathematical models provide possibility to determine pressure at any point of pipeline route during stops of pumping units.

During developing mathematical models for the experimental results was used method of least squares. Hydraulic jump and wave damping factor are estimated for certain values of volume flow in the pipeline before stop and physical properties of oil. Analysis of results from Table 1 showed that all theoretically developed mathematical models of wave damping factor during non-stationary process at the given pipeline

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are correct because coefficient of determination exceeds 90%. The obtained equations properly describe regularities of the pressure changes along pipeline route and recreate the values measured in the experiment with satisfactory accuracy.

Table 1

The value of hydraulic jump at the entrance of oil pump station
and wave damping factor during stops of pumping unit

Lp.	Hydraulic jump at the entrance of OPS (increase)	Wave damping factor, 1/km	Volume flow, m^3/h	Reynolds number	Viscosity, cSt	Operation scheme of the pumping units
1	0.83	0.013	1 578	26 395	30.12	Stop pump 3 at OPS 4
2	0.86	0.016	2 311	39 005	29.85	Stop pump 1 at OPS 4
3	0.99	0.016	2 378	69 615	17.21	Stop pump 1 at OPS 2
4	0.87	0.014	1 634	35 933	22.91	Stop pump 1 at OPS 4
5	1.19	0.015	2 363	74 083	16.07	Stop pump 4 at OPS 3
6	0.98	0.015	2 083	68 771	15.26	Stop pump 2 at OPS 4
7	0.89	0.015	2 281	38 525	29.83	Stop pump 1 at OPS 3
8	0.8	0.017	2 369	66 790	17.87	Stop pump 3 at OPS 3
9	0.95	0.014	2 080	63 782	16.43	Stop pump 1 at OPS 4
10	1.05	0.010	1 134	29 803	19.17	Stop pump 1 at OPS 3
11	0.91	0.016	2 335	50 338	23.37	Stop pump 1 at OPS 2
12	0.9	0.014	2 053	45 108	22.93	Stop pump 2 at OPS 3

The next step of considerations will be developing a general model (6) for forecasting dynamics changes of hydraulic jump along pipeline route caused by stops pumping units. This requires to expressed wave damping factor as a function of operational

parameters of the pipeline and the physical properties of transported oil. Hydraulic jump at the entrance of OPS may be calculated from the equation (3) using parameters of the pipeline and the physical properties of transported oil too. Research will be continued.

4. CONCLUSIONS

Theoretical investigations of hydrodynamic processes in crude oil trunk pipeline within non-stationary operation mode allowed making the following conclusions:

1. During stops of pumping units was observed pressure increasing at the inlet of oil pump station and pressure decreasing at the outlet. Duration of the quick pressure changes not exceed 10–20 sec.
2. The total duration of transient processes depend on the geometric characteristics of the trunk oil pipeline, oil pump hydrodynamic characteristics and physical properties of the transported fluid.
3. Within transient processes was detected that pressure sharply increased at the moment when pressure wave approach to inspection station. Then oil pressure in the pipeline for 25–30 minutes slowly decreased and has stabilized on the value that corresponds to the new non-stationary operational mode of the trunk pipeline.
4. Wave damping factor depend on geometric characteristics of the crude oil pipeline and physical properties of the transported fluid.
5. Mathematical models which were obtained theoretically provide a wide range of volume flow changes in the trunk pipeline and wide range of oil viscosity. The reliability of the mathematical models was confirmed by industrial experiments. That's why these models can be useful for forecasting parameters of transient process caused by stops of pumping units during oil transportation.

REFERENCES

[1] Hrehorsky S.T., Serediuk M.D.: *Improving the technology process of oil pipeline exploitation considering emergency situations*. Ivano-Frankivsk, Ukraine, 2015.
[2] Mazur R.: *Improving the technology process of crude oil transportation by trunk pipelines*. East meets West Conference, Krakow, Poland, 2016.
[3] Bergant A., Simpson A.R., Tijsseling A.S.: *Water hammer with column separation: a review of research in the twentieth century*. Journal of Fluids and Structures, 22, 2006, pp. 135–171.

[4] Asadiniazi M., Saband E.M.: *Study on mechanism and control methods of water hammer in pump station and pipelines*. International Offshore and Polar Engineering Conference, Beijing, China 2010.

[5] Tijsseling A.S., Anderson A.: *The Joukowsky equation for fluids and solids*. CASA Report 06-08, March 2016, TU Eindhoven Netherlands.
(http://www.win.tue.nl/analysis/reports/rana06-08.pdf)