普通高等教育"十一五"国家级规划教材

Fundamentals of Petrophysics

油层物理学

（英文版）

杨胜来　编著

石油工业出版社
Petroleum Industry Press

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内 容 提 要

本书是杨胜来、魏俊之主编的《油层物理学》的英文版。内容涵盖油气藏开发所涉及的基本物理现象、物理过程及物理量之间的关系。全书包括储层流体的物化性质，储层岩石的物理特性和储层中多相流体的渗流机理三大部分。

本书可作为石油工程及相关专业本科生的双语教材，也可供研究生及从事石油地质、采油工程、油藏工程的工程技术人员参考。

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Preface

This book presents fundamental physical and physicochemical knowledge involved in oil & gas development engineering, such as physical and chemical phenomenon, physical process. It is arranged to provide knowledge on properties of porous rock, properties of reservoir fluids (gases, hydrocarbon liquids, and aqueous solutions), and the mechanism of multiphase fluid flow in porous medium. The book also brings together the application of the above theories and knowledge.

This textbook is written to serve the undergraduate teaching of the Petroleum Engineering Major. It focuses on the introduction of basic conceptions, terms, definitions, and theories, placing more emphasis on the width of knowledge rather than the depth. What should be learned through the course includes: the definitions of some essential physical parameters, the physical process, important physical phenomena, influencing factors and engineering applications. In addition, the measuring methods and experimental procedures for the key parameters are also offered.

Through the study of this book, good foundation of knowledge-frame about Petroleum Engineering should be established for student, which is benefit to both their further study and their work in the future when they are engaged in job.

The book is originally arranged to match a 48-class-hour course, but flexibility is permitted during teaching and studying process.

The editing work of this book began from 2002. In 2004, it is translated directly from the textbooks Petrophysics (Yang, 2004) published by the Petroleum Industry Press, Beijing, China, and It was used in teaching in China University of Petroleum, Beijing. It is Mr. Dong Hua, Lü Wenfeng, Li Baoquan, Yang Sisong, Guo Xiudong, Sheng Zhichao, Sun Xiaojuan, Sun Rong, Hang Dazhen, Wu ming, who made contribution during the translation and compiling.

In 2008, Ms. Ma Kai helped to retranslate and recompile the textbook again. In 2010, Ms. Li Min and Mr. Cao Jie helped to read the whole book word by word and made corrections.

I would like to express their sincere thanks and appreciation to all peoples who have helped in the preparation of this book and who have given any helps in the few years in any way.

Due to the limitations of my knowledge and ability, this book may contain mistakes, wrong sentences and so on. Therefore, it is welcomed for the interested readers to make a correction and let me known if any mistake is found.

Yang Shenglai
In Cangping Campus, Beijing
China University of Petroleum

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Section Ⅲ Mechanics of Multi-Phase Flow in Reservoir Rocks

Introduction

1. Why to Exploit Oil & Gas

Energy is the power to drive forwards the industrialization and modernization of the society. The development and utilization of energy governs the competitive strength and comprehensive national power of a country.

Oil & Gas is an important kind of energy, high-quality material for chemical industry, and an important warfare material. Because it is important to both the energy safety and national defense of a country, great attentions have been paid to petroleum industry and oil & gas trade by all of the countries. It is hard to imagine what the society would be without the oil and gas today. It can be say that petroleum plays an important and indispensable role in the economic development of the world.

In the past 60 years since the birth of People's Republic of China, our petroleum industry has growth rapidly. The annual oil production was only 89,000 tons in year 1949. The annual oil production increase up to 170 million tons in 2007, and ranks within the top 4 countries in the world. On the other hand, the consumption of oil and gas also increase greatly with the society and economy development in our country. Since 1997 China had become one of the bigest petroleum consuming countries in the world.

To meet increasing demands for oil & gas, and maintain steadily growth in the national economy, the following policy should be taken:

(1) Explore and discover new oil & gas fields to enlarge the figure of petroleum reserves;

(2) Adopt advanced technology to develop the oil & gas reservoirs effectively;

(3) Apply EOR method to improve the oil & gas recovery and to increase the production rate in the developing reservoirs;

(4) Develop energy-saving techniques, or find alternative energy and new energy, to reduce the amount of consumption for gas & oil;

(5) Cooperate internationally to engage in the development of world petroleum resources.

For every student who will work in the petroleum industry, related knowledge and techniques are required to study and hold reliably, in order to take on the above work successfully.

