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Parameters Analysis of Crude Oil Transport with Pipes

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ABSTRACT

The paper provides an analysis of key parameters such as: heat transfer coefficients, flow, pressure drop, pump power, heat losses and temperature drop in the oil pipeline. Tests were performed on a real oil pipeline plant with a diameter of 457 mm and a length of 91000 m. The oil pipeline is dig into the ground at a depth of 1.5 m. As an experimental fluid, crude oil of the paraffinic type, with a pour point of +8 to +26 ^oC, was used. In order to improve transport properties and prevent the appearance of paraffin inside the pipeline, the crude oil was heated to a temperature in the range of +20 to +50 ^oC. Origin software was used to display the research results. An analysis of the key transport parameters and their mutual dependencies and influences is also given. The aim of the work is to analyze and determine the optimal parameters of crude oil transport, as well as to determine the relation between heating temperature, paraffin content, flow temperature and cooling rate, where oil solid content will not occur. For such research, paraffin type oil was chosen as the experimental fluid.

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1. INTRODUCTION

Due to relatively simple construction and economical cost of transport, pipelines (oil pipelines) are very attractive and profitable kind of transportation systems. They provide transport of oil of high capacity on a very long distances on acceptable investment and operative costs. There aren't so many quality and quantity data for these systems which can provide correct calculation. Crude oil consists of hydrocarbons, water, gas and solid particles of various materials as mechanical additives. Density of crude oil is mostly in range of ρ = (835 – 950) kg/m^3. Every oil field consists of up to 30% of water. Water can be free and emulsified water. Separation of water and salt from crude oil (dehydration) represent the significant part of oil production and also its preparations for pipeline transport (Secerov-Sokolovic et al., 2006; Rukthong et al., 2016).

During construction, pipelines are (in most cases) dig into the ground (1 – 1.5) m. The lengths of main oil pipelines range from several tens to several hundreds of kilometers. On some locations, there are pump stations at the pressure of (60 – 70) bar. Magistral pipelines are sometimes placed above the ground on pillars on heights at (0.5 – 0.75) m (Prstojevic, 2012).

In spite of the great efforts that are made in the world in order to obtain the data, which are relevant in projecting the oil lines, there are still not enough economical solutions of transporting oil with pipes. Main purpose of improving the technique of oil pipeline transport is rising the efficiency and economics of these transport systems, and lowering the energetic and investment costs. That's why further research in this area is crucial in inventing new models and numerical values of relevant parameters for transportation processes which would fit in real systems more realistic. These are the reasons why this work consists of the results of researches on the real part of the main pipeline.

Based on experimental measuring and theoretical researches this paper presents the results for heat transfer coefficient, heat losses through pipeline, pressure failures, pump power, etc. In comparison with different modes of transportation, the transportation of oil through pipelines is the most economical. It is the most obvious when analyzing the supplying of refineries with crude oil (Ahmadpour et al., 2014; Sun et al., 2016a). The presence of paraffin in oil has the effect of reducing flow properties. By heating the oil, its viscosity decreases, and also the losses in friction pressure during pipeline transport, etc. Heating the crude oil improves its flow characteristics (Danilovic et al., 2011, 2012; Rukthong et al., 2016).

Table 1 Characteristics of crude oil

Crude oil heating temperaturet (ºC)	Kinematic viscosity $\nu \cdot 10^6$ (m^2/s)	Density ρ (kg/m^3)	Paraffin content p_r (% mas.)	Pour point t_s (ºC)
20	23	875	3	8
30	18	868	9.3	18
40	15	862	14.7	26
50	11	855	27	35

Crude oils with a paraffin content above 15% are paraffinic oils. Such oils have high pour points and unfavorable characteristics for pipeline transport. The emulsion of water and paraffinic crude oil tends to gelatinize under standstill conditions, when cooling occurs below the pour point, which compromises the safety of restarting the pipeline and reduces transport properties (Danilovic et al., 2012).

According to the literature (Secerov-Sokolovic et al., 2006; Prstojevic, 2012) an analysis of the influence of paraffin and paraffin wax on the pour point is given. Highly paraffinic oil is characterized by a high flowing temperature ranging (15–46) ºC.

