MINISTRY OF EDUCATION AND TRAINING
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RESEARCHES IN TREATING PARAFFIN-RICH OIL IN RONG AND BACH HO FIELDS USING THERMAL - CHEMICAL TO IMPROVE RECOVERY FACTOR

Major: Petroleum engineering

Code: 9520604

SUMMARY OF DOCTORAL THESIS IN PETROLEUM TECHNICAL

Hanoi – 2021

The dissertation is completed at: **Department of Drilling and Production, Faculty of Oil and Gas, Hanoi University of Mining and Geology**

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The dissertation will be defended before the Academic Review Board at the University level at Hanoi University of Mining and Geology at ..... : ..... of date ..... month ..... year ....

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INTRODUCTION

1. The urgency of the subject

In recent years, the oil produced in these fields has declined rapidly. In order to maintain annual production, Vietsovpetro has continuously bring in new fields, such as Nam Rong Doi Moi, Gau Trang, Tho Trang, Ca Tam.... However, most of these fields are small, so the incremental oil volume produced cannot compensate for the rate of decline in the annual production of those large field. Up to now, Vietsovpetro can only maintain oil production at 3.0 - 4.0 million tons / year. In 2020, fields in Block 09-1 are expected to produce only 3.1 million tons. Meanwhile, recently, world oil prices dropped sharply, hovering around 40-50 USD / barrel. In addition, researches to increase production / maintain oil and gas exploitation activities in the Block 09-1 offshore fields is difficult and expensive. Thus, solutions in reducing production costs are very necessary and urgent for Vietsovpetro in particular and Petrovietnam in general at this time. The application of science and technology such as choosing reasonable, complete and efficient solutions in exploiting, processing and transporting oil and gas in offshore fields in Block 09-1 with economic efficiency will be the first priority at Vietsovpetro.

Therefore, the topic *"Researches in treating paraffin-rich oil in Rong and Bach Ho fields using thermal - chemical to improve recovery factor"* is urgent and practical.

2. The purpose of the thesis: Research and develop a chemical - thermal method in treating paraffin-rich oil by taking advantages of available resources at Vietsovpetro in order to reduce costs.

3. Objectivity and scope of the study

- Objectivity: Treatment for paraffin-rich oil using available resources on offshore facilities.

- Scope: Oils from Bach Ho, Rong and connected fields that are exploited by Vietsovpetro on the continental shelf in Southern Vietnam.

4. Research subjects

- Physicochemical and rheological properties of paraffin rich oil, effects of water saturation levels and temperature on rheology of Bach Ho, Rong and Ca Tam crude oil;

- Treatments for paraffin-rich oil using chemical-thermal solutions
- Solutions in optimizing thermal-chemical treatments for paraffin-rich oil in the final stage of exploitation in Vietsovpetro.

5. Methodology and approaches

Searching, collecting and evaluating thermal-chemical treatments for paraffin-rich oil in Vietsovpetro's fields

- Making eexperiment, using algorithms to process the experimental results, establish mathematical equations for the change of rheological properties depending on the water saturation and temperature of crude oil in Vietsovpetro's fields;
- Listing, analyzing and processing survey results, establishing the relationship between the temperature and the depth of the Basement, Oligocene and Miocene layers, setting up the geothermal gradient formula for the layers.

6. Scientific and practical significance

- **Scientific significance:** Chemical-thermal treatments for oil is are applicable in Vietsovpetro's field.
- Establishing the relationship between the viscosity of the water-oil mixture depending on the proportion of water in the mixture and the temperature of the oil
- Diversifying the solutions for paraffin-rich oil treatments in Rong and Bach Ho fields by using the heat of the available gas turbines and using the geothermal heat of the oil well.
- **Practical significance:** Selecting a suitable solution for paraffin-rich oil treatments in Rong and Bach Ho fields

7. New point of the thesis

- Determining the relationship between the viscosity of the oil and water mixture in Vietsovpetro's fields with the percentage of water in the mixture and the temperature by mathematical equation. Propose a specific equation to determine the oil viscosity of Ca Tam oil field.
- Determining the dynamic relationship (mathematical formula) of geothermal gradients of layers (including: basement, oligocene and miocene of Vietsovpetro's fields).
- Utilizing available energy sources (geothermal of oil wells and energy from gas turbine exhaust) to treat Bach Ho crude oil

- proposing a new method and correcting thermal parameters of layers, applying specialized software for calculation, installation of chemical pipes and valve positioning inside production tubing in Bach Ho field.

8. Thesis defending

- Point 1: The thermal-chemical treatment for paraffin-rich oil is a suitable and effective solution at the current exploitation stage at Vietsovpetro's fields.

- Point 2: The viscosity of the oil and water mixture at Vietsovpetro's fields depends on the water content and temperature according to the following equation:

$$\mu = \mu_o * f(W,T) = \mu_o*((\alpha_0 + \alpha_1 \cdot T + \alpha_2 \cdot T^2) \cdot W_2 + (\beta_0 + \beta_1 \cdot T + \beta_2 \cdot T^2) \cdot W + (\gamma_0 + \gamma_1 \cdot T + \gamma_2 \cdot T^2))$$

- Point 3: Efficiently utilizing available energy sources (geothermal of oil wells and energy from gas turbine exhaust) to treat Bach Ho crude oil.

9. Literature review: The thesis is built upon the research results of the author presented in the specialized book (co-author) and in articles published in domestic and international petroleum engieering journals...

10.Thesis contents: The structure of the thesis including an introduction, 3 chapters, conclusion-recommendation and references. The entire contents of the thesis are presented in …. A4 pages, including …. tables, …… figures, ….. appendix

CHAPTER 1: OVERVIEW OF EXPLOITING, PROCESSING AND TRANSPORTING PARAFFIN-RICH OILS

1.1. Overview of exploiting, processing and transporting paraffin-rich oils

Summarizing research results of the thesis shows that oil exploited in Bach Ho, Rong and other connected fields of Vietsovpetro has the following physical and chemical properties:

a) Paraffin content (20-29% KL), freezing temperature (29-36 deg C) is high, 9-15 deg C higher than the lowest temperature of seawater near seabed area (22 deg C). Meanwhile, the temperature of paraffin crystallization in oil exploited in these fields fluctuates around 58-61 deg C;

b) The physical and chemical properties of crude oil in the fields are significantly different: Bach Ho oil has the highest paraffin content (average

26% KL), followed by the oil fields: Rong, Nam Rong-Doi Moi and Gau Trang (fluctuates between 23-24% KL). The paraffin content of Tho Trang crude oil (about 20% KL), is lower than that of other crude oil fields. The highest oil viscosity, was found in crude oil at Gau Trang and Nam Rong-Doi Moi fields;

c) The difference in physical and chemical properties is not only exist among different oil fields, but also between wells of different strata in the same oil field. Lower Miocene layer oils have different properties compared to those of Oligocene and basement layers. They have a much higher density, viscosity, resin and asphaltene content as well as much lower paraffin content.

