Recognition of the Lower Limit of Reservoir Physical Properties

Jinyou Dai 1,2, Yang Wang 2,*, Rui Wang 2 and Lixin Lin 2

1State Key Laboratory of Oil and Gas Resources and Exploration, China University of Petroleum-Beijing, Beijing, China
2School of Petroleum Engineering, China University of Petroleum-Beijing, Beijing, China

*Corresponding author e-mail: petrol_wong@163.com

Abstract. The lower limit of reservoir physical properties is an important parameter for identifying the reservoir and determining the effective thickness in the reserve evaluation, and it is also an important basis for selecting the test interval in the oilfield exploration and development. In view of the basicity and necessity of studying the lower limit of reservoir physical properties, related determination methods have been the research hotspots of reservoir engineers. Existing research results show that the lower limit of the reservoir physical properties is determined under the established process technology conditions, but the lower limit of the reservoir physical properties changes with the development of oil and gas extraction technology. As the basis of effective thickness determination and reserve calculation, the sole determination of the lower limit of the reservoir physical properties is acceptable, and its changes or uncertainties are difficult to understand. Understanding the root cause of this contradictory problem theoretically is of great significance to further research on the lower limit of reservoir physical properties. Therefore, from the perspective of percolation, the author re-understands the lower limit of the physical properties of the reservoir on the basis of systematically sorting out the difference in percolation capacity of pores of different sizes in the reservoir. The results show that: ①There are three types of lower limit of reservoir physical properties, including the lower limit of theoretical physical properties, the lower limit of producing physical properties, and the lower limit of filling physical properties. Among them, the lower limit of theoretical physical properties is the minimum effective porosity and minimum permeability of the reservoir capable of storing and percolating fluid, and its size depends on the geological conditions of the reservoir; the lower limit of producing physical properties is the minimum effective porosity and minimum permeability of a reservoir that can store and percolate fluid under production conditions, and its size depends on both the reservoir geological conditions and the production conditions of the reservoir; the lower limit of filling physical properties is the minimum effective porosity and minimum permeability of a reservoir that can store and percolate oil and gas under the state of reservoir forming, and its size depends on both the reservoir geological conditions and the reservoir forming conditions. Among the three, the lower limit of theoretical physical properties is the smallest, and the lower limit of producing physical properties and the lower limit
of filling physical properties are relatively large. ② At present, the lower limit of reservoir physical properties is mainly determined based on core physical property analysis, oil test and production test data, therefore, it should be the lower limit of producing physical properties. And the lower limit of producing physical properties is closely related to the production conditions, so it is uncertain. On the contrary, the lower limit of theoretical physical properties and the lower limit of filling physical properties are irrelevant to production conditions, so they are certain. ③ The study of the lower limit of reservoir physical properties should be based on the theoretical lower limit and the filling lower limit, while the producing lower limit can reflect the changes in production conditions and can be used as a dynamic index to measure oilfield development, but it should not be used as the focus of research on the lower limit of reservoir physical properties.

Keywords: Theoretical lower limit; Producing lower limit; Filling lower limit; Recognition; Lower limit of physical properties; Reservoir.

1. Introduction
The lower limit of reservoir physical properties is the minimum effective porosity and minimum permeability that can store and percolate fluid, which is usually expressed by a certain value of porosity or permeability [1]. The lower limit of reservoir physical properties is an important parameter to identify reservoir and determine effective thickness in reserve evaluation, and it is also an important basis to select perforation test interval in oilfield exploration and development [2]. In view of the foundation and necessity of the lower limit of reservoir physical properties, the determination method of the lower limit of reservoir physical properties has always been a research hotspot of reservoir engineers [1-35].

At present, the lower limit of reservoir physical properties is mainly determined by core physical properties analysis, oil test and production test data [1-35]. However, due to many factors such as reservoir geological conditions (such as rock properties, fluid properties, reservoir pore structure, formation pressure and temperature, burial depth, etc.) and production conditions (such as process technology, displacement power, etc.), there is no exact physical quantitative method to determine the lower limit of reservoir physical properties [1], and it is difficult to establish the corresponding physical or mathematical model [2]. For this reason, many empirical methods have been proposed to determine the lower limit of reservoir physical properties (such as porosity-permeability cross plot method [3], empirical statistics method [4-5], drilling fluid invasion method [6-7], irreducible water saturation method [8-12], minimum flow pore throat radius method [13-20], mercury injection parameter method [21-22], permeability stress sensitive method [23-25], oil bearing attitude method [26], test method [27-29], distribution function curve method [30-31], oil test method [32], etc.). However, each method has its advantages and disadvantages. In practice, multiple methods are often needed to verify and determine the lower limit of reservoir physical properties (Liu et al, 2014), which results in statistical characteristics and certain indeterminacy of the lower limit of reservoir physical properties, but the lower limit of reservoir physical properties is essentially the only one. However, some scholars [1,33] think that the recognition of the lower limit of reservoir physical property is closely related to the level of oil production technology and development technology. Liu Maoli et al. (2014) pointed out that with the development of process technology, the original non effective reservoir may be converted into industrial oil (gas) reservoir, and the lower limit of reservoir
physical property will change accordingly [33]. This shows that the lower limit of reservoir physical properties is only determinate under the given technological conditions. However, with the development of production technology, the lower limit of reservoir physical property is changing and decreasing. From this point of view, the lower limit of reservoir physical properties is not only determined. As the basis of effective thickness determination and reserves calculation, the change of lower limit of reservoir physical property will have a direct impact on oil and gas reserves. Therefore, the sole determination of the lower limit of reservoir physical properties is acceptable, and its change or uncertainty is difficult to understand. It is of great significance to study the lower limit of reservoir physical properties to find out the cause of the contradiction theoretically. Therefore, from the perspective of seepage, on the basis of systemically combing the difference of seepage capacity of pores of different scales of reservoir, the author reconstructs the lower limit of reservoir physical properties, and then discusses the development direction of the research on the lower limit of reservoir physical properties.

2. Pore seepage capacity analysis of reservoir at different scales

Reservoir is a rock stratum that can store and percolate fluid. The basic characteristics of reservoir are porosity and permeability. Porosity and permeability of reservoir depend on void. The void is the space which is not filled by solid material in the rock, and it can be subdivided into large-scale pores and the narrow connecting part between large pores-throat. Pore determines the ability of reservoir to store fluid, while throat controls the ability of reservoir to percolate fluid, and the two organically combine to form a reservoir space to store and percolate fluid. Therefore, the porous media reservoir space can be regarded as a three-dimensional pore throat network composed of pores and throats, in which the fluid flow obeys the seepage law.

In the three-dimensional pore throat network of reservoir, most pores can always find other pores connected with their matching positions, but there are also a few unconnected pores (or dead pores), and fluid seepage occurs in the connected pores. According to the pore size, the connected pores can be divided into three types: hyper capillary pores, capillary pores and micro capillary pores. Among them, hyper capillary pores are millimeter-sized pores with pore diameters greater than 0.5 mm, in which the fluid can flow freely under the action of gravity. Capillary pores are micron-sized pores with pore diameters between 0.5 mm and 0.2 μm. Due to smaller pore diameter, the fluid particles cannot flow freely under the action of capillary force and the surrounding solid interface molecular force, and can only flow under the action of displacement force (mainly production pressure difference). Micro capillary pores are nanoscale pores with pore diameters less than 0.2 μm. In this kind of pore, the intermolecular attraction is very large, and the fluid cannot flow and is in adsorption state. Obviously, the percolation of reservoir fluid mainly occurs in hyper capillary and capillary pores, while the fluid in micro capillary pores does not have theoretical mobility. Obviously, the percolation of reservoir fluid mainly occurs in hyper capillary and capillary pores, while the fluid in micro capillary pores does not have theoretical mobility. Therefore, the connected hyper capillary and capillary pores are the effective pores of theoretical seepage, while the micro capillary pores are the ineffective pores.

However, under the actual oilfield production conditions, the fluid in the effective pore is not completely mobile, and its flow mainly depends on the relationship between displacement power and seepage resistance. When the displacement force is greater than the seepage resistance, the fluid can flow, and this part of effective pore is flow pore. When the displacement force is less than the seepage resistance, the fluid cannot flow, and this part of effective pore is non-flow pore. In addition, in the process of oil and gas accumulation, oil and gas filling is not completely filled with effective pore space, and the degree of filling mainly depends on the relationship between reservoir forming power and seepage resistance. When the reservoir dynamic force is greater than the seepage resistance, the part of effective pores filled with oil and gas is the filling pores (equivalent to the pores occupied by oil and gas). When the reservoir dynamic force is less than the seepage resistance, the part of effective pores that cannot be filled with oil and gas is the non-filling pores.
### Table 1. Characteristics of pore seepage at different scales and corresponding relationships.

| Classification basis | Connectivity status | Aperture scale     | Theoretical mobility | Producing mobility | Filling mobility |
|----------------------|---------------------|--------------------|----------------------|--------------------|-----------------|
|                      | Connected pore      | Hyper capillary    | Effective pore       | Flowing pore       | Filling pore    |
|                      | Capillary pore      | Capillary pore     | Non-flow pore        | Non-filling pores  |
|                      | Micro capillary     | Micro capillary    | Ineffective pore     | Ineffective pore   |
|                      | Unconnected pore    | Unconnected pore   |                      |                    |

To sum up, the connectivity, pore size, theoretical mobility, production mobility and filling mobility of pores in the reservoir are different, but in general, there are regular corresponding relations and unique seepage characteristics between pores of different scales, which are summarized as table 1. From table 1, it can be seen that the corresponding relations of different pore spaces in the reservoir are: ① total pore of reservoir $\geq$ connected pore $\geq$ effective pore $\geq$ flowing pore. ② total pore of reservoir $\geq$ connected pore $\geq$ effective pore $\geq$ filling pore. ③ The relative size of flowing pore and filling pore space mainly depends on the driving force and reservoir forming force: if the driving force is greater than the reservoir forming force, the flowing pores are larger than the filling pores; if the driving force is less than the reservoir forming force, the flowing pores are smaller than the filling pores. ④ Among them, the effective pore has theoretical mobility, the flowing pore has production mobility, and the filling pore has filling mobility.

3. Recognition of the Lower Limit of Reservoir Physical Properties

3.1. Triplicate of the lower limit of reservoir physical properties

Reservoir pore-throat network is not uniform, because the pore-throat of different sizes, different geometric shapes, different grades of pore-throat are interwoven and connected in different ways, the pore-throat network of the reservoir constitutes a complex connected system, and it is difficult to be accurately represented by an exact model. Whether it is a soil model, a capillary model, or a three-dimensional network model, or a single porosity medium, a dual porosity medium, and a triple porosity medium model, they are only approximations of the pore-throat network of particular type of reservoirs. The complexity of the pore-throat network of the reservoir, especially the order of the pore-throat distribution, will inevitably have a direct and significant impact on the seepage response of the reservoir fluid. In actual oilfield production, under certain conditions where the displacement power (or production pressure difference) of a certain reservoir is constant, usually only the part of the pore-throat network whose pore-throat size is larger than a certain limit will percolate. Some pore-throat networks cannot percolate, that is, the percolation of fluid in the pore-throat network is selective. This phenomenon can be understood as follows: as the size of reservoir pore-throat decreases, the capillary force and the molecular force at the surrounding solid interface on fluid particles increase, and the percolating resistance increases. When the limit of a certain aperture is reached, the displacement force and percolating resistance are in equilibrium. When the diameter of the throat is larger than the aperture limit, the displacement force is greater than the percolating resistance, and the fluid flows. When the diameter of the throat is less than the aperture limit, the displacement force is less than the percolating resistance, and the fluid does not flow.

If the minimum throat diameter of the reservoir fluid that can seep is defined as the lower limit of reservoir seepage aperture, it can be seen from table 1 that the lower limit of reservoir seepage aperture actually includes three forms: the lower limit of theoretical seepage aperture, the lower limit of production seepage aperture and the lower limit of filling seepage aperture. Among them, the lower limit of theoretical seepage aperture refers to the lower limit of pore size of effective pore with theoretical fluidity, and is also the dividing limit of capillary pores and micro-capillary pores. The lower limit of
production seepage aperture refers to the lower limit of flowing pores size with production fluidity. The lower limit of filling seepage aperture refers to the lower limit of filling pores size with filling fluidity.

The seepage of reservoir fluid is the basis of oilfield development. The lower limit of reservoir seepage aperture is the minimum throat diameter for reservoir fluids to percolate, while the lower limit of reservoir physical properties is the minimum effective porosity and the lower limit of minimum permeability for reservoir and percolation fluids [1]. Therefore, both the lower limit of reservoir seepage pores size as a microscopic seepage pores size scale and the lower limit of reservoir physical properties as a macroscopic seepage pores size scale are related to reservoir fluid seepage. If the seepage of reservoir fluid is taken as the link, the lower limit of reservoir microscopic seepage pores size determines the lower limit of reservoir macroscopic physical properties, and the lower limit of reservoir macroscopic physical properties is the concentrated reflection of the lower limit of reservoir microscopic seepage pores size.

In fact, in the study of the lower limit of reservoir physical property, the method of minimum flow pore throat radius is often used to determine the lower limit [4,15,26,34-35]. According to this method, the pores and throats of rocks are the spaces and channels for oil and gas storage and flow. Whether oil and gas can flow out of rocks under a certain pressure difference depends on the size of the throats [4]. Therefore, the radius of the rock throats determines the oil and gas. The key factor is whether it can flow out of the rock under a certain pressure difference [15]. This enables both the storage and oil and gas flow in the minimum throat radius is the minimum flow pore throat radius of oil and gas [26]. After determining the minimum flow pore throat radius of the reservoir, the relevant curves of pore-throat radius, porosity and permeability can be drawn according to the principle of statistical analysis, and the corresponding lower limit value of porosity and permeability can be calculated according to the minimum flow pore throat radius [34]. According to this method, the thickness of 0.1 μm is equivalent to the water film thickness attached to the surface of water-wet clastic rock, which is the minimum flow throat radius of oil and gas, and the corresponding porosity and permeability values are the lower limit of reservoir physical property [35]. Obviously, this understanding has both advantages and disadvantages. The advantage lies in that the lower limit of reservoir physical properties is related to the lower limit of seepage aperture and the lower limit of reservoir physical properties is demarcated at a specific throat radius (0.1 μm). The disadvantage is that the determination of the minimum flow pore-throat radius as a fixed value (0.1 μm) is not sufficient. According to the water film theory, there is a close relationship between water film thickness and displacement pressure. The greater the displacement pressure is, the thinner the water film thickness is, that is, the water film thickness is a function of displacement pressure [36-37]. Therefore, the minimum flowing throat radius should not be a fixed value, but change with the changing of production conditions. However, the idea of this method is clear, that is, the determination of the lower limit of reservoir seepage aperture is of great significance to the study of the lower limit of reservoir physical properties.

Since the lower limit of reservoir seepage pores size can be used to determine the lower limit of reservoir physical properties and the relationship between the two is monotonically increasing [4,15,26,34-35], it indicates that there is a corresponding relationship between the lower limit of reservoir seepage pores size and the lower limit of reservoir physical properties. Therefore, corresponding to the lower limit of theoretical seepage pores size, lower limit of production seepage pores size, and lower limit of filling seepage pores size, the lower limit of reservoir physical properties can also be divided into lower limit of theoretical physical properties, lower limit of producing physical properties, and lower limit of filling physical properties. Among them: ①the lower limit of theoretical physical properties is the minimum effective porosity and minimum permeability of the reservoir capable of storing and percolating fluid, which can be understood as the lower limit of the reservoir physical properties corresponding to the lower limit of theoretical seepage pores size; ②the lower limit of producing physical properties refers to the lower limit of the minimum effective porosity and minimum permeability of the reservoir capable of storing and percolating fluids in the production state, which can be understood as the lower limit of the reservoir physical properties corresponding to the lower limit of the pores size of the reservoir production; ③the lower limit of filling physical properties
is the minimum effective porosity and minimum permeability of a reservoir that can storage and percolate oil and gas under the state of reservoir accumulation. It can be understood as the lower limit of reservoir physical properties corresponding to the lower limit of filling seepage pores size. In view of the triple connotation of the lower limit of the physical properties of the reservoir, it is necessary to have a deep understanding of the influencing factors and properties of the lower limit of theoretical physical properties of the reservoir, the lower limit of producing physical properties, and lower limit of filling physical properties.

3.2. Influencing factors and properties of the lower limit of reservoir physical properties

The lower limit of theoretical physical properties is the minimum effective porosity and minimum permeability of the reservoir capable of storing and percolating fluid, and it can be understood as the lower limit of the reservoir physical properties corresponding to the lower limit of the theoretical seepage pores size of the reservoir. Due to the different geological conditions of different reservoirs in different regions, such as rock properties, fluid properties, pore structure, burial depth, formation temperature and pressure environmental conditions, there are great differences. The solid interface has a large difference in the forces acting on the fluid molecules. The strength of the fluid particles in the capillary pores due to capillary forces and the surrounding solid interface molecular forces are very different, resulting in different theoretical physical property lower limits for different reservoirs in different regions. However, for specific reservoirs in specific areas, the lower theoretical physical properties of the reservoir are basically the same, because the rock properties, fluid properties, pore structure, burial depth, formation temperature, and pressure environmental conditions of the reservoir are basically the same. Therefore, the lower limit of theoretical physical property can be regarded as the inherent property of the reservoir, and its size mainly depends on the reservoir geological conditions. And the specific lower limit of theoretical physical properties is a certain value.

The lower limit of filling physical properties is the minimum effective porosity and minimum permeability of a reservoir that can accumulate and percolate oil and gas under the state of reservoir accumulation, and it can be understood as the lower limit of the reservoir physical properties corresponding to the lower limit of the pore diameter of the reservoir accumulation. The lower limit of filling physical properties is related not only to the reservoir geological conditions, but also to the hydrocarbon accumulation conditions. However, for certain reservoirs, the dynamics of oil and gas accumulation in the geological historical period are fixed and not transferred by human factors, and they will not change with changes in production conditions. Therefore, the lower limit of filling physical properties of specific reservoirs can be considered as a definite value.

The lower limit of producing physical properties is the minimum effective porosity and minimum permeability of a reservoir that can store and percolate fluids under production, and it can be understood as the lower limit of the reservoir physical properties corresponding to the lower limit of the pore diameter of the reservoir production. The lower limit of producing physical properties is not only related to the reservoir geological conditions, but also to the oilfield production conditions that including the production technology. With the change of production conditions, the lower limit of production physical properties will also change, so the lower limit of producing physical properties of a specific reservoir is not a certain value.

At present, the lower limit of reservoir physical properties is mainly determined based on core physical properties analysis, oil test and production test data. It belongs to the lower limit of producing physical properties, so it is uncertain: ① From a short time scale, under the conditions of the given production technology, due to the lack of a unified production pressure differential quantitative scale for core analysis, oil test and production test data, therefore, the lower limit of producing physical properties will present a certain degree of indeterminacy. ② From a longer time scale, with the development of the production technology, due to the core analysis, oil test and production test data do not have a unified quantitative scale for process technology, therefore, the lower limit of producing physical properties will present greater indeterminacy. In terms of these issues, Guo (2004) pointed out that the effective thickness permeability of Daqing oilfield was limited to 100-150 mD in the 1960s,
decreased to 25-40 mD in the 1980s, and decreased to 0.5-1.0 mD in the 1990s. The increased “out-of-
surface reserves” has made great contributions to increasing reserves and stabilizing production in the
Daqing oilfield since the 1990s. Therefore, the reason why it is difficult to accurately determine the
lower limit of reservoir physical properties is in addition to the “no exact physical quantitative method”,
which may also be related to the lack of uniform production conditions quantitative scales in test data.

In summary, the lower limit of producing physical properties of the reservoir is closely related to the
production conditions, and it is not an inherent property of the reservoir, nor is it a determined value.
On the contrary, the lower limit of theoretical physical properties and the lower limit of filling physical
properties have nothing to do with production conditions, they are relatively stable properties of a
specific reservoir, and they are deterministic.

3.3. Relationship between three lower limits of reservoir physical properties

Among the lower limit of theoretical physical properties, the lower limit of producing physical
properties and the lower limit of filling physical properties, the lower limit of theoretical physical
properties is the minimum limit that the reservoir can percolate fluid, which is the smallest of the three
properties. The lower limit of producing physical properties is greater than the lower limit of theoretical
physical properties, which is determined by the fact that the size of flowing pores is smaller than the
size of effective pores. And, the lower limit of filling physical properties is greater than the lower limit
of theoretical physical properties, which is determined by the fact that the size of filling pores is smaller
than the size of effective pores. The relative size between the lower limit of producing physical
properties and the lower limit of filling physical properties depends on the relationship between
displacement power and reservoir accumulation power: if the production pressure difference is greater
than the filling pressure, the lower limit of producing physical properties is less than the lower limit of
filling physical properties; if the production pressure difference is less than the filling pressure, the lower
limit of producing physical properties is greater than the lower limit of filling physical properties.

In actual oilfield development, the interpretation conclusions of reservoir logging generally include
oil layers, oil-water layers, water layers and dry layers. Generally, the oil layers and oil-water layers that
can store and percolate oil and gas are collectively referred to as effective reservoirs (or oil-bearing
reservoirs), and the oil layers, oil-water layers, and water layers that can store and percolate fluids are
collectively referred to as reservoirs. Because the relationship between reservoirs and effective
reservoirs (or oil-bearing reservoirs) is containing and being contained, the lower limit of reservoir
physical properties and the lower limits of effective reservoir (or oil-bearing reservoir) physical
properties are actually two different concepts and cannot be confused with each other. In addition, the
lower limit of reservoir physical properties is lower than the lower limit of the effective reservoir
physical properties because it is easier to enter the large pore-throat network with lower resistance when
oil and gas is filled.

According to the connotation and properties of the lower limit of reservoir physical properties (3.1,
3.2), it can be known that the lower limit of theoretical reservoir physical properties is actually “the
lower limit of reservoir physical properties” in the traditional sense, and the lower limit of filling
reservoir physical properties is actually “the lower limit of effective reservoirs (or oil-bearing reservoirs)
physical properties”. Therefore, the study of the lower limit of reservoir physical properties should focus
on the lower limit of theoretical physical properties and the lower limit of filling physical properties.
And the lower limit of producing physical properties can reflect the changing of production conditions,
which can be used as a dynamic index to measure oilfield development, and should not be used as the
focus of the lower limit of reservoir physical properties.

4. Conclusion

(1) There are three types of lower limit of reservoir physical properties, including the lower limit of
theoretical physical properties, the lower limit of producing physical properties, and the lower limit of
filling physical properties. Among them, the lower limit of theoretical physical properties is the
minimum effective porosity and minimum permeability of the reservoir capable of storing and
percolating fluid, and its size depends on the geological conditions of the reservoir; the lower limit of producing physical properties is the minimum effective porosity and minimum permeability of a reservoir that can store and percolate fluid under production conditions, and its size depends on both the reservoir geological conditions and the production conditions of the reservoir; the lower limit of filling physical properties is the minimum effective porosity and minimum permeability of a reservoir that can store and percolate oil and gas under the state of reservoir forming, and its size depends on both the reservoir geological conditions and the reservoir forming conditions. Among the three, the lower limit of theoretical physical properties is the smallest, and the lower limit of filling physical properties and the lower limit of producing physical properties are relatively large.

(2) At present, the lower limit of reservoir physical properties is mainly determined based on core physical property analysis, oil test and production test data, therefore, it should be the lower limit of producing physical properties. And the lower limit of producing physical properties is closely related to the production conditions, so it is uncertain. On the contrary, the lower limit of theoretical physical properties and the lower limit of filling physical properties are irrelevant to production conditions, so they are certain. The study of the lower limit of reservoir physical properties should be based on the theoretical lower limit and the filling lower limit, while the producing lower limit can reflect the changes in production conditions and can be used as a dynamic index to measure oilfield development, but it should not be used as the focus of research on the lower limit of reservoir physical properties.

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