Implementation and operation of anti-pressure systems of oil pipelines

A F Barkhatov, A G Gumerov, A M Shammazov, R A Fazletdinov and R V Vafin

1Ufa State Petroleum Technological University, 1, Kosmonavtov St., Ufa, Republic of Bashkortostan, 450062, Russia
2Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russia

E-mail: vsh@of.ugntu.ru

Abstract. The article analyzes the issue of protection of oil pipelines from high-pressure waves arising from pressure pulsation, water impacts during normal or abnormal shutdown of pumping units or an intermediate pumping station caused by the unauthorized closure of valves, etc. Main aspects of implementation of anti-pressure systems (APS) were considered and economic criteria for their installation on existing and projected oil pipelines were determined. An example of calculation of non-stationary processes required to substantiate the expediency of using high-pressure pumps at intermediate oil pumping stations was presented. The main types of system designs, features of their operation and planned maintenance were presented.

1. Introduction

Russian oil pipelines transport are complex. They have a branched pipeline network.

The Transneft company which is the largest national operator delivering liquid hydrocarbon raw materials transports 83% of all Russian oil. The company has over 68 thousand km of main oil pipelines, more than 500 oil pumping stations (PS), 24 million m³ of tank containers [1-5].

The scale of company activities implies a high load and uninterrupted operation of the pipeline network.

At the same time, deviations from standard modes of transportation, pressure pulsation and hydraulic shocks are possible. Their consequences can damage equipment or cause oil outflow into the environment.

Regular or abnormal shutdowns of an aggregate or an intermediate oil pumping station (PS) are accompanied by an increase in pressure, resulting in a steep pressure wave propagating upstream in the direction of the previous station. Due to friction losses, the initial perturbation dies out, i.e., its steepness and amplitude decrease. Reaching the previous station, the pressure wave increases pressure at the station outlet. To maintain the setpoint at the LPS outlet, the automatic control system (ACS) of pressure creates a wave of pressure reduction (vacuum). If the speed of the SAR is not enough to offset the surge pressure, the pressure of the outlet of the pump station can reach the setpoint. General station protection systems shut down a single pump or a station. When this protection is triggered, the pressure wave reduction begins to propagate towards the incoming wave of pressure. As a result of wave interference,
the pressure in the linear part (LP) of the pipeline decreases. However, before the wave reaches the previous OPS, the pressure in the area between the stations may exceed the allowable working pressure of the main pumping station (MPS) which can cause depressurization of the pipeline.

In most cases, protection of sections of the LC pipes from overpressure in transient processes caused by the disconnection of the main pumping unit (MPS) or the whole pump station is protected by means of anti-pressure systems (APS).

2. Methods and materials
The first description of MPS protection methods was presented in the works by R.R. Burnett [2, 3] who considered the Trans-Arabian MP with a diameter of 750/775 mm.

Protection of the site adjacent to the disconnected oil pumping station was carried out by dumping a part of the oil flow through the programmable valve into a 800 m$^3$ tank. After shutting down the pump, the valve quickly opened, and the set pressure at the inlet of the pump was maintained. Then, the valve was closed at a fixed speed [3].

However, this method could not be applied at Russian stations due to the fact that their abnormal disconnection (more than 90% [4]) was caused by the uninterrupted supply of electricity. It was necessary to adapt this idea to the Russian conditions.

In 1970, technical requirements for the APS [5] were formulated by the “Giprotruboprovod” company. Arkron-1000 (Figure 1) is a hydraulically connected vessels. The APS consists of a separation tank into which antifreeze (ethylene glycol) is poured. Its density is higher than oil density. Due to this, the liquid creates an insulating barrier against contamination of APS elements with mechanical impurities and oil paraffin. The separation tank is connected with a hydropneumatic accumulator (HPA) which is filled with ethylene glycol and air under the pressure of 5-6 kgf/cm$^2$ [6]. The HPA is connected with the Flex-Flo valve.

The Flex-Flo valve is a core with slots and a rubber stockings. At a steady state, the pressure in the gas cavity of the valve is equal to the pressure in the pipeline. When disconnecting the MPA or the OPS, the valve inlet pressure rises much faster than the pressure in the air chamber of the valve. The increase in pressure is determined by the resistance of the regulating choke and the volume of the gas space of the battery. As a result, the rubber stocking is stretched, and oil from the pipeline is discharged into the pressure-free reservoir through slots in the core. Then, the pressure in the air chamber increases, and the rubber stocking moves to the core.