The research shows that the properties of crude oil in Bach Ho, Rong and other connected fields have very complex properties, high paraffin deposition. Under conditions of low temperature and flow in the pipeline, it will create large deposition of paraffin, block the pipeline and cause the risk of interrupting operation. Therefore, the technology requirement to ensure uninterruptedly collecting, processing and transporting paraffin-rich oil by pipeline is necessary for Vietsovpetro.

1.2. Experience in exploiting and transporting paraffin-rich oil at foreign fields and Vietsovepetro's fields

1.2.1. Overview of the crude oil processing and transportation methods

At present, around the world, there are many methods to transport paraffin oil by pipeline. Based on the physical and chemical properties of the oil to be transported, the appropriate transport method and technology are chosen. Usually, the methods of treating crude oil for pipeline transportation include:

- Use low viscosity oil or solvent to mix with paraffin rich oil
- Heat treatment (heating the oil to a temperature higher than the temperature of paraffin crystallization)
- Treatment of oil with special chemicals to reduce the freezing temperature (PPD)
- Transporting oil with water (oil in water)
- Transporting oil saturated with gas (at high pressure)
- Insulation pipe coating.

1.2.2. Experience in transporting paraffin rich oil offshore around the world

a) Minas Oil Field (Indonesia)

Oil produced in Minas, Indonesia fields are oil with high viscosity and freezing temperature. Transported by the pipeline connecting offshore and onshore.

b) Bombay High Oil Field (India)

Oil produced has chemical and physical properties similar to those extracted in Bach Ho field in the continental shelf of Vietnam. To ensure safer transportation, pipes are insulated, placed underground and buried deep in the sea floor.

c) Uzen, Mangaslux oil fields (Kazashtan (former Soviet Union))

Paraffin rich oil is mix with hot water to transport along the pipelines

Thus, depending on the conditions of each field, each stage, different oil treatments and technological solutions can be applied in transporting paraffin rich oil by pipeline.

1.3. Difficulties and challenges due to the specific conditions of Vietsovpetro's fields in handling paraffin-rich oil transportation

- Challenges due to the nature of crude oil exploited in Vietsovpetro's fields;
- Paraffin deposition problem in the transport pipeline;
- Salt deposition in the oil production, treatment and transport system and the problem of stable water oil emulsion;
- The characteristics of the pipeline used to transport oil exploited in the fields of Bach Ho, Rong and connected fields;
- The problem of pressure impulses in the oil production, treatment and transportation system;
- The thesis focuses on solving the first two challenges mentioned.

1.4. The technological solutions for transporting high-paraffin oil that have been applied at Vietsovpetro

- Heating the oil to a temperature higher than that of paraffin crystallization;
- Using chemical that lowering freezing temparature (PPD).
- Transporting oil saturated with gas (oil transportation system connected to separator)
- Mixing paraffin rich oil with condensate produced.

Conclusion chapter 1.

The study results show that:

- The system of producing, processing and transporting oil in Bach Ho and Rong fields is unique, was formed and developed in the period from 1985 to 2017. There are pipes without insulation coating for transporting paraffin rich oil.
- Research on physical and chemical properties of crude oil shows that: oil in Vietsovpetro's fields contains high paraffin content, freezing temperature and viscosity. To transport this oil, it is necessary to apply treatment to decrease the freezing temperature to the point that less than the ambient temperature of the pipeline in order to be transported to the storage place;
- There are many methods of treating oil for transportation by pipeline. However, each method is only suitable for a type of oil, and different methods can be applied in different stages
- At Vietsovpetro, many different solutions had been applied for each period and specific conditions. One of the solutions being applied effectively is the thermal-chemical solution;
- Bach Ho and Rong fields have passed the peak production period. In addition, the influence of political and economic conditions, oil prices plummeted, so optimizing the thermalization solution in accordance with the available production system at this stage is an urgent problem for Vietsovpetro

CHAPTER 2: STUDY ON PARAFFIN DEPOSITION, RHEOLOGY AND SOLUTIONS FOR TREATING HIGH-PARAFFIN OIL IN BACH HO AND RONG FIELDS FOR PIPELINE TRANSPORTATION

2.1. Research on paraffin deposition, deposition mechanism and treatment solutions

2.1.1. Deposition of paraffin in oil and gas production

During the production process, the oil flows up, along the well, to the surface system. This process is associated with pressure and temperature reduction, separating the gas phase from the mixture of fluids. When processing in surface equipment, the following processes will occur: separation of light fractions, associated water, (reduced temperature due to exothermal proccess, changes in pressure). During the process of pumping oil through the pipes to the storage place, the fluid temperature continues to decrease. The imbalance in thermodynamics and phase equilibrium in the above processes will disturb the composition state of the substances in the mixture, such as: the solubility of the large molecular paraffin. When the temperature drops to a certain point, the paraffin begins to crystallize.

2.1.2. Mechanism of paraffin deposition

There are 3 mechanisms that promote paraffin deposition, namely, molecular diffusion, relative shear movement and thermal (braono) motion. Braono movement occurred during deposition but was not clear when compared with other mechanisms. Therefore, petroleum engineers are interested in only two mechanisms: molecular diffusion and dispersion due to the relative shear motion.