2. What is Petrophysics

Petrophysics is a science about the physical property and physic-chemical phenomena involved in an oil & gas reservoirs and during the exploiting of an oil & gas reservoirs. It primarily includes 3 aspects:

(1) The physical properties of the reservoir fluids, including physical properties of oil, water

and gas at high-pressure and high-temperature, and the law that governs their phase-changing.

(2) The physical properties of the reservoir rocks, including porosity, permeability, saturation and sensibility of the formation rocks.

(3) The physical properties of multi-phase fluids in porous media and their seepage mechanisms.

A petroleum reservoir is geological structure which consisted of formation rock, which is a porous medium, and the oil & gas contained in the porous medium.

The reservoir, which is the objectives we study, is buried thousands of meters below the earth-surface, so the reservoir fluids are under states of high-pressure and high-temperature. At this state, the crude oil dissolves large volume of gas, therefore the physical properties of the underground reservoir fluids is vastly different from those of the subaerial ones.

This textbook is aimed to introduce the fundamental physical properties of the reservoir fluids and rocks, including terms, concepts and related knowledge, to help students to build foundations for their professional studying in the future.

3. History of the Petrophysics

Petrophysics is a science branch with history about 80 years. In the 1930s, some oil field engineers in America and Russian noticed the influence of the reservoir fluids on the production rate of oil wells, and then did some preliminary test and measurement on the fluid-property. During the 1930s, a monograph about reservoir fluids was compiled in Russian. In 1949, M. Mosket, an American, wrote a book named 'Physical Principles of Oil Production', in which the related research and practical information present in the first half of the twentieth century were collected and gathered. It illustrated the reservoir fluids information from a physics perspective and guided oil field development technically for various drive-typed reservoirs. In 1956, Ф. И. Котяхов, Russian, wrote a book named "Fundamental of Petrophysics". This was the first book especially for the Petrophysics and it established the base for this subject.

In China, professional team in researching and teaching on Petrophysics was setup during 1950s. The first university specialized on petroleum in China, Beijing Petroleum College, was founded in 1953. In BPC, Russian expert Ш. К. Гиматудинов was invited to teach the course Petrophysics, and postgraduates researching on Petrophysics were firstly trained.

From 1950s and on, with the discovery and development of large oil fields, such as Daqing oil field, Liaohe oil field, Dagang oil field, etc, the science on Petrophysics in China was vigorously promoted. Research institutes and laboratories were established in every oil field, as well in the capital city, Beijing. A large number of research on the Petrophysical and EOR study was made and achievements had yielded.

During the 1960s, several books that recorded the research achievements in China were published in succession, and large numbers of articles and papers was published on magazines and journals.

Nowadays, the science of Petrophysics has already become an indispensable part of the knowledge system in the development of oil fields, and it is sure that it will play more important roles in the coming days, to conquer more complicated problems we will face during the oil field development.

In the world, some monographs were published in the 1970s. The physical properties of carbonate reservoirs were systematically illustrated in these books from an exploiting perspective. In those books, fractured reservoirs were also studied for its deposits, forming mechanisms and reserve calculation, etc.

In 1977, two books both written by Russians were published. The mechanism of the reservoir-oil's seepage in the formation was probed from a physic-chemical standpoint. The books stressed that only by strengthening the study on the physic-chemical mechanisms of the formations could the recovery ratio are enhanced.

At the end of the 20th century, the researches were focused on the following study, such as carbonate formations, clasolites, induced porosity, the non-Newtonianism of the reservoir fluids, and the application of the phase state equations. At the same time, the modern experimental and measuring techniques and the application of computing technology had also made new progress, too.

Up to now, the Petrophysics science has been developed preliminarily. A comparatively theory integrated system is framed. And the experimental and measuring techniques are also standardized, for example, standards for conventional core analysis, special core analysis, EOR experiments, flow test for the formation sensibility, and physical analysis of the reservoir fluids have already developed.

However, it should be noted that, due to the heterogeneity of the reservoir rocks and fluids and the complexity of some physical processes in oil formations, lack of mature cognition for some phenomena still exists here and there. As research progressing, the science of Petrophysics will certainly continue to develop.

Looking forward to the 21st century and further, the science of Petrophysics will continues to develop and step onto a new stage in both breadth and depth. Its development will have the following characteristics:

(1) Synthesis: By the infiltration and mutual coordination with other near disciplines, new borderline theories may be formed.

(2) Innovation: New theories may have to be applied to solve new problems.

(3) Practicality: Developing process may be simulated truly and really at reservoir conditions by using new experiment technology.