The research results are presented in [7, 8]. The purpose of the calculation was to determine the value of excessive pressure between the non-stationary and stationary modes of operation of the main oil pipelines. The method on is described in [9, 10].

![Diagram of the Arkron-1000 APS](image-url)
Calculations were carried out on the throughput capacity of the MN with nominal diameters of 1200, 1000, 800, 700 mm without taking into account individual characteristics of each MN: CAP settings at the stations, DRE of the LP sections and rheological oil properties. The results of calculations in [8] cannot be unified for all MNs, but they are a basis for APS application requirements.

3. Justification of the need for APS by calculating non-stationary processes
To perform calculations of non-stationary processes, including those performed in order to check the need for APS at an intermediate PS, special software was used. For example, the Giprotruboprovod, JSC used the Stoner Pipeline Simulator. In order to confirm the accuracy of the mathematical model and calculations, this software was certified and verified. If the test results are positive, the software is entered in the Transneft software register.

The process of calculation of non-stationary processes is divided into the following stages: construction of a mathematical model of the pipeline; transient calculations.

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At the stage of mathematical model construction, the hydraulic model and the model of automation of the technological section of the pipeline were built. The hydraulic model describes hydrodynamic processes occurring in the pipeline, and includes various combinations of the location of the high-pressure pump at intermediate pumping stations of the technological section of the trunk pipeline which is a single hydraulic system. The model of automation describes the operation of general station protection systems under the overpressure. They operate in accordance with the automation standards.

At the stage of calculation of transient processes, various abnormal situations are simulated (shutting down of the pumping station, valve closure, etc.).

Results of calculations of non-stationary processes of the existing oil pipeline are presented for one possible variant: the APS is installed on the intermediary OPS-4. The characteristics of a simulated main oil pipeline are as follows: nominal diameter - 1000 mm; length of the technological area - 1000 km; number of intermediate pumping stations - 3. Rheological properties of the pumped oil are as follows: density - 870 kg / m³; kinematic - 18 cSt.

The position of the OPS on the route and benchmarks are presented in Table 1.

| Name of the OPS | Route position, km | Benchmark, m |
|----------------|-------------------|--------------|
| OPS -1         | 0                 | 209.3        |
| OPS -2         | 253.31            | 212.4        |
| OPS -3         | 505.67            | 205.9        |
| OPS -4         | 762.85            | 43.9         |
| OPS -5         | 1000              |              |

The parameters of the design mode with a capacity of 37.0 million tons / year (5062 m³ / h), as well as the number and type of pumping units used are presented in Table 2.
Table 2. Parameters of the design mode.

| Name of the OPS | Pressure, kgf/cm² | Support pump | Main pump |
|----------------|-------------------|--------------|-----------|
|                | OPS inlet NPC outlet | Output of the OPS Type of the pump | Amount, pcs. | Type of the pump |
| OPS -1         | 45.1              | NGPNA-3600-120 | 3 | NM 3600 / 1.25-230 |
| OPS -2         | 4.5               | -             | - | NM 7000-210 |
| OPS -3         | 5.0               | 45.5          | - | NM 10,000 / 0.5-210 |
| OPS -4         | 4.5               | -             | - | NM 7000-210 |
| OPS -5         | 3.8               | -             | - | - |

SAR pressure on the pumping station is based on the method of throttling. The diameter, the number of regulators in and the full stroke time of the valves are presented in Table 3.

Table 3. The characteristics of OPS gate throttling nodes

| Name of the OPS | DN. mm | Number of regulators, pcs. | Full-time shutter, s |
|----------------|--------|----------------------------|----------------------|
| OPS -1         | 350    | 2                          | 8                    |
| OPS -2         | 500    | 2                          | 8                    |
| OPS -3         | 500    | 2                          | 8                    |
| OPS -4         | 500    | 2                          | 8                    |

The values of regulation and automatic protection settings are presented in Table 4.

Table 4. Settings for SAR regulation and automatic protection.

| OPS | SAR setting Limit (disconnection of the 1st MNA) | Protection setting / holding time | Protection setting Limit (disconnection of the 1st MNA) | Pressure after regulating dampers Emergency (disconnection of the OPS) SAR setting | Protection setting Limit (disconnection of the 1st MNA) | Emergency (disconnection of the OPS) SAR setting |
|-----|-----------------------------------------------|----------------------------------|-----------------------------------------------|-------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
|     | kgf/cm²                                      | kgf/cm²/s                        | kgf/cm²//s                                    | kgf/cm²                                        | kgf/cm²                                        | kgf/cm²                                        |
| OPS -1 | 4.5                                          | 4.05 // 10                       | 3.8 // 15                                     | 45.1                                           | 47.4                                           | 49.2                                           |
| OPS -2 | 4.5                                          | 4.05 // 12                       | 3.8 // 20                                     | 57.5                                           | 60.4                                           | 61.5                                           |
| OPS -3 | 5.0                                          | 4.5 // 12                        | 4.3 // 20                                     | 45.5                                           | 47.8                                           | 49.6                                           |
| OPS -4 | 4.5                                          | 4.05 // 12                       | 3.8 // 20                                     | 64.0                                           | 67.5                                           | 68.0                                           |