In the paper (Hermoso et al., 2017) three types of oil with different densities were considered: (874, 894 and 889) kg/m^3. By heating the oil up to 40ºC, the density does not change significantly. By heating the oil above 40ºC, the density of the oil decreases with the increase in temperature. A linear decrease in density with increasing temperature is observed. The density mainly depends on the temperature in the area of normal pressures (1 – 200) bar.

In the literature (Tanaskovic, 1998a; Prstojevic, 2012) discussed the issue of diluting crude oil, with the aim of reducing viscosity and improving conditions for pipeline oil transportation. The flow properties of crude oil that has a high paraffin content and high viscosity oil can be greatly improved if the oil is mixtured with petroleum products such as: diesel fuel, gasoline or kerosene.

The problem of transporting paraffin oil can appear after starting the pump after overhaul or failure, and these problems are especially pronounced in the winter period, which reduces the transport properties (Davidson et al., 2004; Qinglin et al., 2017).

A decrease in temperature directly causes an increase in the mass of deposited paraffin and an increase in the viscosity. In range (35–50) °C, deposition intensity is relatively low, while at lower temperatures it increases. As the temperature decreases, the deposition intensity increases exponentially. This also affects on the transport properties of the oil (Danilovic et al., 2011).

In the literature, the issue of starting the flow during pipeline transportation of paraffinic crude oil, after a stoppage period, has been considered. Stoppage means the interruption of transportation for a certain period of time when the oil in the pipeline cooled down (Davidson et al., 2004; Tolmac et al., 2020a). If a stoppage occurred during the transportation and appearance of solid paraffin particles, a higher pressure of pump will be required when starting the pump. (Prvulovic & Tolmac, 2006; Neascu et al., 2007).

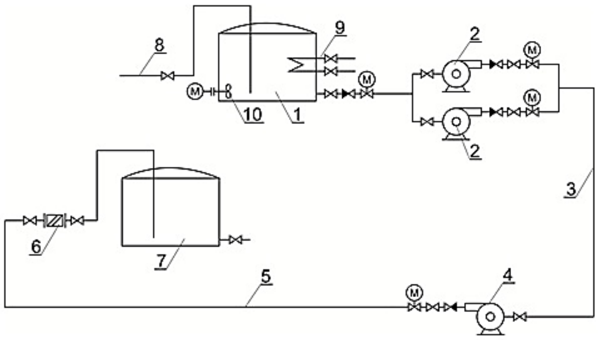

Fig. 1 Scheme of experimental plant, 1-reservoir, 2-pump, 3- pipeline, 4-pump, 5-main pipeline, 6-flow meter, 7-reservoir, 8-supply pipeline, 9-heat exchanger, 10-homogenizer

Based on the given data from the literature review and the previous research, it was established that there is not enough qualitative and quantitative data for crude oil pipeline transport. Therefore, research in this area is necessary in order to find optimal transport solutions.

2. MATERIALS AND METHODS

Scheme of experimental plant is shown on Fig. 1. Crude oil from tank (1), transports by the pumps (2), oil pipeline (3) to the pump (4). Using the pump (4) and the main oil pipeline (5), oil is transported to the measuring station (6) and tank (7). In tank (1) crude oil has been preheated on temperature of (20 – 50) ºC depending on paraffin content. Heating power of heat exchanger is 9300 kW. Depending on temperature of heating (20, 30, 40, 50) ºC time for heating is (3, 6, 12 and 18) hours. At the maximum loading height, which is 10 m, tank has 12560 m^3 of oil.

As seen in Table 1, the results of measuring the physical characteristics of crude oil are given. Measurements included crude oil density, crude oil viscosity and pour point. Heating temperature of crude oil increases by t = (20 – 50) ºC, there is a decrease in viscosity by $\nu = (23 \cdot 10^{-6} - 11 \cdot 10^{-6})$ m^2/s, while the density does not change significantly.

Pumps (2) provide the pressure on pump input (4), at (5–6) bar. Heating of the oil pipeline (3) D_n= 323 mm is done with water wapor using the pipeline D_p= 25 mm. The water vapor pressure is 12 bar and the temperature is 200 C, Fig. 2. Oil pipeline is isolated, so oil flow is isothermal. Depending on the heating temperature of crude oil (20, 30, 40, 50) ºC, water vapor consumption is (465, 765, 1020,1275) kg/h.