2.2. Study on the rheology of crude oil in Vietsovpetro's fields

2.2.1 Bingham viscous fluid model

Oil exploited in Bach Ho and Rong fields are paraffin rich oils with high viscosity and freezing temperature, distinguished by their physical and chemical properties. At high temperatures, they are Newton fluids, whose viscosity is independent of the rate of strain. As the temperature drops, paraffin crystallization begins, the oil gradually exhibits non-Newtonian properties, which cannot be described simply by viscosity but also by shear stress. That is, the effect of stress is required to break the paraffin crystal structure in the oil. Mostly, especially in the basement objects of Vietsovpetro's fields, the most suitable flow pattern is the viscous-flexible fluid model (Bingham model). The rheological properties of high-paraffin oil and high viscosity in Bach Ho and Rong fields were determined by specialized equipment Rotovisco RV-20. Studies show that, in the Newtonian state, the viscosity of the oil depends only on temperature and shear stress and can be expressed as a function in the following form:

$$\tau = \mu_d * \gamma$$

When the temperature drops below the critical temperature Tc, the oil exhibits non-Newtonian properties. The flow curve in this temperature range is similar to that of the Bingham viscous fluid model.

$$\tau = \tau_\circ + \mu_d * \gamma$$

In the non-Newtonian state, the paraffin rich oil is catalytic, which is characteristic of the colloidal system, manifested by a re-optimized arrangement of its structure over time. The strength of the structure increases and the equilibrium limit is reached. During structural formation, the static shear stress can be increased many times. Therefore, in a stationary state, the oil can solidify in the pipeline. The time required to reach the limit for solid structure formation is highly dependent on the chemical and physical properties of the oil and on external conditions. The special feature of the oil in the non-Newtonian state is the need for an initial shear stress τ_(°)to break the original structure and bring the oil into a flowing (active) state.

2.2.2. Bulkley-Herschel non-linear viscous fluid model

The studies on the rheology of many paraffin oils in the Bach Ho basement layer, done before (1986-1997), have determined that: the flow regime of Bach Ho and Rong oil is described by the Bingham liquid model. However, some recent results show that: the oil exploited in the north of Bach Ho field in the Oligocene layers has the difference in the flow curve of Oligocene oil in the northern area of Bach Ho field. The result helps determine the rheology of Oligocene layer oil at Bach Ho field when the temperature is lower than 37^0C which is a non-linear viscosity model named Bulkley-Herschel model. It is presented as follows:

$$\tau = \tau_\circ + K\left(\frac{dv}{dr}\right)^n;\ \ \tau_\circ = f_1(T)\ ;\ K = \ f_2(T);\ \ n = f_3(T);$$

2.3. Research results of Bach Ho & Rong oil rheology at the end of exploitation stage

2.3.1 Mathematical models for rheology of water-oil emulsions

In Vietnam, the rheology of crude oil has been studied a lot, especially crude oil of Bach Ho and Rong fields. However, the previous results published are mostly in single-phase form and research results of multiphase rheology (for oil-water mixture, oil-water-gas mixture) is very limited. In fact, in the process of exploiting and transporting products, it is often done for the mixture of oil-gas, oil-gas water or water oil. The composition and properties of these fluids are different.

In the world, there are many studies on the effect of watercut on rheological properties of crude oil. Many studies have identified this relationship. For example, for emulsions with the rate of phase scattering W <0.05, the viscosity of water-oil emulsion μnt can be determined with relatively high accuracy by Einstein's formula:

$$\mu_{nt} = \mu_d (1 + 2,5W),$$

In addition, scientists also gave other calculation formulas such as, Vand gave the theoretical formula to determine the viscosity of a water-oil emulsion and then it was experimentally calibrated:

$$\mu_{nt} = \mu_d (1+ 2,5W + 7,17W^2 + 16,2 W^3)$$

V.I. Kotanov has conducted research on turbulent flow in pipes of "water - diesel" emulsion, "water - kerosene", "water - gasoline", "water - insulating oil" and confirmed that technical calculations (with tolerance within ± 10%) by the above formula can determine the viscosity of emulsion with the rate of phase scattering W <0.4.

The Benskovski V. G. equation for an emulsion of a paraffin oil with a water (scattering phase) ratio W <0.35 has the following form:

$$\mu_{nt} = \mu_d (1 + 7,1W)$$

To determine the viscosity of an oil emulsion, any of the following equation can be used:

- Richardson E.G Equation:

$$\mu_{nt} = \mu_d e^{kw}, \text{ trong đó } k = 2,5$$

- Brinsman Equation::

$$\mu_{nt} = \mu_d (1 - W)^{-k}, \text{ trong đó } к = 2,5$$

- Teilor Equation:

$$\mu_{nt} = \mu_d (1+25W\frac{\mu_w+0.4\mu_d}{\mu_w+\mu_d})$$

with μ_w is viscous of phase scattering.

- Medvedev V. F. Equation:

$$\mu_{nt} = \mu_d (1 + 0,25W + 4W^2)$$

- E. Hatschek Equation:

$$\mu_{nt} = \mu_d (1 + \sqrt[3]{w})^{-1}$$

- Sibri Equation:

$$\mu_{nt} = \mu_d (1 + \sqrt[3]{1,3W})^{-1}$$

Analysis of the emulsion viscosity determination shows that there was no formula used to determine this value in general. In fact, for each specific case it is necessary to find the most compatible formula. The above formulas do not take into account the change of rheology of emulsion compared to temperature. This is especially important for non-Newtonian oils where temperature greatly affects the rheology of the crude oil as well as the emulsion when the crude oil is in scattering medium.

2.3.2. The study results on the rheology of the Bach Ho and Rong petroleum emulsion

In Vietnam, on the basis of crude oil properties of Bach Ho, some research results were given as follow:

a. In the case the temperature changes between 26°C < T < 34°C and the water saturation is within 0 < w < 68%:

$$\mu_{nt} = K_{\mu}\mu_{o26}[1 + 1,2 \times 10^{-2}K\mu^{-0.5}W - 2,5 \times 10^{-4}K\mu^{-0.8}W^{2}+6,67 \times 10^{-6} K\mu^{-0.85}W^{3}]$$

b. In the case the temperature changes between 37°C < T < 55°C and the water saturation is within 0 < w < 68%:

$$\mu e = K_{\mu}\mu_{037}[1 + 1,3 \times 10^{-2}K\mu^{-0.7}W - 9,0 \times 10^{-4}K\mu^{0,2}W^{2}+6,67 \times 10^{-6} K\mu^{1.5}W^{3}]$$

For the case where the temperature is in the range 34°C < T < 37°C, when the emulsion changes from Newton liquid to non-Newtonian liquid, the effective viscosity can be determined based on the extrapolation method.

2.4 Results of research on rheology of Ca Tam oil and water emulsion

Initial research content of the thesis proposes oils from Bach Ho and Rong. However, during the implementation of the thesis, the author realized that the exploited products in these fields were treated with PPD chemicals for transport and demulsifier for water separation. The water content in these field is currently too large (50-70% V). In addition, to increase and maintain the fields output, many types of chemicals are often applied to wells. For the above reasons, the use of the Rong or Bach Ho oil samples will significantly affect the research criteria and results of the thesis. After studying the physical-chemical properties of Ca Tam oil, it was found that the physical and chemical properties of the oil produced in Ca Tam field were similar to that of the oil exploited in Rong field. Products at Ca Tam field, Block 09-3 / 12, after being exploited, are transported to Rong field by separate pipeline for general treatment. Therefore, in order to maintain the reality of the product and the accuracy of the research results, the author used Ca Tam oil sample to replace Bach Ho / Rong oil for conducting research.

In the current period, the water content in oil produced in Ca Tam field is low. The creation of artificial emulsions for Ca Tam oil will be done in the laboratory. The water oil emulsion under the laboratory conditions is almost identical to the actual oil emulsion, model 3 can be applied.

The rheological properties of the Ca Tam oil emulsion are determined as follows: Pour a water oil emulsion sample from a glass flask into the beaker. The probe of the MV Viscometer Rotovisco VT-550 system is set up at the initial temperature. The emulsion was kept stable for a period of 15 minutes, then the sample was cooled by a refrigerating device at a rate of 0.15°C/min. Kinematic viscosity is determined at the strain rate of $20s^1$, performed from the initial temperature to a temperature of 22°C (equivalent to the lowest temperature of seabed where the transport pipeline is installed).

2.4.4. . Mathematical models of crude oil rheology of Ca Tam oilfield

The equation describing the rheology of Ca Tam crude oil is written in the form of a mathematical equation, which is an equation depending on the water saturation variables W% and the fluid temperature T°C:

$$\mu = \mu_o f(W, T)$$

Mathematical models are constructed based on a combination of experimental equations. From there, the results that are closest to those obtained in the laboratory are selected. Selective equations are used to simulate the movement of oil and gas mixtures with a given external impact condition (water saturation, temperature). Firstly, we define the underlying equation for when the temperature is constant:

$$\mu = f(W)$$

The data to build the equation are taken from experimental results and the data in the laboratory. The water saturation variable dependent equation in crude oil, on viscosity has a general form of the quadratic equation - dependent curve (with the minimal error). From the actual results obtained in the laboratory it is possible to determine the coefficients (a_i) :

$$\mu = a_0W^2 + a_1W + a_2$$

The coefficients of the equation can be determined by constructing the matrix of experimental points closest to the simulation curve. The next step is to make table 1 to show the matrix of points to build the dependent curve of the equation at the survey temperatures of 31°C, 35°C, 40°C, 45°C, 50°C, 55°C, 60°C.

On the basis of the data in Table 1, the equation μ = μo * f (W,) is considered for different temperature ranges and water saturation:

• ***Case 1:*** When the oil temperature fluctuates from 31ºC - 40ºC, the water saturation is less than 20% V:

Based on the experimental results, calibrating all equations by excel software to choose the appropriate equation with the smallest allowable error (quadratic equation).

The system of equations describes rheology as follows:

$$\left.\begin{aligned} \mu_{31oC} &= 0{,}0206\ W^2 + 0{,}1788\ W + 78{,}552\ ;\ R^2=0{,}999 \\ \mu_{35oC} &= 0{,}0278\ W^2 + 0{,}1569\ W + 71{,}151\ ;\ R^2=0{,}999 \\ \mu_{40oC} &= 0{,}0261\ W^2 + 0{,}3675\ W + 62{,}385\ ;\ R^2=0{,}999 \end{aligned}\right\} \quad (I)$$

whereas R^2– coefficient of determination

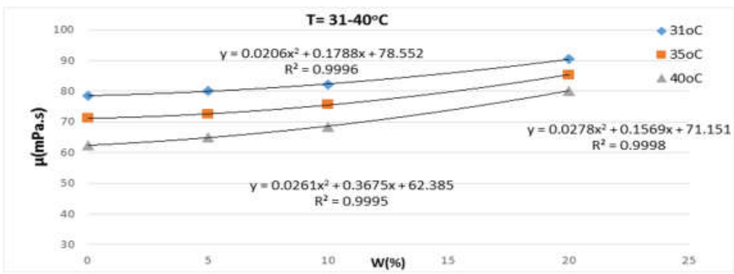

Figure 5 – Crude oil viscosity vs water saturation under temperatures of 31-40oC 31-40ºC

The measurement error of the tests performed in the laboratory as determined by the standard mean εtb, εtb shall not exceed 5% to ensure the accuracy and reliability of the results obtained.

The next step of the simulation is to compute the coefficients of the equation using data from the system of equations (I) according to the increasing temperature sequence as shown in Table 2.

Table 2 – Equation coefficients (I)

Equation	**TºC**	**Coefficients**		
		a0	**a1**	**a2**
μ = f(W)	31	0.0206	0.1788	78.552
	35	0.0278	0.1569	71.151
	40	0.0261	0.3675	62.385

Calculating the coefficients to get the quadratic equation depends on 03 variables: viscosity, water saturation and temperature:

$$\mu = \mu_o\, f(W, T) = \mu_o\, ((\alpha_0 + \alpha_1\, T+ \alpha_2\, T^2)\, W^2 + (\beta_0 + \beta_1\, T + \beta_2\, T^2)\, W + (\gamma_0 + \gamma_1\, T + \gamma_2\, T^2))$$

with αi, βi и γi (i = 0, 1, 2) – the coefficients are determined according to table 2, μ_o - the viscosity of scattering medium at T (31°C) (mPa*s), μ - emulsion viscosity at T(mPa*s), W – sample water saturation (%), T- test temperature (°C)

The correlation between viscosity, water saturation and temperature

$$\left.\begin{aligned} 0{,}0206 &= \alpha_0 + \alpha_1\, 31 + \alpha_2\, 31^2 \\ 0{,}0278 &= \alpha_0 + \alpha_1\, 35 + \alpha_2\, 35^2 \\ 0{,}0261 &= \alpha_0 + \alpha_1\, 40 + \alpha_2\, 40^2 \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} 0{,}1788 &= \beta_0 + \beta_1\, 31 + \beta_2\, 31^2 \\ 0{,}1569 &= \beta_0 + \beta_1\, 35 + \beta_2\, 35^2 \\ 0{,}3675 &= \beta_0 + \beta_1\, 40 + \beta_2\, 40^2 \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} 78{,}552 &= \gamma 0 + \gamma_1\, 31 + \gamma_2\, 31^2 \\ 71{,}151 &= \gamma 0 + \gamma_1\, 35 + \gamma_2\, 35^2 \\ 62{,}385 &= \gamma 0 + \gamma_1\, 40 + \gamma_2\, 40^2 \end{aligned}\right\} \quad (3)$$

Solving the system of equations (1-3), we have:

$$\alpha = -0{,}2931+ 0{,}0175\, T – 0{,}00024\, T^2 \quad (4)$$

$$\beta = 6{,}0863 – 0{,}545\, T + 0{,}0052\, T^2 \quad (5)$$

$$\gamma = 134{,}893 – 1{,}8807\, T + 134{,}893\, T^2 \quad (6)$$

To calibrate the experimental results, we have the coefficient Ω=1/μo = 1 / 78.5 = 0.0127. Combining equations (4-6), general equation describing rheological properties of Ca Tam crude oil with crude oil temperature fluctuating 31°C-40°C and water content less than 20% is as follows:

$$\mu = \mu_o\, f(W, T) = 0{,}0127\, \mu_o\, ((-0{,}2931+ 0{,}0175\, T – 0{,}00024\, T^2)\, W^2 + (6{,}0863 – 0{,}3545T+ 0{,}0052\, T^2)\, W + (134{,}893 – 1{,}8807\, T + 134{,}893\, T^2))$$

The maximum allowable error of the rheological equation above compared to the actual measurement is 5.4%.

• ***Case 2:*** When the crude oil temperature (31-40ºC), the water saturation is about 20-65% V:

General equation describing rheological properties of Ca Tam crude oil with crude oil temperature fluctuating from 31-40ºC and water saturation fluctuating 20-65% is as follows:

$$\mu = \mu_o\, f(W, T) = 0{,}011\, \mu_o\, ((1{,}3479 - 0{,}050\, T + 0{,}00065\, T^2)\, W^2 + (-78{,}760 - 3{,}313\, T - 0{,}044\, T^2)\, W + (1182{,}666 - 47{,}956\, T + 0{,}629\, T^2))$$

The maximum allowable error of the rheological equation above compared to the actual measurement is 6.8%.

• ***Case 3:*** When the crude oil temperature (45ºC -60ºC) and the water saturation is less than 20% V::

General equation describing rheological properties of Ca Tam crude oil with crude oil temperature fluctuating from 45-60oC and water saturation less than 20% as follows:

$$\mu = \mu_o\, f(W, T) = 0{,}038\, \mu_o\, ((0{,}4800 - 0{,}01695\, T + 0{,}00017\, T^2)\cdot W^2 + (-6{,}284 + 0{,}288\, T - 0{,}00314\, T^2)\, W + (64{,}674 - 1{,}1443\, T + 0{,}0061\, T^2))$$

The maximum allowable error of the rheological equation above compared to the actual measurement is 4.8%.

• ***Case 4:*** When the oil temperature (45ºC -60ºC) and the water saturation fluctuates between 20-65%:

General equation describing rheological properties of Ca Tam crude oil with crude oil temperature fluctuating between 45ºC -60ºC and water saturation fluctuating 20-65% V is as follows:

$$\mu = \mu o\, f(W, T) = 0{,}0177\, \mu_o\, ((0{,}4800 - 0{,}01695\, T + 0{,}00017\, T^2)\, W^2 + (-6{,}284 + 0{,}288\, T - 0{,}00314\, T^2)\, W + (64{,}674 - 1{,}1443\, T + 0{,}0061\, T^2))$$

The maximum allowable error of the rheological equation above compared to the actual measurement is 8.0%.

Summary of research results found that:

- Rheological equation of emulsion of Ca Tam field depends not only on the water saturation but also on the temperature of the mixture;

- From the test results and rheology equation, when the content in the mixture is less than 15% V, the effect of scattering phase on the rheology of the oil-water emulsion is not great. This effect increases gradually when the water content exceeds 20% V and gradually increases to the phase transition point;

- Based on experimental results and calculated rheology equations of Ca Tam crude oil at different water saturations and temperatures, it allows forecasts and is the basis for technical solutions designing before transporting crude oil of Ca Tam field into the complete production system.

2.5. The technological solutions for processing and transporting paraffin-rich oil that have been applied at Bach Ho field, Vietsovpetro

- Oil treatment by heating and using Crompic chemicals;
- Transporting oil - gas mixture simultaneously;
- Transportation of oil saturated with gas with a preliminary air separator;
- Heat treatment combined with chemical to reduce the freezing temperature to transport Rong oil to Bach Ho field;
- Transporting oil diluted with condensate

Conclusion chapter 2

Bach Ho and Rong crude oils are produced from different layers: Basement, Oligocene, Miocene and all of them have high levels of paraffin, high viscosity, which is a challenge for the prodcution and transportation by offshore pipeline:

- Depending on the temperature, oil of Vietsovpetro follows different rheological models:
- At temperatures $t^o > 37^oC$, it follows the Newton liquid rheology model;
- Temperature $t^o < 37^oC$, it follows the Bingham or Bulkley-Herschel model;
- The rheology studies of the two-phase mixture in the past and the current period show that the rheology of the water-oil mixture worsens when the proportion of water in the mixture increases. With the saturation less than 10% V, the effect of water on the rheology of the water-oil mixture is negligible. The viscosity of the water oil emulsion will gradually increase and reach the maximum value when the water saturation reaches 68% V, this is the phase transition point of the Bach Ho petroleum emulsion (water-in-oil emulsion to an oil-in-water emulsion);
- By analyzing and evaluating of Vietsovpetro's paraffin-rich oil treatment technology solutions over time, it is observed that the thermochemical solution is widely applied and is especially suitable for the final phase of exploitation of large fields and beginning phase of small marginal fields.

CHAPTER 3. RESEARCH TO IMPROVE THE EFFICIENCY OF PRAFFIN-RICH OIL TREATMENT WITH FOR PIPELINE TRANSPORTATION IN VIETSOVPETRO'S FIELDS AND CONNECTED FIELDS

3.1. Heat treatment solution for transportation of crude oil at Vietsovpetro's fields

- ***Effects of heat treatment on freezing temperatures of crude oil***

One of the methods of lowering the freezing point of crude oil is to heat the oil. The oil that is heated to a specified temperature will have an identified freezing temperature value. The freezing temperature of the oil depends on initial level of heat. The freezing temperature of crude oil is determined by ASTM D-97 method. For crude oil in Vietsovpetro's fields, the freezing temperature of oil depends on the level of heat. Table 3 shows the results of freezing temperature of oil corresponding to the heat level.

Table 3. Effects of temperatures on the freezing point of the White Tiger and Dragon crude oil

Oil heats to temperature	Freezing temperature, ºC	
	White Tiger	Dragon oil
50	32.5	26.5
60	31.5	26
70	27	25
80	26.5	19
90	25	17

- ***The effect of chemicals reducing freezing temperature (PPD) on the fluid rheology of Vietsovpetro's fields.***

Experience shows that the most effective method of reducing freezing temperature and viscosity of crude oil is to use freezing temperature reduction (PPD) chemicals. Reducing the viscosity and freezing temperature of crude oil will increase the mobility of oil at low temperatures. However, the most effective method is to reduce paraffin deposition during production and transportation by pipeline at low temperature conditions. Figure 6 below are some laboratory results on the effect of PPD on paraffin deposition in Dragon field after PPD treatment at a temperature of 65^{0}C.

3.2. Research on completing thermalization solutions in crude oil treatment under Vietsovpetro's specific conditions

At the final stage of production as of Vietsovpetro's field at present, the oil production rate decreases, the wellhead temperature only fluctuates around 28-50^{o}C. In order to reduce viscosity, freezing temperatures and limit paraffin deposition in pipeline, it is necessary to heat crude oil to a temperature not lower than 65^{0}C (about 5^{0}C above WAT temperature). As such, the cost will be enormous for the supply of heat to the oil.

With optimizing purposes, we have researched to take advantage of the available heat sources on offshore infrastructures at White Tiger and Dragon fields of Vietsovpetro. In this chapter, the author will carry out detailed research on these solutions:

- Take advantage of the energy source of emissions from turbine engines on offshore platform to heat the oil;
- Take advantage of the heat source of the oil well (geothermal) to treat the oil with PPD chemicals.

3.2.1 Research on heating oil using the energy source of emissions from turbine engines on central technological platform

Central Technological Platform No. 2 (CTP-2), receiving productions from fixed rigs (MSPs) and jack-up rigs (BK), is designed to separate gases and water before commercializing. Production then transported to FSO container ships for storage and export to customers. At the final stage of the production phase, in addition to the declining output, the wellhead temperature of products is relatively low, as in the case of White Tiger field. The oil temperature from rigs in Bach Ho field to CTP-2 is around 35-45^{o}C., the water content in the product is 50-70% V. Meanwhile, the temperature required for effective water separation in the electric field equipment system (EG) installed on the CTP must be at 60-65oC. As proposed in the "Bach Ho field development plan 2008 & 2013", for efficient water separation on CTP-2, it is necessary to install a heater system on the CTP-2 to heat the oil up to 60-65^{o}C.

Figure 7, is the principal diagram that takes advantage of the heat source from the gas turbine on the PPD-40000 to heat crude oil on the CTP-2.

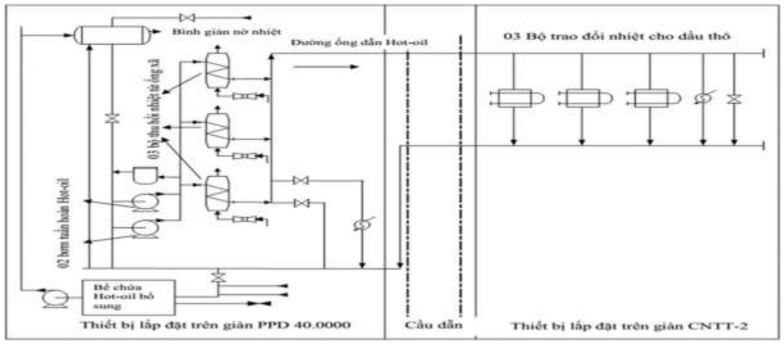

Figure 7. Heating system diagram for crude oil on CTP-2

The technological parameters when the heater system works on the CTP-2 are shown in the table below:

	Flow of oil and water	**Temperature input T-1**	**Temperature output T-1**		
	T/24h	^{O}C	Min	Max	TB
T-1-A	3500	40	52	96	66
T-1-B	3500	40	54	97	67
T-1-B	7000	40	51	95	66

The use of heat from the exhaust gas turbines on ppd-4000 has allowed the oil on CTP-2 to be heated up to 60-62°C, ensuring effective water separation on CTP-2 and securing the transportation line to Vietsovpetro's FSO tanker.

This solution, which has brought great economic efficiency for Vietsovpetro, is not required to invest and install any additional heater on CTP-2 in Bach Ho field.

3.2.2. Research on heating oil using geothermal energy from production wells

3.2.2.1. Geothermal gradient and determination of geothermal gradient at the Continental Shelf of Vietnam

The geothermal gradient of the well is the temperature that varies with the well depth for each 100m, symbol G, physical unit oC/100m.This gradient is determined by the bottom temperature of the well minus the surface temperature of 26-35°C (at the tropical zone)or 10-15°C (with temperate zone) and divided by the depth of the well.

The results of the study show that temperature gradients in some sedimentary basins on the Vietnamese continental shelf are presented in Table 5.

Table 5. The smallest, largest and average value of temperature gradient and thermal flow of sedimentary basins containing oil and gas on the continental shelf of Vietnam.

No.	Sedimentary basin	Geothermal gradien (°C/100m)		
		Min	Max	Average
1	Song Hong	2,93	4,24	3,59
2	Nam Con Son	2,6	4,15	3,59
3	Cuu Long	2,26	3,35	2,28

The average geothermal gradient on Earth is around 2.5-3°C/100m.Thus, in the continental shelf of Vietnam, the thermal gradient of Cuu Long basin is equivalent to the Earth's average geothermal gradient while the remaining basin are higher.

3.2.2.2. Geothermal gradient in the White Tiger and Dragon fields

The White Tiger and Dragon fields belongs to the Cuu Long Basin on the Continental Shelf of Vietnam with the sea depth at about 50 m. Vietsovpetro's White Tiger field has been produced since 1986. As the number of wells is increasing, temperature measurement in wells is carried out when conducting surveys to monitor and establish an database for research purposes. Based on the results obtained above, the author has summarized and studied further to determine the specific geothermal gradient for each object in the White Tiger and Dragon fields.

Thereby, the geothermal gradient characteristic curve will be determined based on the linear equation: **y=ax+b.**

Parameters a1, a2, a3, b1, b2, b3, which are the characteristic of each geothermal gradient of the objects in the White Tiger field, are determined as follows:

$$T_{Móng} = 0{,}0329 * H + 0.2736$$

$$T_{Oligoxen} = 0{,}0225 * H + 42{,}907$$

$$T_{Mioxen} = 0{,}0217 * H + 26{,}103$$

Where as: H- Absolute depth, m.