To determine the feasibility of the APS, it is necessary to calculate transient processes that occur after the disconnection of intermediate NPCs in a maximum transfer mode for the variant without and with the APS.

The results of mathematical simulation of the pipeline during OPS emergency disconnection without and with the APS are presented in Table 5.
Table 5. Estimated maximum inlet pressures at intermediate station inlets

| Name of the OPS | Allowable transient pressure*, MPa | Maximum pressure in the transition process without APS, MPa | Maximum pressure in the transition process with APS, MPa |
|-----------------|----------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| OPS -2          | 3.78                             | 3.99                                                     | 3.09                                                     |
| OPS -3          | 3.67                             | 3.47                                                     | 3.49                                                     |
| OPS -4          | 3.78                             | 3.12                                                     | 3.09                                                     |

* 110% of the maximum allowable pressure when the pump is running

Graphs of pressure changes at the pump station inlet and outlet are shown in Figures 2 and 3, respectively.

![Figure 2](image1.png)  
**Figure 2.** Pressure change at the inlet of intermediate pumping stations in case of emergency shutdown of OPS-4

![Figure 3](image2.png)  
**Figure 3.** Pressure change at the outlet of intermediate pumping stations in case of emergency shutdown of OPS-4

The volume of oil discharged into the tank through the APS node is presented in Figure 4.

![Figure 4](image3.png)  
**Figure 4.** Changes in the volume of AP release at the OPS-4

According to the results of the calculations, we can draw the following conclusions:
- in case of emergency shutdown of the OPS-4 without the APS, there is no excessive SP of the pipe sections of the linear part; the maximum pressure in the supply pipelines of the OPS-2 is 40.70 kgf / cm² which exceeds the maximum allowable pressure (35 kgf / cm²) by 14%;
- in case of emergency shutdown of the OPS- 4 with the APS, there is no excessive SP of the pipe
sections of the linear part; no excessive nominal pressure of the equipment and supply pipelines of the OPS-2.

The absence of excessive nominal pressure at the inlet of the NPS-3 is due to the difference in the flow of the transition process with and without APS nodes at the disconnecting OPS-4 (Tables 6, 7).

### Table 6. Transient events when the OPS-4 (without APS) is disconnected.

| OPS   | Simulation Event                                      | OPS APS operation         | Time, s |
|-------|-------------------------------------------------------|----------------------------|---------|
| -     | Stationary transfer mode with a design capacity of 37.0 million tons/year (5062 m/h) | -                          | 0       |
| OPS-4 | Emergency shutdown of the OPS-4                       | Simultaneous disconnection of all working MPA | 60      |
| OPS-3 | Protection operation                                   | Simultaneous disconnection of all working MPA | 326     |
| OPS-2 | "Emergency pressure at the OPS outlet Protection operation | Simultaneous disconnection of all working MPA | 620     |

### Table 7. Transient events when the OPS-4 (with APS) is disconnected.

| OPS   | Simulation Event                                      | OPS APS operation         | Time, s |
|-------|-------------------------------------------------------|----------------------------|---------|
| -     | Stationary transfer mode with a design capacity of 37.0 million tons/year (5062 m/h) | -                          | 0       |
| OPS-4 | Emergency shutdown of the OPS-4                       | Simultaneous disconnection of all working MPA | 60      |
| OPS-3 | Protection operation                                   | Simultaneous disconnection of all working MPA | 348     |
| OPS-2 | "Emergency pressure at the OPS outlet Protection operation | Simultaneous disconnection of all working MPA | 635     |

Analysis of transient events showed that when there is an APS, the maximum pressure at the OPS outlet does not reach the emergency pressure setpoint, does not cause the simultaneous emergency shutdown of all pumping units and allows to reduce the maximum pressure at the station inlet in order to avoid the excessive SP of pipe sections of the linear part.

### 4. Technical schemes for implementing air traffic control systems

Currently, there are two versions of APSs.

The first one is Arkron-1000 with hose Flex-Flo valve. Its design is presented in Figure 1. The principle of operation was described above.

The second one is domestic APS-Zx2000-4.0, APS-3x4000-4.0 produced by Transneftemash plants (Figure 5).

The main elements correspond to the "Arkron-1000". However, there are some differences. Separation tank (2) is directly connected with angle-type safety valves (3). Delays in the line between the separation tank and the valve are provided by changes in the flow area of the control throttle valve (3) and the number of HPA (4) involved in the work. The HPA is a cylindrical container partially filled with nitrogen. They are gas caps. In the stationary mode of operation, the HPA pressure is equal to the line pressure. After the development of the transition process, the line pressure grows, gas is compressed, and part of the antifreeze flows into the HPA cavity.
Figure 5. Technological scheme of the air traffic control system for variant 2: 1 - technological line of the pump station; 2 - separation tank; 3 - throttle valve; 4 - hydropneumatic battery; 5 – angle-type type safety valve; 6 - disposal tank

In a stationary mode of operation, the APS valve piston is in the closed position due to the force of the spring and the pressure of the antifreeze supplied from the separation tank. With delays in the line created by changes in the number of connected HPAs and the degree of opening of the throttling valve, the pressure above the valve piston becomes lower than the pressure ensuring its closure; as a result, the valve opens ensuring the disposal of oil and reducing the rate of pressure increase at the inlet of the pump station. As the separation fluid returns from the HPU, the pressure drop across the locking element of the relief valves decreases and the APS valve closes.

Evaluation of the APS performance of the internal combustion engine is carried out according to the instructions of the manufacturers; in particular, the level of the liquid in the separation tank is monitored. If the pressure in the receiving pipeline is below 1.5 MPa, antifreeze will flow from the open middle valve, the level is considered acceptable. The condition of the oil discharge valves and the retaining device is monitored.

The cause of an abnormal increase in the level of liquid may be a failure of the oil discharge valve caused by the rupture of the valve chamber, a battery diaphragm, an antifreeze leakage, an excessive air (gas) flow in the battery.

The cause of the failure of the internal air traffic control system can be the clogging of the overflow valve filters, the failure of the pump of the antifreeze filling system.

Problems can arise during the maintenance and repair of the Arkron-1000 valves. This is due to the need to maintain the performance of the equipment after a complete shutdown of the PS, because there are no shut-off lines isolating lines with APS valves from the station pipelines.

When it is impossible to repair the valves, uncontrolled leakage of oil can occur.

5. Results and discussion

Currently, the need for APSs is confirmed by calculations. If calculation results confirm the need for APSs, in accordance with standards for MPs, technical and economic comparison of variants with APS and replaced pipeline sections where pressure exceeds the allowable values is carried out.

In order to compare the costs of APSs and replacement of sections, the main DN pipelines of the Transneft Company were compared. The costs of APSs and replacement of sections were determined as the arithmetic average of the array of analyzed objects in 2016 prices. The results are presented in in Table 8.

For projected MPs, the cost of the high pressure pump must be compared with the cost of increased wall thickness of the pipeline sections in which the pressure may exceed the allowable values. The results are presented in Table 8.

Table 8 shows that according to capital costs, the single air traffic control system is equivalent to a complete replacement of 3.93 km of LC of the DN 1200 pipeline or 9.22 km of the DN700 pipeline. In this case, the APS should be installed if the length of the section is lower than the above estimate.
Table 8. Comparison of the APS and UCL piping costs

| DN mm | Operating MN | Designed MN |
|-------|--------------|-------------|
|       | The length (km) of the pipeline section at a cost equal to one APS | The length (km) of the pipeline section at a cost equal to one APS with an increase in pipe wall thickness by: |
|       |             | 1 mm        | 2 mm        |
| 1200  | 3.93        | 43.21       | 21.61       |
| 1000  | 5.40        | 54.01       | 27.00       |
| 800   | 8.35        | 66.80       | 33.40       |
| 700   | 9.22        | 73.73       | 36.86       |

On the projected MP, instead of installing a high-pressure system, it is possible to increase the wall thickness of the pipeline by 1 mm over a 43.21 km (DN1200) section. At the same time, an increase in the SP of the sections of a future MP is more expedient, since it will increase the service life of the pipeline and reliability of the pipeline system.

6. Conclusion
1. The APS can reduce pressure in transients caused by disable intermediate stations or their individual units by reasonable calculation of transients.
2. From the economic point of view, when operating existing and designing new pipelines, options are possible under which an increase in SP of the sections where excessive pressure in transients may be higher than the allowable one will be more expedient than installing APSs.

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