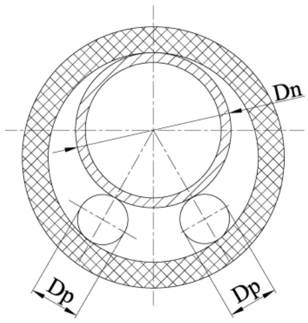

Fig. 2 Scheme of oil pipeline heating (3)

Table 2 Data for pipeline (3)

Pump 2	Oil pipeline 323 mm	Tank 1
Q=305 m^3/h	D=301.7 mm	diameter 40 m
H= 80 m	l = 1550 m	height 12.7 m
N=132 kW	s =100 mm	volume 15000 m^3
n=2950 min^{-1}		isolation thickness 100 mm

Table 3 Data for main pipeline (5)

Pump 4	Oil pipeline 457 mm
Q=900 m^3/h	D=428.4 mm
H=335 m	l =91000 m
N=1000 kW	s =100 mm – isolation thickness
n =2960 min^{-1}	

On the oil pipeline route (3) there are 3 block valves in order to isolate pipeline segments in the case of any accidents, or leakage. Oil pipeline is placed on pillars on 0.75 m above the ground. Basic oil pipeline data (3) are in Table 2.

Oil transportation conducts through the main pipeline (5) with the pump (4) to the tank (7). Depending of temperature and transport capacity, the pressure drop moved in the interval Δp = (35 – 40) bar. Transport capacity is (560 – 700) m^3/h. In Table 3 the basics data for main pipeline are given.

On certain places where main pipeline route (5) passes through major watercourses block stations are built along with the block valves for isolating the segments in the case of accidents. Along the oil pipeline route there are five block stations with its block valves made from the full profile. Oil pipeline is dig into the ground on 1 m. During the transport oil cools and transmits its heat to the environment, which causes a temperature drop in the oil pipeline (5).

3. RESULTS AND DISCUSSION

This paper presents experimental and theoretical researches on the part of main oil pipeline route (5) 91000 m in length and 457 mm in external diameter, according to the scheme of experimental plant on Fig. 1. Based on that, all relevant parameters of the process and relations between them has been determined: coefficient of heat transfer and heat losses through the oil pipeline, relation of pump power and flow change, change of temperature along the oil pipeline, etc.

Working range flow is between q = (0.155 – 0.194) m^3/s, speed of streaming is (1.08 – 1.35) m/s, and Raynolds number varies in this interval Re = (11762 – 50565), and based on that streaming is turbulent. Difference of the oil temperature at the beginning and at the end of the pipeline for the examined flow range is t = (10 – 12) ºC, so streaming of oil through pipeline (5) is non isothermal.

3.1 Heat Transfer Coefficient and Heat Losses

Heat transfer coefficient depends on many influential parameters: pipeline diameter, pipe thickness, isolation thickness, convective characteristic etc. (Skrbic, 2006; Tolmac et al., 2007). Based on (Sasic, 1976; Prstojevic, 2012), the heat transfer coefficient of isolated oil pipeline varies in range of(0.58 – 1.38) W/m^2K. In case of non-isolated oil pipeline protected with anti-corrosion band is (1.75 – 2.5) W/m^2K.

Viscose fluids such as crude oil need to pre-heated before entering the pipeline. Heated crude oil cooled through the pipeline and transmits its heat to the environment. Temperature to which crude oil cools has huge practical significance. Cooling of heated crude oil in general goes to the temperature above the temperature of pour point (Danilovic et al., 2012; Sun et al., 2016a; Tolmac et al., 2017).

Heat transfer coefficient through the oil pipeline has dominant influence on speed of cooling the oil in the oil pipeline. According on research (Sasic, 1976) heat conduction coefficient of isolated oil pipeline 400 mm in diameter, is 0.520 W/mK.

Figure 3 shows relation between heat conduction coefficient (kD_m) and thickness of isolation (s). For isolation thickness in range of s = (25 – 100) mm, the heat conduction coefficient is in range of kD_m= (0.32 – 0.70) W/mK.