Note that the formulas mentioned above are only used for depth intervals within the research scope and are dynamic formulas. Depending on the time of analysis and the actual temperature, the above parameters will be adjusted for each object of the well. The results are shown in the following shapes:

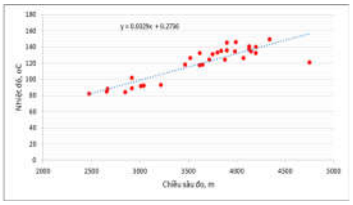

Figure 8. The dependence of temperature on the depth of the basement object

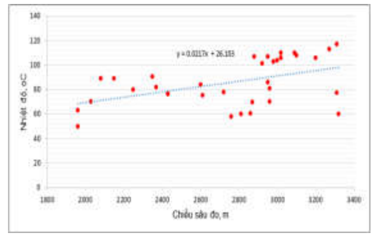

Figure 9. Temperature dependence on the depth of the Miocene object

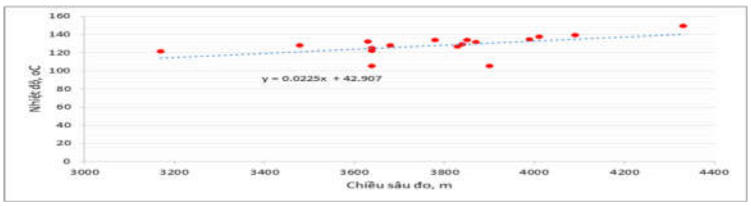

Figure 10. Temperature dependence on the depth of the Oligocene object

3.2.2.3. Method of taking advantage of geothermal energy in heat treatment solution to transport paraffin-rich crude oil by pipeline in Vietsovpetro

Crude oil produced on the jack-up rigs (BK) of the White Tiger and Dragon field is transported in the form of a mixture of oil and gas by pipeline to fixed rigs (MSPs) or central technological platform (CTP) for processing. The oils produced on these rigs are all paraffin-rich oils, with high viscosity and freezing temperatures. Therefore, to ensure the transportation of this oil by pipeline from BK rigs to MSP or CTP, crude oil needs to be treated with PPD chemicals. The results of the rheology study of crude oil produced in the White Tiger and Dragon fields shows that in order to treat paraffin-rich oil effectively, crude oil must have a temperature higher than 65ºC (T≥65ºC) (higher than the paraffin crystallization temperature of about 5-10ºC). Figure 11 presents the oil treatment efficiency of Vietsovpetro field depending on the temperature.

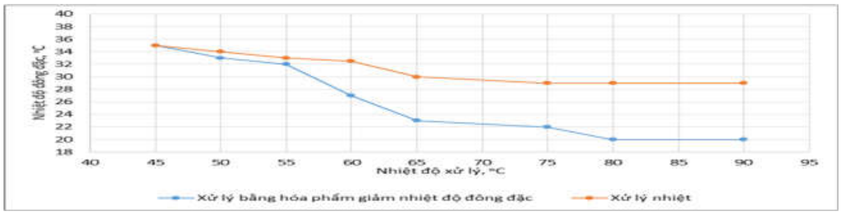

Figure 11. Correlation between oil treatment temperature and freezing temperature of oil achieved after thermal treatment

Thus, the efficiency of oil treatment with chemicals reduces the freezing temperature only achieved at the oil temperature T≥ 65°C. Therefore, the design of the installation of chemical pipelines into the well and the location of the valve at a depth of T≥65°C temperature is essential. The determination of the positioning of the valve is carried out based on the temperature gradient characteristic of the field.

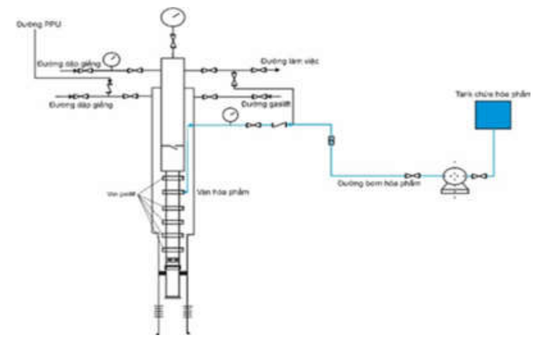

Figure 12. Chemical pump pipe installation principal diagram

- **Determination of PPD chemical pump valve installation depth**

Currently, most of the wells produced in Vietsovpetro are assisted with gaslift system, so the problem of transporting more paraffin-rich oil is even more difficult due to the decrease in the temperature of the mixture of the oil flow and gaslift flow. Therefore, the treatment of oil in the well before the well product enters the collection pipeline will improve the efficiency of oil treatment for transportation by pipeline.

Therefore, the location of the installation of the pump chemical valve should be considered with all of the above factors. On the basis of the results obtained on the geothermal gradient for each specific production object, the product temperature in some specific wells is the input of the software that accurately determines the location of the installation of the chemical valve, where the temperature of T≥65 °C. Specific applications for determining the location of the installation of the valve put the chemical into the well are as follows:

Well A: belongs to the White Tiger field, expected bottom depth of 2926m, the production interval is: 2819-2845m, (Lower Miocene). From the results of analysis of oil samples obtained during exploration phase shows that the oil temperature at the surface is low (29-45°C). for the treatment of oil with chemicals, it is necessary to install pipelines and chemical valves for this well. The positioning of the valve is based on the temperature gradient of the flow and the interval parameters, PVT, well deviation, gas injection mandrel depth and gaslift flowrate as an input.

This software is used to simulate fluids in steady-state flow with the aim of modeling the flow of multiple phases in the "formation- well" system and in the oil and gas producing, processing and transportation system. Modeling well designs and well equipment from simple to complex, designing artificial lift equipment, such as gaslift or electric submersible pumps, optimizing gaslift systems or electric submersible pumps to improve production output, minimizing the amount of gaslift or energy required for electric submersible pumps to reduce costs to a minimum. The temperature gradient calculation is a process in the design and optimization of gaslift system and electric submersible pump.

After entering all the necessary parameters for the construction of well A model, we continue to analyze the temperature according to the depth of the well, with the flow of the well expected to be 95 m^3/day. The results are shown in Figure 13.

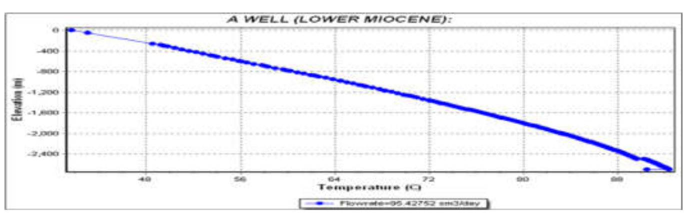

Figure 13. Gradient well temperature A with Q=95 m^3/day

Thus, the depth of installation of the chemical pump valve to inject PPD chemicals into the oil flow of the well will be effective at the depth of the well not less than 1005m (> =1005m).

Well B: in the central area of the Dragon field, expected bottom depth of 2303 m, the production interval is 2200-2245m, from the lower Miocene object. The results of analysis of the crude oil sample of the well show that the oil has a high paraffin content, the oil temperature at the surface is low, about 30-44°C. It is necessary to install a chemical valve for the treatment of oil with PPD chemicals. The result is shown in Figure 14.

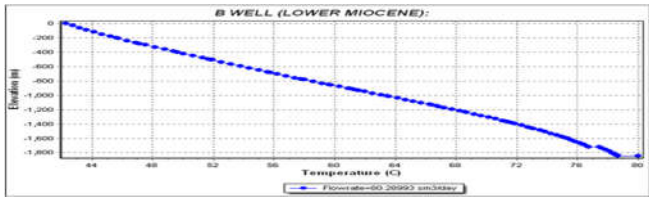

Figure 14. Gradient well temperature B with Q=80m3/day

Thus, the depth of installation of chemical valves for pumping PPD chemicals for well B must not be less than 1077m (>=1077m).

Conclusion chapter 3

- As a result of the study, there is no common solution for treating paraffin-rich oil for all fields or for individual rigs at every production stage. Oil treatment solutions for oil production and transportation are selected on a case-by-case scenario and depend on the characteristic of that area;
- The temperature for oil treatment is only effective when the oil temperature is not lower than 65°C and the optimal result can be achieved at oil temperature of 80-90°C;
- Using the heat source available on offshore infrastructure in Bach Ho field to heat up paraffin-rich oil in Block 09-1 is an effective and economical solution in the current conditions of Vietsovpetro;
- As a result of the study, dynamic relationships (formulas for calculation) of geothermal gradients have been identified for producing object, including the Miocene, Oligocene and Basement layers in the field in Block 09-1 of Vietsovpetro.
- The determination of the geothermal gradient of the product layers of different wells allows accurately determining temperature along the wells. Thus, the location of ppd chemical pump valves can be accurately determined, improving the efficiency of oil treatment, especially with oils being treated with chemical that have low wellhead temperature and producing with gaslift system.

GENERAL CONCLUSION

- Bach Ho and Rong crude oil is the type of crude oil with high paraffin content, viscosity and freezing temperature, which is a big challenge in exploitation and pipeline transport, especially in the period of declining capacity, low rate and temperature of oil;
- The water content in the oil increases, the rheology of the oil is getting worse. However, when the water content in the oil exceeds 68%V, the viscosity of the oil decreases. Thus, the phase transition point of water-in-oil emulsion to oil-in-water of Bach Ho crude oil is 68%V;
- On the basis of the research, for the first time the author gives the formula for determining the viscosity depending on the temperature of the fluid, exploited in the fields of Bach Ho, Rong and Ca Tam, which is the basis to provide the parameters inputs for the design and improvement of the technology system for product collection, processing and transport between the platform/ between fields in block 09-1 of Vietsovpetro;
- The research results show that the effective effect of PDD when processing crude oil at Vietsovpetro's fields is only in the condition, the oil temperature is not less than 65°C, and optimal results are obtained when the oil temperature reaches 80-90°C;
- Using available thermal energy on the platforms in Bach Ho field to heat oil to a temperature not lower than 65°C and utilizing the geothermal of the oil well to treat oil by PPD chemical is an effective solution and effective in the current Vietsovpetro's conditions;
- The results of the study have allowed to establish dynamic relationships (formulas to calculate) of geothermal gradients for the reservoirs, including the Miocene, Oligocene and Basement in Vietsovpetro's fields at block 09-1, as the basis for calculation and determination of the depth of oil wells, where the temperature is not lower than 65C for the design, installation of pipes into wells and determination of the installation location of chemical valves;
- The thesis's research results not only serve the design of new wells that need to use valve to pump chemicals into wells in Bach Ho and Rong field, but also can be applied to other fields which have the similar conditions of PVN.

LIST OF ARTICLES PUBLISHED BY THE AUTHOR:

1. Phan Đuc Tuan and others (2015), "The challenge and solution to transport oil with high paraffin condition by uninsulated pipeline from RP-1 to RP-3, Dragon Field" - Journal of Science & Technology, Vietnam, May 2015, 42-45 pag.
2. Phan Đuc Tuan and others "Physical and chemical properties of paraffin-rich oil exploited in the fields of Vietsovpetro, Journal of Mining Science and Technology – Geology, number 54, 04-2016 (Celebrating the 50th anniversary of the Department of Drilling - Exploitation), pp. 29-34;
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5. Phan Đuc Tuan and others "Application of geothermal gradients in chemical heat treatment to transport paraffin rich oil in Bach Ho and Rong fields at Cuu Long's basin", Petroleum Magazine, number 5/2018, pp. 29-34.
6. Phan Đuc Tuan and others (2016), "Some experiences in transporting paraffin rich oil in Vietsovpetro's and connected fields", Scientific report at the Scientific Conference to commemorate the 35th anniversary of the establishment of Vietsovpetro and the 30 years of the first ton of oil exploitation, Volume II, pp. 68-77.
7. Phan Đuc Tuan and others "Vietsovpetro: Develop technological solutions for treating and transporting paraffin-rich oil", Journal of Science and Technology of Vietnam, number 04/2015, pp. 28-31;
8. Phan Đuc Tuan and others (2017), "Study on the rheological properties of crude oil in Bach Ho and Rong fields for transport by offshore underground pipeline", Petroleum Magazine, number 01/2017, pp. 24-32;
9. Phan Đuc Tuan and others, Research utilizing heat from exhaust system of gas turbines generating on PPD-40,000 platform to heat crude oil on CNTT-2, Bach Ho field, Journal of Mining Science and Technology – Geology, number 60, pp. 65 – 70.
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11. Phan Đuc Tuan and others, "Study of optimization of high paraffinic crude oil transportation through uninsulated pipeline RP-1 → UBN-3". 2nd Conference on Integrated Petroleum Engineering, Hanoi, October 19th 2017, pp. 217-225;
12. Phan Đuc Tuan and others, "Experience of assessment on oil&gas transportation pipeline by using simulation tools at joint venture Vietsovpetro". 2nd International Conference on Integrated Petroleum Engineering, Hanoi, October 19th 2017, pp. 211-216.