4. The Aim and Learning Methods for Petrophysics

Petrophysics is a core course for students majored in Petroleum Engineering, or Oil Field Chemistry and Petroleum Geology. It is the aim of this course for students to have a firm grasp of the fundamental and professional knowledge and skills about Petroleum Engineering.

As a science branch, Petrophysics is based upon experiments, so the both theories and practice are important. Therefore, students should pay enough attention on the laboratory experiment and finish some exercise as home work involved in this book.

The SI unit system is adopted in this book, while some English engineering units are also briefly introduced. For example, when citing some particular equations like Darcy's Law, the original Darcy units are reserved. It's necessary for the readers to master the unit system that are used in concerned equations.

Section Ⅰ Physico-chemical Properties of Reservoir Fluids

Introduction

The crude oil, gas and water which reserved in oil or gas reservoirs are called reservoir fluids. Buried thousands of meters below the land-surface, the reservoir fluids in primitive underground state are subjected to an environment of high-pressure and high-temperature. High-pressure enables the crude oil dissolve large volume of gas, so the physical properties of the underground reservoir fluids are vastly different from those of the subaerial ones.

Along with the movement of the reservoir fluids from the formations to the wellbores and then to the oil tank on surface, their pressure (p), temperature (T) and volume will be continuously changing, i. e. the pressure and temperature decreases. As p and T changes, some other phenomena occur such as degasification, shrinkage of crude oil, expansion of gas, and wax precipitation. For these changes do have some effect on the oil & gas production rate. So, it is necessary to study the phenomena and laws to determine and optimize oil & gas production accurately.

At the stages of exploration of an oil field, the fluid physical properties are very useful to predict and determine the reservoir type, to ascertain the existence of gas-cap and to determine whether the gas will condensate in the formation or not, etc. Above work require a great deal of deep and thorough knowledge about the fluid physiochemical properties as well as the laws of phase-changing that governing the process.

During reservoir development, the static and dynamic changes of the fluid parameters are indispensable to the accomplishment of the the production management. The fluid parameters include the fluid volume factor, solubility coefficient, compression coefficient, viscosity of oil, and so on. These parameters are of great significance to gain efficient and economical development of the oil fields.

Chapter 1 Chemical Composition and Properties of Reservoir Fluids

Petroleum is a mixture of naturally occurring hydrocarbons, which may exist in solid, liquid or gaseous states depending upon the conditions of reservoir pressure and temperature. Petroleum in liquid or gaseous states is called oil or nature gas separately.

Both the crude oil and natural gas are hydrocarbons in terms of chemical structure. It's already confirmed that the hydrocarbons in petroleum are made up mainly of three kinds of saturated hydrocarbons: alkanes, aromatics and cycloalkanes. In fact, unsaturated hydrocarbons such as alkene and alkyne are not usually present in crude petroleum. Alkanes are also called paraffin series whose general chemical formula is C_nH_{2n+2}. Owing to the variation of molecular weight, alkanes exist in forms different from each other. For example, at room pressure and temperature, the $C_1 \sim C_4$ are in a gaseous state, and they are the predominant contents of natural gas. The $C_5 \sim C_{15}$ are in a liquid state, and they are the predominant contents of crude oil. The C_{16^+} are in solid state at ambient condition, commonly known as paraffin.

At reservoir condition, the solid hydrocarbons exist in oil in the form of solute or crystal. Therefore, both the crude oil and natural gas are hydrocarbons in terms of chemical structure.

1.1 Chemical Properties of Crude Oil

1.1.1 The Elemental Composition of Oil

By analysing oil's elemental composition, it is comprised predominantly of carbon and hydrogen elements and also contains a small quantity of sulfur, oxygen, nitrogen, as well as some others like trace elements.

The percentages of the carbon and hydrogen contents in crude oil are listed in Table 1 - 1. Seen from the table, crude oil consists of approximately 83% ~ 87% carbon and 11% ~ 14% hydrogen, and the sum of C + H is up to 95% ~ 99% by weight. For some oil from oil fields in China, the hydrogen-to-carbon molar ratio tends comparatively high.