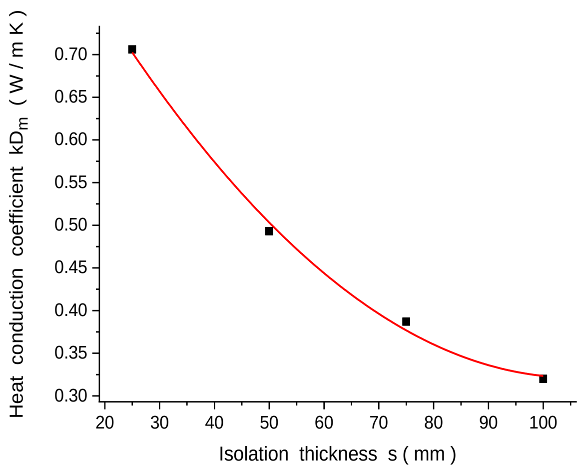

Fig. 3 Relation of heat conduction coefficient (kD_m) and isolation thickness (s)

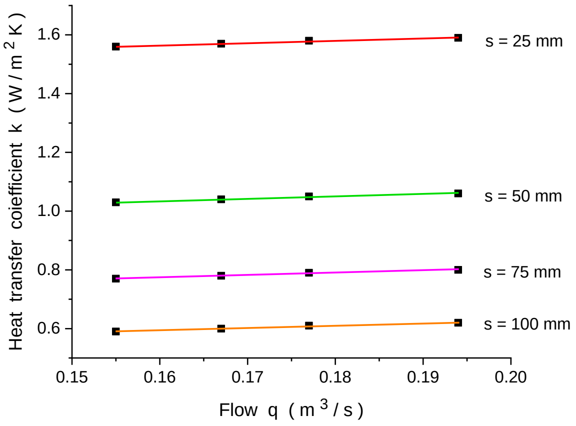

Fig. 4 Relation of heat transfer coefficient (k) and flow (q), for various values of the isolation thickness (s)

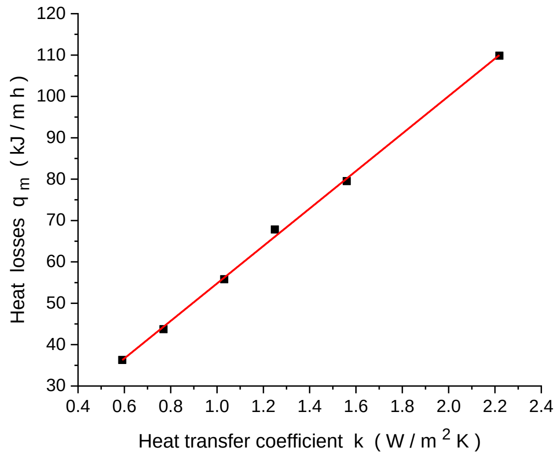

Fig. 5 Heat losses through the oil pipeline

Figure 4 shows relation of heat transfer coefficient (k) and flow (q) for various values of the isolation thickness. Reducing the isolation thickness the heat transfer coefficient and heat losses raises. It also increases the temperature difference of the oil in the beginning and at the end of a pipeline.

If the pipeline isolation thickness is s=100 mm, heat transfer coefficient is k = 0.60 W/m^{2}K, and heat conduction coefficient is kD_m = 0.32 W/mK. Reducing the isolation thickness results in raising the heat transfer coefficient. If we're talking about non isolated pipeline when s = 25 mm, heat transfer coefficient is k = 1.60 W/m^{2}K, and heat conduction coefficient is kD_m = 0.70 W/mK. For isolation thickness in range of s = (25 – 100) mm, the heat transfer coefficient is in range of k = (0.6 – 1.6) W/m^{2}K. Change of flow has no significant influence on heat transfer coefficient, Fig. 4. According to the (Sasic, 1980), mentioned heat transfer coefficient is in range of (0.40 – 3.50) W/m^{2}K.

Figure 5, shows the results of research for main pipeline (5). The relation between heat losses through the oil pipeline according to the heat transfer coefficient. Heat losses depend on heat transfer coefficient, pipe length and diameter and oil temperature in the beginning and at the end of a pipeline. Heat losses are increased as temperature difference of oil at the start and at the end of a pipeline increases.

Authors proposed numerical model for calculating heat losses, under non-isothermal mode of transportation of crude oil by underground pipelines, (Neacsu et al., 2007). Heat losses are (45 – 100) kJ/mh. According to Fig. 5, for a heat transfer coefficient in range of k = (0.6 – 2.2 W/m^{2}K), heat losses through the pipeline (5) are in range of q_m = (35 – 110) kJ/mh. This model gives possibility for calculating heat losses on the whole length of a pipeline, for various time intervals during the transport of oil.

Optimal heat temperature of crude oil (before entering the pipeline) depends on paraffin content, pour point temperature and specific work conditions of oil pipeline (Chang, et al., 1999).

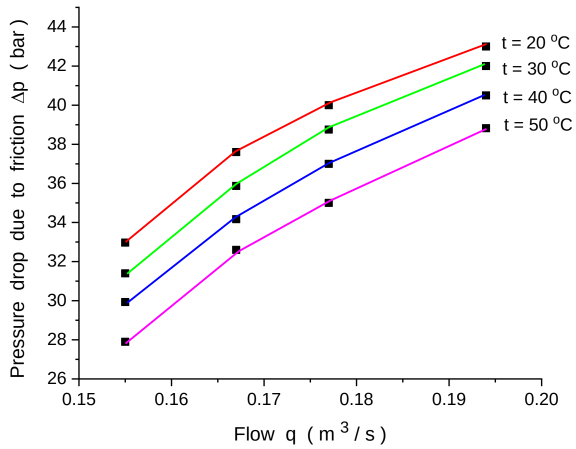

Fig. 6 Pressure drop due to friction depending on the flow of crude oil

3.2 Pressure Drop and Pump Power

Figure 6 shows the results of research showing relations depending on pressure decease (Δp), flow (q) and temperature (t). Due to increase in flow and decrease in temperature, there was an increase in pressure drop.

For the main oil pipeline (5), with a transport capacity in range of q = (0.155 – 0.194) m^3/s, a value of pressure drop due to friction was obtained in interval Δp = (28 – 38 bar), for an initial oil temperature oft = 50 °C, Fig. 6. Due to the temperature drop by Δt = 10 °C, the pressure drop increases by 3 to 4%. For the flow rate in range of q = (0.155 – 0.194) m^3/s, the pressure drop due to friction is in range of Δp = (33 – 43) bar, for an initial oil temperature of t = 20 °C.

According toresearch (Sun et al., 2016a), pressure drop value is Δp = 50 bar, pipeline diameter is 300 mm and its length is 32000 m. Oil pipeline is dig into the ground. Started temperature of oil is 66 °C, and transport capacity is 345 m^3/h (300t/h).

Based on research (Sasic, 1976), pressure drop due to friction is Δp = 21 bar, pipeline diameter is 400 mm and its length is 91000 m. Oil temperature is 50 °C and transport capacity is 347 m^3/h (330 t/h).

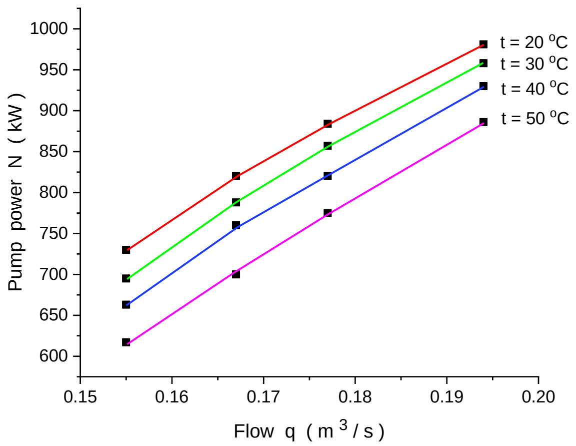

Fig. 7 Relations between pump power and flow change

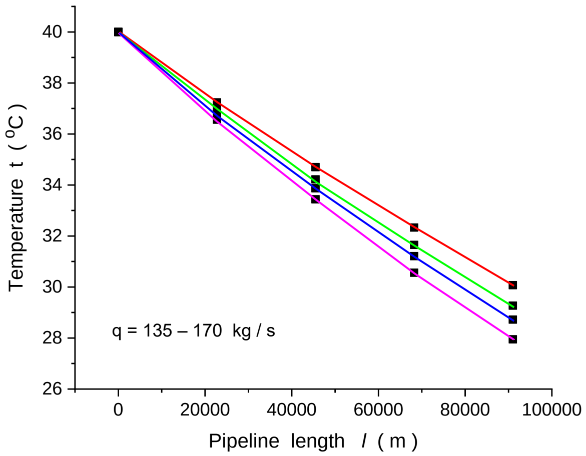

Fig. 8 Temperature change along the oil pipeline for various flows, when started temperature of oil is t = 40 °C

According to (Prvulovic & Tolmac 2012), pressure drop due to friction depending of flow capacity through pipeline at diameter 200 mm and at length of 11000 m, is Δp = 11 bar. Oil temperature is 45 °C and transport capacity is 100 m^3/h (92 t/h).

