Experimental study of the influence of starting pumping units on the value of oil pressure in oil-trunk pipelines

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Abstract

Having made experimental studies by modern measuring instruments at the existing pipeline we obtained pressure change regularities during unsteady hydrodynamic processes taking into account operation technology and characteristics of domestic oil pipeline pumping equipment.

There have been studied regularities of the rotor speed and pressure of NM oil pumps variations over time at their starting. There is revealed the change in transported oil pressure over time at the inlet and outlet of a pumping station during pumping units startings.

There have been built exponential dependences of the value of abrupt reduction and increase of oil pressure on the distance to the place of disturbance occurrence. The intensity of a low and high oil pressure wave damping in the pipeline are estimated.

Keywords: *a high-pressure wave, abrupt increase in pressure, the attenuation coefficient of the wave, unsteady hydrodynamic processes, velocity of propagation of a high-pressure wave.*

An energy component of oil-trunk pipelines are oil pumping stations (OPS) equipped with centrifugal pumping units. There are set four pumping units, often equipped with various rotors, at each OPS. One of the energy efficient ways to regulate the volume of oil transportation by a pipeline is the use of different combinations of started pumps at each OPS. That is why startings and stops of pumping units accompany exploitation of oil-trunk pipelines.

Each pumping unit stop or starting at the OPS leads to material breach of the established operation mode of an oil pipeline and causes unsteady processes, characterized by fleeting changes in the operating pressure upon transported liquid flow [1–3].

We have studied regularities of transient processes caused by stops of oil pipeline pumping units in papers [4–8]. The results of experimental studies of the impact of pumping units stops upon transient processes regularities in oil-trunk pipelines are presented in works [4, 5, 8]. There were analyzed the results of industrial experiments performed on the operating area of the current pipeline. The manuscripts [5, 6] contain results of theoretical studies of pressure change regularities in an oil-trunk pipeline during transient processes caused by stops of pumping units.

Starting an OPS pumping unit also has an impact on the operational mode of an oil-trunk pipeline but this issue is not the subject of additional studies of domestic and foreign scientists.

One of the main parameters that determines the functionality and reliability of the main pipeline operation is the value of operating pressure at the input and output of each OPS and in any point of the linear part. Pressure increase over the maximum allowable value can cause emergency situation, and unacceptable pressure reduction at the inlet of an OPS results in dangerous cavitation effects in pumps.

The above mentioned determines the relevance and importance of researches of pressure change regularities at transients in oil-trunk pipelines, caused by stops of pumping units.

The aim of the work is to establish pressure change regularities caused by stops of pumping units in an active oil-trunk pipeline.

The following tasks have been solved during the research:

identifying pressure change regularities made by HM oil pumps over time at their starting;

establishing regularities of pressure changes in the transported fluid at the inlet and outlet of an OPS at pumping units startings;

identifying patterns of waves propagation of high- and low-pressure in the linear part of a pipeline at pumping units startings.

Research methods include measuring parameters of oil motion in oil-trunk pipelines, mathematical processing of results applying computer technologies.

Industrial experiments of transient hydrodynamics at pumping units startings are conducted at a domestic oil pipeline of nominal diameter 700 mm and length

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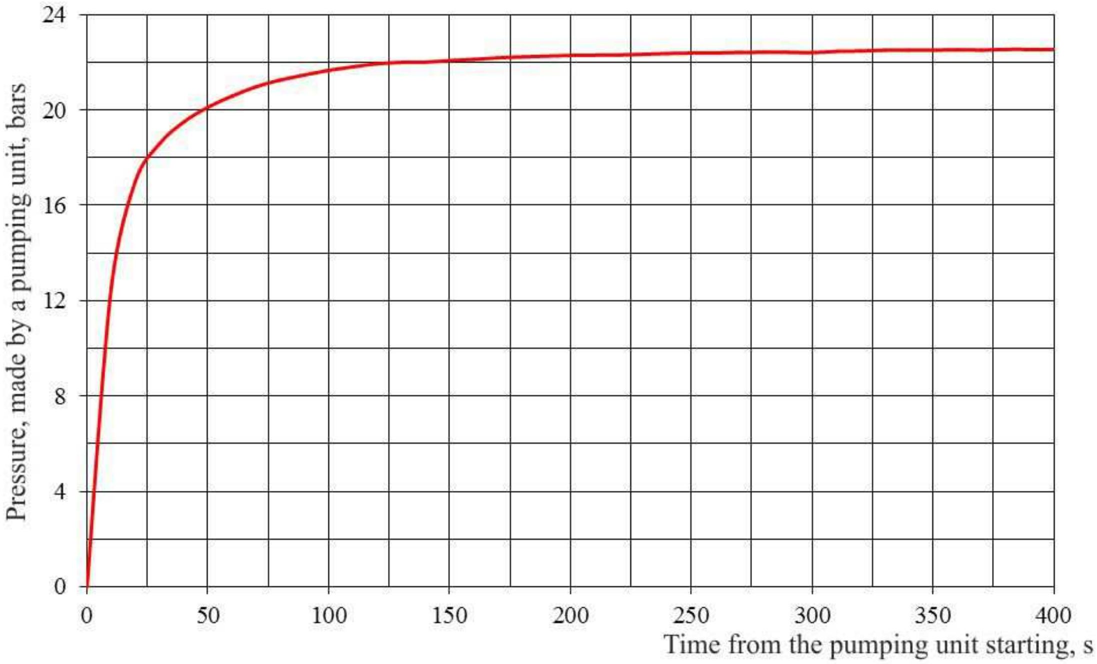