Table 1 - 1 Hydrogen and Carbon Contents and Their Molar Ratio in Crude Oil

Elemental content / Oilfield or Country	Content of C(wt) %	Content of H(wt) %	Content of C + H(wt) %	H/C molar ratio
Daqing, China	85.7	13.3	99.0	1.86
Shengli, China	86.3	12.2	98.5	1.68
Karamay, China	86.1	13.3	98.4	1.85
Dagang, China	85.7	13.4	99.1	1.88
Canada	83.4	10.4	93.8	1.60
Mexico	84.2	11.4	95.6	1.62
Iran	85.4	12.8	98.2	1.80
Columbia	83.6	11.9	95.5	1.67
Romania	87.2	11.3	98.5	1.56
Russian	83.9	12.3	96.2	1.76

The non-carbon and non-hydrogen element make a total contribution less than 1% ~5% and is the subordinate element in crude oil. However, these elements all exist in oil as derivatives of the hydrocarbons. The derivative compounds bearing these elements take up a much greater percentage than 1% ~5% and have strong effect on the properties of oil. For the reasons talked above, the existence of these elements should not be ignored.

Generally, compared with other countries, crude oil produced in China possesses lower sulfur content and higher nitrogen content as shown in Table 1 - 2. Taking Dagang and Daqing oil as examples, their sulfur percentages are both only 0.12%. The oil from Gudao and Jianghan has the highest sulfur-content in China, and is still lower than that of other countries. For the nitrogen content, it is usually larger than 0.3% for crude oil in China, and this high level is quite rare in foreign countries. An investigation once taken among 210 samples from some abroad oil fields shows that only 31 of them possess nitrogen content above 0.3%.

Table 1 - 2 Sulfur and Nitrogen Content of Crude Oil

Elemental Content / Oilfield	Sulfur(wt) %	Nitrogen(wt) %
Daqing, China	0.12	0.13
Shengli, China	0.80	0.41
Gudao, China	1.8 ~2.0	0.50
Dagang, China	0.12	0.23
Renqiu, China	0.30	0.38
Jianghan, China	1.83	0.30
The Highest Content in World	5.50	0.77
The Lowest Content in World	0.02	0.02

Besides, crude oil also contents a quite tiny quantity of trace elements, including vanadium, nickel, iron, cobalt, magnesium, calcium, and aluminum, and each individual of them takes up a content less than 0.03%.

1.1.2 The Hydrocarbon Compounds in Crude Oil

It's reasonable to classify the compounds contained in crude oil into two general groups: hydrocarbons and non-hydrocarbons. The relative contents of hydrocarbons and non-hydrocarbons are not fixed but varys a lot in different reservoirs. For example, the hydrocarbon content makes a contribution up to 90% in some types of light oil, while this value may also be lower than 50%, and even as low as to 10% ~30% in heavy oil.

1.1.2.1 The alkane in crude oil

Alkane, sometimes referred to as chain hydrocarbon, is acyclic branched or unbranched hydrocarbons with the general formula C_nH_{2n+2}. Obviously, alkine is saturated hydrocarbons.

Alkanes are chemically inactive and inert to react with other materials unless they are subjected to the conditions of heating, catalyst or photochemical action, in which they can engage in kinds of reactions such as halogenation, sulfonation, oxidation, cracking, etc.

The hydrocarbon materials in crude oil include normal alkanes and isoparaffins and the former group usually takes up a larger share. Especially, the paraffin-base oil often holds normal alkanes in an amount as rich as the total sum of the isoparrifins with the same carbon number. For instance, analyses of the gasoline fractions (60 ~ 140℃) of the Daqing oil show that it possesses a 38% share of normal alkanes while only has a 15% share of its counterpart isoparaffins. However in the asphalt-base oil, as shown in some foreign oil fields (e. g. the Borneo oil), the normal alkanes take a smaller share.

Among the various isoparaffins, the most abundant ones are the derivatives with two or three methyls while the ones with four methyls or other big branches occur in a small amount.

1.1.2.2 The cycloalkanes in crude oil

Cycloalkanes (also called naphthenes) are chemicals with one or more carbon rings to which hydrogen atoms are attached according to the formula C_nH_{2n}. As another major component in petroleum, the cycloalkane is chemically stable, too. Organic chemists have already synthesized cycloalkanes with varing number of carbon atoms, but only cyclopentane and cyclohexane, which respectively contain five or six carbons in a single ring, can abundantly exist in crude oil.

Apart from the single-ringed ones, there also exist cycloalkanes with two or more rings in oil. The two rings of a double-ring cycloalkane may be uniform, both being cyclopentanes or cyclohexanes, following a "one cyclopentane, one cyclohexane" pattern. Besides, the rings are dominantly connected in parallel. What should be noted is that crycloalkanes with three or more rings are also present in crude oil.