On Fig. 7 the research results are shown which are showing relations between pump power (N), flow (q), temperature (t) and crude oil viscosity (*v*). Viscosity increases with temperature decrease. By increasing the flow and decreasing the temperature of crude oil the pump power raises.

Transport of higher viscosity oil requires higher pressure drop and pump power, Figs 6 and 7. Based on the research results, with a transport capacity in range of q = (0.155 – 0.194) m^3/s, the pump power is in range of N = (670 – 925) kW, at an initial oil temperature of t = 40 °C. If the initial oil temperature is t = 30 °C, the pump power ranges from N = (700 – 950 kW), etc.

During the transport of crude oil with high percentage of paraffin, higher pump pressure is required. If fluid movement is constant with no change that can be noticed when fluid reaches the pour point temperature (Tanaskovic, 1998a; Sun et al., 2016a;) and then there won't be problems if all of this is done.

Choice of the pump power generators has a huge significance for oil and its derivatives transportation. Depending on the pressure drop and pump power, the number of pump units is determined. (Davidson et al., 2004; Tolmac et al., 2020b).

For transport of oil by pipes, the highest pressure of the pump varies from (50 – 60) bar, according to recommendations from the literature (Prvulovic et al., 2013; Tolmac et al., 2017). By choosing huge number of pump generators with less thrust and capacity, bigger number of pump stations is received along the oil pipeline route. This requires more complex construct solution, higher costs of maintenance and larger number of employees in this area of expertise. Chosen pump generators should be the same type on the whole oil pipeline route, this is important for lightly maintenance and eventual replacement.

3.3 Temperature Decrease Along the Oil Pipeline

Transport capacity, pipeline diameter and physical characteristics of crude oil, and also the length of pipeline (Banerjee et al., 2017; Tolmac et al., 2017;) are most influential parameters on optimal heating temperature. Figure 8 shows relations of temperature change along the whole oil pipeline route for various values of crude oil flow, with started temperature of t = 40 °C.

For the operating regime of the flow in range of q = (135 – 170) kg/s, at the initial oil temperature of t = 40 °C, the temperature drop was in range of Δt = (10 – 12) °C, on the entire length of the oil pipeline, Fig. 8. Main oil pipeline (5) is isolated with polyurethane foam at thickness of 100 mm. On capacity of (135) kg/s (560) m^3/h, time for transporting and cooling the crude oil is T= 23 h. On capacity of 170 kg/s (700) m^3/h, time for transporting and cooling the crude oil is T=18 h. Based on those facts, cooling speed of transported oil is (0.52 – 0.55) °C/h.

Time for cooling the oil in the oil pipeline, to the pour point, has huge significance. Knowing the speed of cooling the crude oil in the oil pipeline, can determine non pumping intervals without reaching the pour point (Al-Kayiem et al., 2017; Banerjee et al., 2017). Based on that cost of heating crude oil depend on temperature and time of heating (Danilovic et al., 2011).

Figure 9 shows relation of temperature change along the whole length of pipeline for various values of crude oil flow, if starting temperature is t = (20, 30, 40, 50) °C. Oil is heated above paraffin melting point, and at that point paraffin are in liquid stage. Heated crude oil cools down while flowing through the pipeline and transmits its heat to the environment. The temperature drop on the oil pipeline route *l* = 91000 m is in range of Δt = (10 – 12) °C, depending on the transport capacity in range of q = (135 – 170) kg/s.

Problems of temperature decreases in an isolated oil pipeline due to interruption or stopping the flow has also

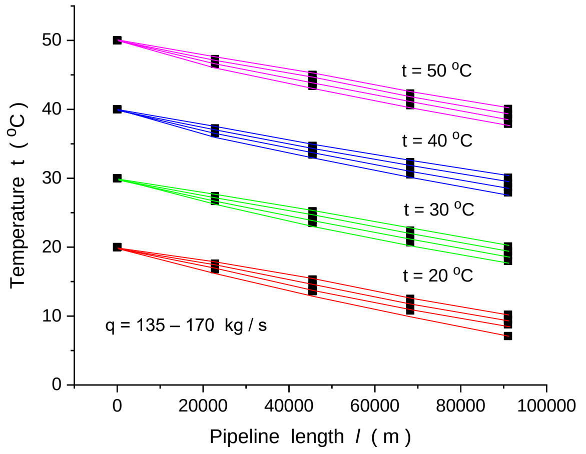

Fig. 9 Temperature changes along the oil pipeline for different values of the crude oil flow, with started temperature (20, 30, 40, 50) °C

been considered (Tanaskovic, 1998b; Sun et al., 2016a). The most intensive cooling happens in the first 50 hours, when oil cools down in $\Delta t = 25$ °C, and cooling speed is 0.50 °C/h. Inner diameter of pipeline is 273 mm, external diameter is 292 mm, isolation thickness is 50 mm.

Determination of cooling time, namely when the temperature of heated oil in underground oil pipeline, fall down on the temperature of pouring point, which isn't a simple process and depends on many influential parameters (Sun et al., 2016a, b). Some of those parameters are: mass of the ground which surrounding the pipeline, temperature zone in which pipeline is laid and depth of pipeline burying. Deeper underground higher amount of heat is accumulated and temperature field deviates much more from theoretical. Cooling process is affected by physical parameters, such as heat conduction, specific ground temperature etc.

While heated crude oil is transported, need to be precisely carefully about re-establishing the oil flow after interruption. If flow interruptions are shorter, level of cooling the oil pipeline is smaller and it is easier to re-establish oil flow in pipeline, namely started pressure need to be smaller for re-establish the flow (Erkut & Gzara, 2008).

4. CONCLUSION

The choice of power pump generators is very significant for oil and oil derivates transport. According to pressure drop and pump trust force, the number of pump units is determined. When choosing a pump with a lower thrust pressure, the number of pump units increases.

For various values of temperature and viscosity, the curves and their relations are experimentally determined:

- Coefficient of heat transfer and heat losses through oil pipeline
- The pressure drop is in function of the crude oil flow.
- Relations between pump power change and flow
- Temperature change along the oil pipeline route.

It has been established that:

- Pressure drop depends on temperature and viscosity. Viscosity increases by lowering the temperature. Increasing the flow and reducing the temperature increases the pressure drop.
- Pressure drop on the whole oil pipeline route is key parameter to calculate power of the pump.
- Flow increasement and lowering temperature of crude oil increases the pump power.
- When transporting paraffinic crude oil of higher viscosity, a significant increase in pressure and pump power is required.
- Heated crude oil cools down while flowing through the pipeline and transfers its heat to the environment. Temperature decrease along the whole pipeline route is (10 – 12) °C.
- Cooling speed while oil pipeline transport, in stationary thermic and hydraulic regime varies in range of (0.52 – 0.55) °C/h, depending on capacity.
- The temperature of paraffin oils must be higher than the pour point.
- Transporting crude oil with high percentage of paraffin, on temperatures below pour point require higher pumping-trusting pressure.
- During the transport of crude oil with high percentage of paraffin, for temperature drop $\Delta t = 10$ °C, the pressure drop increases by 3 to 4%. If fluid moving is constant and there is no change that can be noticed when fluid reaches the pour point none of problems can be shown.

Based on the results given in the paper, it is possible to determine pressure drop, pump power, temperature decrease, speed of cooling and heat loses through the oil pipeline. These results are useful for managing risk of forming wax or paraffin in the pipeline and securing crude oil flow.

Based on the given analysis, future research can be directed at generalizing the problem of transporting crude oil through pipes and finding optimal operating parameters and appropriate solutions for efficient transportation of different types of oil of different quality.

The research results indicate the possibility of practical application, given that they are based on verified experimental data obtained on a real plant. The results of the research can be useful for designers and users of such and similar transport systems.

The practical significance of the research is reflected in the possibility of increasing the efficiency and reliability of transport by choosing optimal transport parameters.

The paper presents the results of research into operating parameters at a real plant for the transportation of crude oil.

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