Figure 1 – Change of pressure created by the NM 3600-230 pumping unit during its starting

400 km. Four OPS, equipped with modern NM oil pumps, operate on the pipeline route. There are also set 14 checkpoints (CP), equipped with modern means of pressure fluid control, at the section of pipeline. For measuring transported fluid pressure there are applied modern pressure sensors Mikrotran F-R Fishers of accuracy 0.075–0.100.

Oil pressure measurement was performed with a frequency of 0.2 s during fast transient processes in an oil pipeline. A design diagram of operational area of the pipeline is shown in [4].

Density of transported oil varied in the range from 864 to 875 kg/m^3 during industrial experiments. The coefficient of kinematic viscosity of oil ranged from 16 to 35 cSt.

Experimental studies of NM 3600-230 pumps loading with different rotors have shown that the rotating frequency of a pump shaft reaches a nominal value of 3000 rpm almost instantly, within 10 s after their starting.

Figure 1 shows a graphical dependence of pressure made by the NM 3600-230 pumping unit at its starting according to the data of industrial experiment. Figure 1 shows that the pressure created by the pumping unit rapidly increases from zero to 18.6 bar for 30 s, then it increases with less intensity according to nonlinear relation within the time interval from 30 to 120 s, and it is virtually stabilized at the value corresponding to the flow of oil in pipeline after 240 s. We have obtained the following mathematical dependences of pressure created by a pumping unit (bar) during its starting upon time t for the pump, the loading of which is shown in Figure 1:

for the first phase – in the time range from 0 to 30 s it is the following one:

$$p = 6.651 \cdot 10^{-4} t^3 - 5.725 \cdot 10^{-2} t^2 + 1.736t; \qquad (1)$$

for the second phase – in the time range from 30 to 120 s:

$$p = 4.526 \cdot 10^{-6} t^3 - 1.422 \cdot 10^{-3} t^2 + 0.1646t + 14.73. \quad (2)$$

Formulas (1) and (2) can be used as boundary conditions for solving the system of equations of non-steady fluid flow in the pipeline during theoretical research of the influence of pumping units starting on the operating mode of an oil-trunk pipeline.

Processing of a large number of industrial experiments results showed that there are observed transient changes in pressure at the inlet and outlet of the respective OPS during pumping unit starting, namely, the pressure decreases at the OPS inlet and increases at its outlet.

To illustrate the results of experimental studies of pressure change regularities in an oil-trunk pipeline at transients caused by starting pumping units there is chosen one of the operating modes at which one trunk pumping unit operated at OPS 1 and OPS 3. Consumption of oil in the oil pipeline before starting an additional pumping unit was 1140 m^3/h.

A pumping unit was launched at the OPS 2 at 3.17 p.m. A graphic pattern of pressure reduction at the OPS inlet during starting a pumping unit is shown in Figure 2.

Figure 2 shows that pressure of transported fluid has abruptly decreased at the OPS inlet from 18.4 bars to a value of 9.0 bars for 30 s after starting the pumping unit, then the pressure continued to decline and reached a value of 7.3 bars for 2 min, then the pressure increased by nonlinear law to the value corresponding to the new steady mode of the pipeline operation for 20 min at the OPS inlet.

Thus, during starting a pumping unit we can divide the process of pressure change at the OPS inlet into the following three stages: the first one lasts for 30 s and the pressure suddenly decreases; the second one lasts up to

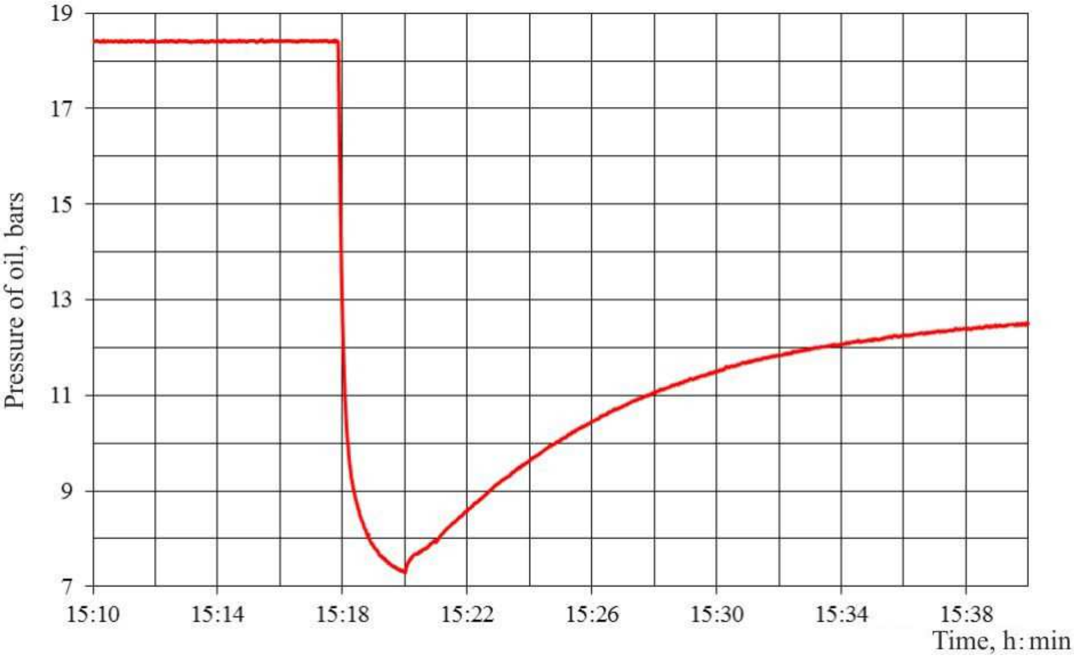

Figure 2 – Change of oil pressure over time at the OPS 2 inlet in during starting a pumping unit based on the experiment results (oil flow before starting was 1140 m^3/h)

2 min and the oil pressure slowly decreases, and the third one lasts up to 20–25 min, being characterized by pressure increase to the value corresponding to the new steady operation mode of the pipeline.

The dependences of pressure at the OPS inlet, where the pumping unit was launched, for the operating mode being analyzed upon time *t* are the following ones (see Figure 2):

for the first phase of the transition process in the time range from 0 to 30 s:

$$\Delta p_{in} = -4.223 \cdot 10^{-4} t^3 + 3.288 \cdot 10^{-2} t^2 - 0.9201 t + 18.41; \quad (3)$$

for the second phase of the transition process in the time range from 30 to 130 s

$$\Delta p_{in} = -1.895 \cdot 10^{-6} t^3 + 6.405 \cdot 10^{-4} t^2 - \\ -7.854 \cdot 10^{-2} t + 10.82\ ; \quad (4)$$

for the third phase of the transition process in the time range from 130 to 1300 s

$$\Delta p_{in} = 2.883 \cdot 10^{-9} t^3 - 1.069 \cdot 10^{-5} t^2 + \\ +1.425 \cdot 10^{-2} t + 5.592\ . \quad (5)$$

Reduced pressure wave caused by starting a pumping unit at OPS 2 flows at the speed of sound at the pipeline to OPS 1 causing abrupt and relatively slow changes of pressure in each section of the pipeline. Figures 3 and 4 illustrate patterns of pressure changes over time at a distance of 31 and 46 km from the occurrence of disturbance based on the results of an industrial experiment.

Figures 3 and 4 revealed the same tendency to reduction of oil pressure during the transition process. When a low pressure wave approaches the checkpoint there is observed an abrupt decrease in oil pressure, and after this oil pressure declined relatively slowly in this section of pipeline for several minutes, then it increased and stabilized at the value corresponding to the new steady state mode of pipeline operation.

Analysis of Figures 3 and 4 shows that there is observed fast fading of low pressure wave due to hydraulic energy losses when the distance from the place of disturbance increases. In its turn, it causes a decrease in the amplitude of abrupt pressure decrease and in the overall duration of the pressure stabilization. Amplitude of the jumping decrease of pressure is 4 bars, and the duration of the transition process is not more than 12–15 min at a distance of 46 km from OPS 2 (Figure 4).

According to the results of industrial experiment there is built a graphical dependence of the amplitude of the jumping drop in oil pressure upon the distance to the place of disturbance (Figure 5). There has also been done a mathematical modeling of experimental data using Microsoft Excel software.

It is established that the dependence of an oil pressure drop on the distance to the OPS, where a pumping unit is launched, can be described by an exponential function of the following form

$$\Delta p = \Delta p_{in} \exp(-K_{al} x), \quad (6)$$

where Δp_{in} is the value of the jumping oil pressure drop at the OPS inlet, where a pumping unit is launched; K_{al} is the attenuation coefficient of a low-pressure wave; x is the distance from the OPS, where the pumping unit was stopped, to an arbitrary point of the oil pipeline located before the disturbance place (along the movement of oil).

We have obtained the following dependence of the value of the jumping oil pressure drop (bar) upon the distance to the pumping unit starting (km) for an industrial experiment, the results of which are analyzed above

$$\Delta p = 9.16 \exp(-0.01252 x). \quad (7)$$

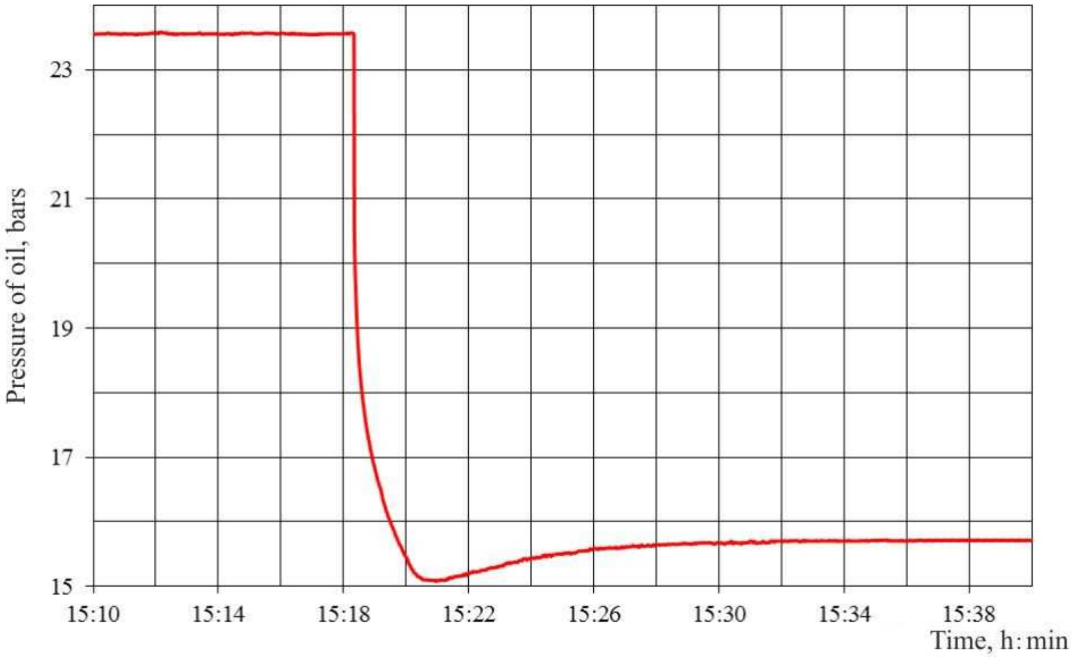

Figure 3 – Change of oil pressure over time at the distance of 31 km to OPS 2 where the pumping unit was launched based on experimental results (oil flow before starting was 1140 m^3/h)

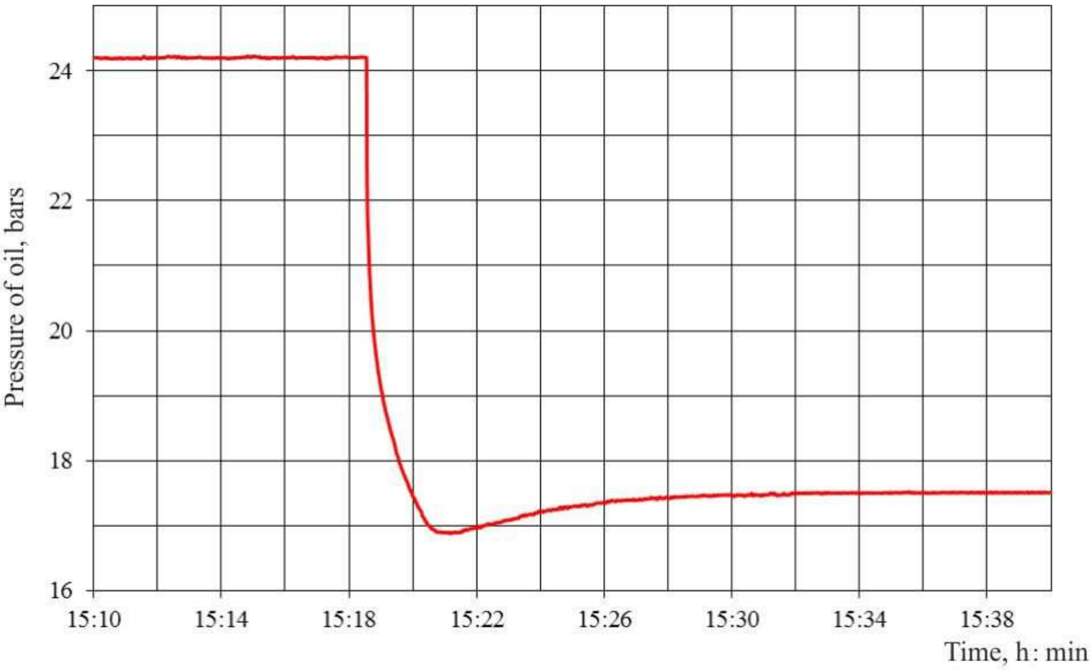

Figure 4 – Change of oil pressure over time at the distance of 46 km to OPS 2 where the pumping unit was launched based on experimental results (oil flow before starting was 1140 m^3/h)

Similarly, we can study pressure changes at the OPS 2 outlet when starting a pumping unit based on the example of the above-described mode of pipeline operation. Figure 6 illustrates a graphic pattern of pressure increase at the OPS outlet when starting a pumping unit.

Figure 6 shows that the pressure of a transported fluid at the outlet of the corresponding OPS has abruptly increased from 18.4 to 27.5 bars in 30 s after starting a pumping unit, then the pressure increased to 29.2 bars with much less intensity over the period of about 100 s, then for 20 min it has increased significantly slowly at the OPS outlet according to a nonlinear law to a value corresponding to the new steady operation mode of the pipeline.

Thus, the process of pressure changes at the OPS outlet when starting a pumping unit can be divided into three stages: the first one lasts up to 30 s and corresponds to the almost sudden increase of pressure; the second one lasts up to 2 min, corresponding to a slower decrease in oil pressure, and the third one lasts for 20–25 min, corresponding to a slower pressure increase (compared to the second stage) to the value of the new steady operation mode of a pipeline.

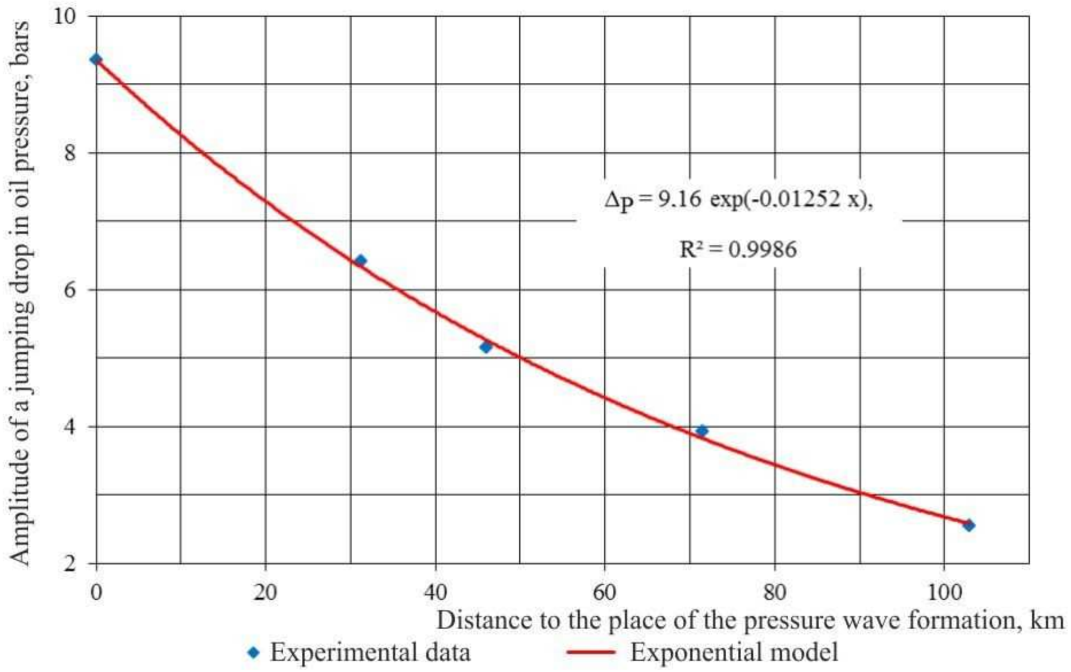

Figure 5 – Dependence of the value of a jumping drop in oil pressure upon the distance to the OPS 2 where the pumping unit was launched based on the experiment results (oil flow before starting was 1140 m^3/h)

Figure 6 – Change of oil pressure over time at OPS 2 outlet when starting a pumping unit based on experimental results (oil flow before starting was 1140 m^3/h)

We have obtained the following dependences of pressure at the OPS inlet, where the pumping unit was launched, upon time t for the operating mode being analyzed (Figure 6):

for the first phase of the transition process in the time range from 0 to 30 s

$$p_{out} = 2,492\cdot10^{-4}t^3 - 2.470\cdot10^{-2}t^2 + 0.8208t + 18.37; \quad (8)$$

for the second phase of the transition process in the time range from 30 to 130 s:

$$p_{out} = 2.009\cdot10^{-6}t^3 - 6.506\cdot10^{-4}t^2 + \\ +7.747\cdot10^{-2}t + 25.70\,; \quad (9)$$

for the third phase of the transition process in the time range from 130 to 160 s

$$p_{out} = 3.727\cdot10^{-9}t^3 - 1.325\cdot10^{-5}t^2 + \\ +1.704\cdot10^{-2}t + 27.19\,. \quad (10)$$

A high-pressure wave, caused by starting a pumping unit at OPS 2, flows at the speed of sound at a pipeline to OPS 3, causing abrupt and relatively slow

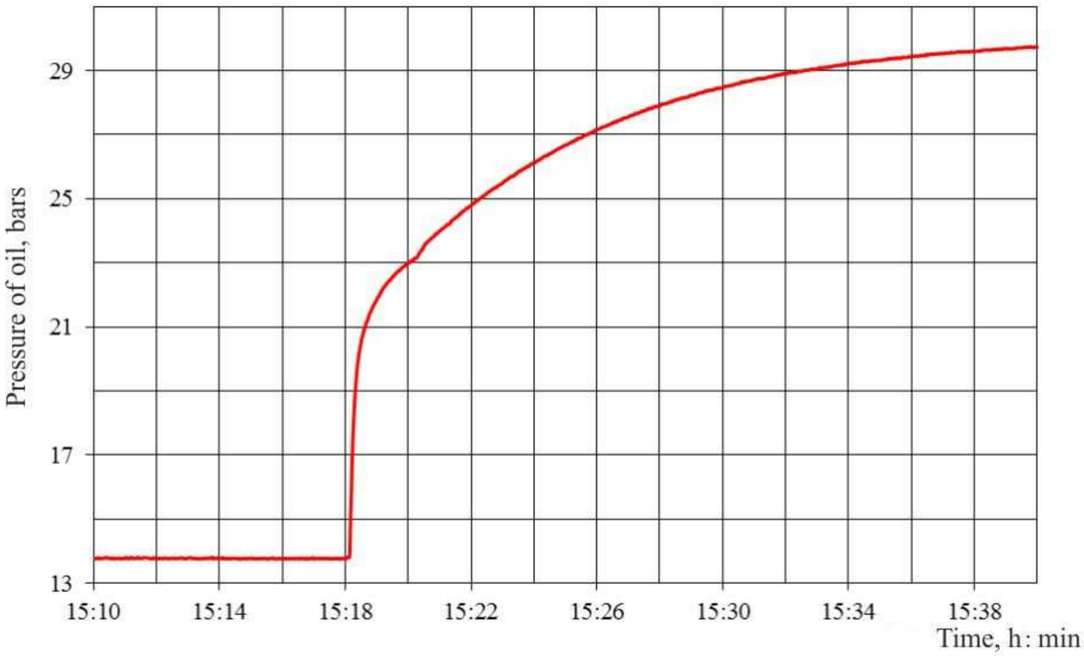

Figure 7 – Change of oil pressure over time at the distance of 19 km from OPS 2 when starting a pumping unit based on experimental results (oil flow before a pump starting was 1140 m^3/h)

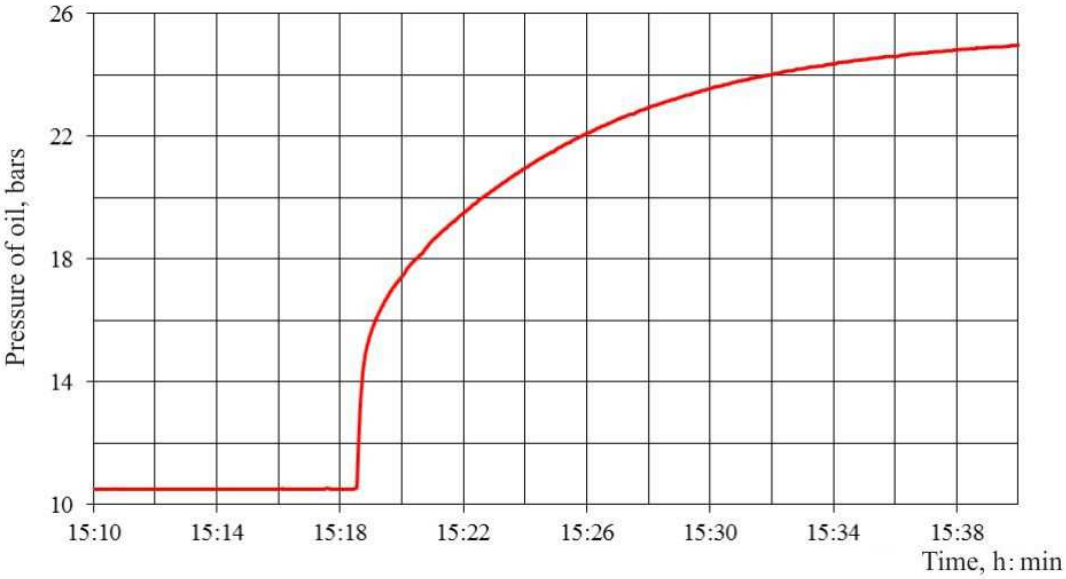

Figure 8 – Change of oil pressure over time at the distance of 19 km from OPS 2 when starting a pumping unit based on experimental results (oil flow before starting was 1140 m^3/h)

increases in pressure in each section of the pipeline. Figures 7 and 8 illustrate the patterns of pressure changes over time at a distance of 19 and 44 km from the place of the pumping unit starting based on the results of an industrial experiment.

Figures 7–8 have revealed the same tendency to oil pressure increase during a transition process, caused by starting a pumping unit. At the time of a pressure wave approach to the checkpoint there was an abrupt increase in oil pressure, and after this oil pressure was growing relatively slowly for 20–25 min at a given pipeline section, and then it stabilized at a value corresponding to the new steady operation mode of a pipeline.

If the distance from the disturbance place increases there is observed a gradual attenuation of an increased pressure wave and decrease of the amplitude of an abrupt pressure increase. The total duration of the pressure stabilization does not substantially depend on the distance to the disturbance place.

There is built a graphic dependence of the amplitude of the oil pressure increase on the distance to the place of disturbance based on the results of an industrial experiment (Figure 9). We have done mathematical modeling of experimental data using Microsoft Excel software.

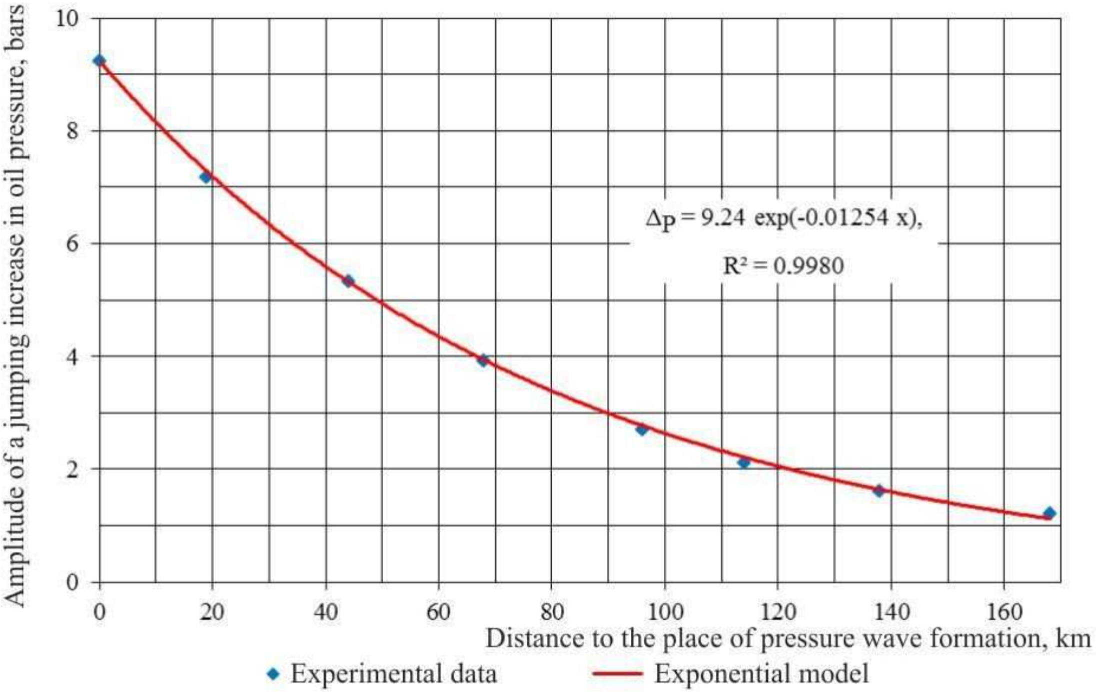

Figure 9 – Dependence of the value of a jumping increase in oil pressure upon the distance to the OPS 2 where a pumping unit was launched based on experimental results (oil flow before pump starting was 1140 m^3/h)

It is established that the dependence of a jumping increase in oil pressure on the distance to the OPS, where a pumping unit is launched, can be described by an exponential function of the following form:

$$\Delta p = \Delta p_{in} \exp(-K_{al} x), \tag{11}$$

where Δp_{in} is the value of a jumping increase in oil pressure at the OPS inlet, where one (or several) pumping unit is launched; K_{al} is the attenuation coefficient of an increased pressure wave; x is the distance from the OPS, where the pumping unit was stopped, to an arbitrary point of an oil pipeline located after the disturbance place.

We have obtained the following dependence of the value of an oil pressure drop (bar) upon the distance to a pumping unit starting (km) for the experiment, the results of which are analyzed above

$$\Delta p = 9.24 \exp(-0.01254 x). \tag{12}$$

Pulses of reduced and increased pressure, formed at the inlet and outlet of OPS, where the pumping unit is launched, spread in pipeline at the speed of sound, which can be theoretically defined by the following formula:

$$c = \sqrt{\frac{K/\rho}{1 + KD/\delta E}}, \tag{13}$$

where ρ is the density of the transported fluid at pumping conditions; K is an elastic modulus of transported fluid; D is the inner diameter of a pipeline; δ is the thickness of a pipe wall; E is an elastic modulus of a steel pipe.

The rate of propagation of the pressure wave in a pipeline is calculated according to the formula (13) using conventional reference data, and it equals $c = 995$ m/s for an industrial experiment being analyzed.

The Table 1 contains the results of determining the actual velocity of pressure waves caused by running a pumping unit of an OPS 2, obtained by processing data for an industrial experiment.

The analysis of experimental studies of the patterns of transition processes caused by starting pumping units allowed us to confirm the result that was obtained earlier in the work [4]. The actual speed of propagation of a pressure wave is about 1110 m/s for the studied pipeline, which is 12% higher than the value predicted by the formula (13).

Experimental research of influence of starting a pumping unit on patterns of oil pressure change in a pipeline allowed us to draw the following conclusions:

1. During starting NM oil-trunk pipeline pumping units their loading time is 10 s relative to the rotary frequency and up to 2 min relative to the pressure made by the pump. The process of starting a pumping unit includes three stages, characterized by different intensity of its pressure increase.

2. When you start a pumping unit there is observed an abrupt decrease in pressure at its inlet and, respectively, pressure increase at its outlet. At an OPS inlet and outlet the maximum pressure change is close to half the pressure, made by a pumping unit at the average flow of oil during the transition process.

3. When starting a pumping unit we can divide the process of pressure change at the OPS inlet and outlet into three stages: the first one, lasting for 30 s, corresponds to the sudden decrease in pressure; the second one, lasting for up to 2 min, corresponds to a slower decrease in oil pressure, and the third one, lasting for 20–25 min, is characterized by pressure

Table 1 – Experimental data and results of calculating the actual velocity of waves propagation caused by starting a pumping unit

Location	Time of pressure wave formation, h:min:s	Distance from the place of wave formation, km	Time of pressure wave flowing to the chosen section of the pipeline, s	Velocity of the pressure wave propagation, m/s
OPS 1	15:19:23	102.91	92.0	1119
CKPT 32	15:18:56	71.45	64.4	1109
CKPT 1	15:18:33	45.99	41.6	1106
CKPT 2	15:18:20	31.23	28.4	1100
CKPT 4	15:18:08	18.40	16.6	1108
CKPT 5	15:18:31	43.81	39.2	1118
CKPT 6	15:18:52	66.92	60.4	1108
OPS 3	15:19:17	95.34	85.6	1114
CKPT 7	15:19:33	113.72	102.0	1115
CKPT 8	15:19:55	137.68	123.6	1114
CKPT 9	15:20:22	167.64	150.2	1116
CKPT 10	15:20:38	184.96	166.2	1113
OPS 4	15:20:44	191.74	172.2	1113
CKPT 12	15:21:27	240.15	216.0	1112
CKPT 13	15:21:45	260.18	233.8	1113
CKPT 14	15:22:02	279.21	251.0	1112
Final point	15:22:13	291.51	261.8	1113
		Average velocity		**1112**

increase to a value corresponding to the new steady operation mode of a pipeline.

4. The amplitude of pressure changes wave is significantly reduced during its movement in the pipeline, leading to the attenuation. The dependence of an abrupt increase (decrease) of pressure upon the distance to the disturbance site can be reliably described by an exponential dependence.

5. Based on the obtained experimental results there is confirmed the value of the actual velocity of propagation of an oil pressure wave in the pipeline. Its value is 12% higher than the value that is calculated by the standard formula.

In the future, there will be developed methods for calculating an attenuation coefficient of a high and low pressure wave depending on the physical properties of the transported fluid, geometric characteristics and operational parameters of a pipeline based on the results of industrial experiments.

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Експериментальні дослідження впливу запусків насосних агрегатів на величину тиску нафти в магістральних нафтопроводах

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Шляхом експериментальних досліджень, що проведені з використанням сучасних засобів вимірювання на діючому нафтопроводі, одержано закономірності зміни тиску за неусталених гідродинамічних процесів з урахуванням специфіки технології експлуатації та характеристик насосного обладнання вітчизняних нафтопроводів.

Досліджено закономірності зміни у часі обертової частоти та тиску нафтових насосів серії НМ під час їх запусків. Виявлено характер зміни у часі тиску транспортованої нафти на вході і виході нафтоперекачувальної станції при запуску насосних агрегатів.

Побудовано експоненціальні залежності величини стрибкоподібного пониження та підвищення тиску нафти від відстані до місця виникнення збурення. Оцінено інтенсивність затухання хвилі пониженого та підвищеного тиску нафти в нафтопроводі.

Ключові слова: *коефіцієнт затухання хвилі, неусталений гідродинамічний процес, стрибкоподібне підвищення тиску, хвиля підвищеного тиску, швидкість поширення хвилі підвищеного тиску.*