1.1.2.3 The aromatic hydrocarbons in crude oil

The existence of benzenoid aromatic hydrocarbons is quite common in all kinds of crude oil. According to related materials, it's said that more than forty kinds of benzenoid homologues, which hold a variety of alkyl side-chains with different carbon numbers, were once separated from the oil produced in America. The side-chains can be either alkyl or naphthenic. Through the analysis on the gasoline fractions (< 160℃) of the oil from China's Daqing, Shengli, Renqiu, and Xinjiang oil fields, among the more than 100 kinds of nonnumeric hydrocarbons that are quantitatively measured there are about 10 benzenoid aromatic types.

1.1.3 The Non-Hydrocarbon Compounds in Crude Oil

In crude oil, the elements such as sulfur, nitrogen and oxygen exist in the form of hydrocarbon compounds or colloidal and bituminous substances. Due to the impurities, they are collectively called non-hydrocarbon compounds. Obviously, these compounds belong to polar substance.

(1) Oxygen containing chemicals: naphthenic acid, phenol, fatty acid, etc.

(2) Sulfur containing compounds: sulfureted hydrogen, thiol, thioether, thiofuran, etc. Besides, there is also elemental sulfur in crude oil.

(3) Nitrogen containing compounds: some heterocyclic compounds like pyrrole, pyridine, quinoline, indole, carbazole, etc.

(4) Colloid and asphaltene: colloid and asphaltene in crude oil belong to non-hydrocarbons, and they are mostly high molecular and heterocyclic compounds that comprise oxygen, sulfur, and nitrogen elements. In addition, they possess high or moderate interfacial activity and have great influence on such oil properties as color, density, viscosity, and interfacial intension. In a word, to know the characters of these compounds is of utmost importance in the development of oil reservoirs.

1.1.4 Molecular Weight, Wax Content and Colloid & Asphaltene Content in Crude Oil

1.1.4.1 The molecular weight

The smallest molecule present in oil & gas is methane and its molecular weight is 16. While the greatest one is the asphaltene, which can be as large as several thousand. Because oil & gas is a mixture of many molecules, the molecular weight of crude oil varies in a wide range of several couples of hundred.

1.1.4.2 Wax content

Wax content, expressed as a percentage, is the ratio of the wax, or called paraffin, to the ozokerite at normal temperature and pressure. Wax, a kind of white or thin yellow solid substance, composed of high alkanes, i. e. $C_{16} \sim C_{35}$, possesses a molecular weight of 300 ~ 500 and a melting point of 60 ~ 90℃. Ozokerite, with atom-number ranging from 36 to 55, is a naturally-occurring odoriferous mineral wax (paraffin) predominantly comprised of complicated crystalline hydrocarbons with high boiling point. Its molecular weight range is 500 ~ 730 and its melting point range is 60 ~ 90℃. Deep under the ground, the wax and ozokerite are usually dissolved in crude oil in a colloidal state, and they will crystallize from the oil when oil is produced through the wellbore with pressure and temperature drop.

1.1.4.3 Colloid content

Colloid in crude oil is a kind of polycyclic aromatic hydrocarbon compounds bearing subordinate elements such as oxygen, nitrogen and sulfur. Colloid usually has comparatively high molecular weight about 300 ~ 1000. It's usually dissolved in oil in a semisolid and dispersed state. It can be soluted in organic solvent like sherwood oil, lubricating oil, gasoline and chloroform.

The colloid content refers to the wt percentage of the colloid in crude oil, ranging from 5% to 20%.

1.1.4.4 Asphaltene content

Asphaltene is non-pure-hydrocarbon compounds with high molecular weight (> 1000) and is a kind of polycyclic aromatic black solid. It is insoluble in alcohol or sherwood oil but dissolves readily in benzene, chloroform and carbon dioxide.

In crude oil asphaltene exists in a very tiny amount usually less than 1%. In fact, high asphaltene content leads to poor oil quality.

Colloid and asphaltene, with gradual gradation in molecular weight from one to the other, are distinguished from each other unobviously. The difference between them is: (1) The colloid is a viscous liquid while the asphaltene is a formless and fragile solid. (2) The colloid is soluble in low molecular hydrocarbons while the asphaltene is not.

1.1.4.5 Sulfur content

Sulfur content is the wt percentage of the sulfur in crude oil, Although Sulfur content is usually less than 1%, the presence of this little amount of sulfur has a quite big effect on the properties of crude oil.

The related data about the properties of crude oil is shown in Table 1-3, Table 1-6 and Table 1-7.

1.2 Physical Properties and Classification of Crude Oil

1.2.1 Physical Properties of Crude Oil

The most commonly considered physical properties of curde oil are color, density, viscosity, freezing point, solubility, calorifics value, fluorescence, optical activity, etc. In this lesson, the physical properties of the commercial stock-tank oil will be discussed.

1.2.1.1 Color

Owing to different components, crude oil is variously colored. It can be in the colors of chocolate brown, dark brown, dark green, yellow, brownish yellow, light red, and so on. The color of oil depends on the relative contents of the light and the heavy hydrocarbons, the colloid and the asphaltene contents in it. Generally speaking, the more colloid and asphaltene, the darker the oil will be. So, to some extent the color of the oil reflects the content of heavy constituents in it.

1.2.1.2 Density and specific gravity

The oil density is the mass per unit volume of oil under stardard conditions of pressure and temperature. Its mathematical expression is:

$$\rho_o = \frac{m_o}{V_o} \tag{1-1}$$

where: ρ_o—the density of crude oil, kg/m^3;

m_o—the mass of crude oil, kg;

V_o—the volume of crude oil, m^3。

The specific gravity of tank-oil is defined as the ratio of the density of tank-oil (ρ_o) to the density of water (ρ_w), both under specified conditions of pressure and temperature. In China and former Soviet Union, the specific gravity is customarily referred to as the ratio of the density of the 1atm & 20℃ crude oil to the density of the 1atm & 4℃ water, and the expression for it is d_4^{20}. In petroleum industries in some western countries like U. K and U. S. A., the standards condition is temperature 60℉ (15.6℃) and the atmospheric pressure, and the Greek letter γ_o is used to indicate the specific gravity. Since the temperature conditions are not the same, γ_o and d_4^{20} differ from each other both in physical significance and numerical value. The conversion relationship between them is: $\gamma_o \approx 1.002 \sim 1.004 d_4^{20}$.

$$\gamma_o = \frac{\rho_o(p,T)}{\rho_w(15℃,1\text{atm})}; \ \gamma_{oi} = \frac{\rho_o(p_i,T_i)}{\rho_w(15℃,1\text{atm})} = \frac{\rho_{oi}}{\rho_w(15℃,1\text{atm})}$$

In western countries the *API* (American Petroleum Institute) scale for crude oil is also used. The API gravity (*API*) can be expressed mathematically as follows:

$$API = \frac{141.5}{\gamma_o} - 131.5 \qquad (1-2)$$

In the equation, γ_o is the specific gravity of the crude oil at 1atm and 60℉(15.6℃).

Based on the equation (1-2), the *API* of water is 10. The *API* of crude oil increases with the decrease of its counterpart specific gravity γ_o. In fact, the *API* also increases as the solubility of gas in oil raises under certain conditions of pressure and temperature. In other words, the *API* is in direct proportion to the solubility of the gas, and this is the advantage of the *API* gravity to indicate the density of underground crude oil.

1.2.1.3 Freezing point

The freezing point of crude oil is defined as the critical temperature at which the liquid crude oil solidifies and loses its liquidity at a specified pressure. It associates much with the contents of the wax, colloid & asphaltene, and light-hydrocarbons in the crude oil, and the influencing factors are rather complicated. Generally speaking, the larger its light-hydrocarbon content is, the lower its freezing point; the larger its heavy-hydrocarbon content is, especially the wax, the higher its freezing point. The freezing point of crude oil is usually within the range of -56 ~ 50℃. when the freezing point is above 40℃, it is called "high-freezing crude oil".

Most of the crude oil in China is wax-base one, and the high wax content inevitably results in high freezing point. For example, Daqing crude oil, having a wax content up to 25% ~ 30%, possesses a freezing point about 25 ~ 30℃.

1.2.1.4 Viscosity

The reservoir fluids——oil, gas and water are all viscous fluids. Viscosity, caused by molecular friction within oil, is a material property that measures a fluid's resistance to flow. It is defined as the ratio of the shear stress per unit area within the flowing liquid to the velocity gradient at any point. The viscosity signifies the level of difficulty that the liquid meets in flowing. High viscosity has stronger resistance, so it is difficult to flow.

As shown in Fig. 1-1, viscous fluid is filled in any two flat plates parallel to each other. Distance between the two plates is dy, the plate area is A, the velocity of the nether plate with its attaching fluid is v, the upper plate with its attaching fluid is $v + dv$, and the inner frictional resistance force between plates is F. According to the Newton's law of viscosity, we can get that: