



## Measurement of Relative Permeability Curves of Cores with Different Permeability and Lengths under Unsteady-State

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### ABSTRACT

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*unsteady-state, relative permeability curve, oil-water, gas-water, core length, iso-permeability point*

The oil-water and gas-water relative permeability curves are important reference data for the dynamic analysis and numerical simulation of oil and gas reservoir exploitation. Although the petroleum industry of China and other countries have formulated reference standards for the measuring methods of relative permeability of cores, they haven't given the definite reference values of the core length, therefore we cannot know for sure whether different core length values are required in the measurement and whether the core length has an impact on the measurement results. In view of this gap, this paper conducted a research on the relative permeability of cores with different lengths. The core samples are artificial core with similar properties as the outcrop cores of the Halfaya Oilfield (Iraq), in our experiment, the oil-water and gas-water relative permeability curves of the sample cores were measured and the results suggest that, for the oil-water relative permeability curves, as the core length grows, the iso-permeability points move to the right, and they basically stabilize when the core length is greater than 20cm; as for gas-water relative permeability curves, in case of low-permeability cores, under constant injection pressure, as the core length grows, the iso-permeability points and the two-phase co-permeation areas present an obvious tendency of moving to the left, but when the core length is greater than 20cm, such tendency is not obvious, and the high-permeability cores do not have such characteristics. These results indicate that, the unsteady-state two-phase relative permeability measurement experiments obtained accurate results at a core length of about 20cm, which provided a reference for similar experiments in subsequent research.

## 1. INTRODUCTION

Field scholars have done a lot research on the relative permeability of two-phase fluids and obtained fruitful results. Foreign studies started earlier in this aspect, for instance, scholars found through experiments that when two-phase fluids flow in a porous medium at the same time, the permeability of each phase will be greatly reduced due to the Jamin effect [1-3]. In 1937, Muskat et al. found for the first time that for a same core, the permeability value measured with gas flow is generally higher than that measured with fluid flow, and the lower the core permeability, the more obvious the difference. After that, scholar Klinkenberg proposed the slippage effect of gas in micro-diameter tube flows. The research of scholar Leverett and others suggested that the relative permeability of water and gas phases is a function of their respective saturation [4-6]. Esmacili et al. [7] reviewed the results of previous studies on the impact of temperature on the two-phase relative permeability, and proposed that it's not appropriate to generalize the impact of temperature on relative permeability, they also pointed out that the relative permeability of a particular oil reservoir may (or may not) change with temperature. Lai and Miskimins [8] explored a new technique for measuring the two-phase relative permeability under non-Darcy flow conditions and their results showed that the relative permeability calculated by the

non-Darcy flow model for gas is higher than that calculated by the Darcy flow model. In addition, experiments on the impact of confining pressure on the gas-water relative permeability also indicate that, as the confining pressure increases, the gas-phase relative permeability decreases significantly, but its impact on the water-phase relative permeability is not obvious.

In China, the research on two-phase relative permeability started relatively late. In existing studies, scholars Ren et al. [9] found through experiments that when there's residual water in low-permeability cores, the flow pattern of gas in the core is related to core permeability, water saturation, and pressure gradient. Jiang et al. studied on the characteristics of gas-water relative permeability and found that the inaccuracy and distortion of the reference permeability is one of the reasons that the gas-phase relative permeability is greater than 1. Based on the Thomas model and taking the start-up pressure gradient into consideration, Wang et al. [10] established a 3D gas-water two-phase full-implicit permeation model for low-permeability fractured gas reservoirs. Yi et al. [11] designed a back-pressure device for the measurement of the relative permeability of high-temperature and high-pressure unsteady-state water-displaced gas, breaking through the limitation that the relative permeability curve of water-displaced gas can only be achieved via the steady-state method, and the measurement has the merits of fast and accurate [12]. Dong et al. [13] studied the characteristics of multi-phase permeation under certain

formation temperature and pressure conditions, and obtained the permeability curves of oil-gas, oil-water and gas-water multi-phase permeation; their results showed that, under certain formation conditions, the oil-water, oil-gas, and gas-water two-phase permeability of low-porosity and low-permeability rocks is relatively weak; but for high-porosity and high-permeability rocks with fractures or pores, the co-permeation areas of oil-water, oil-gas, and gas-water are relatively wide, and the displacement efficiency is higher.

Domestic and foreign studies on the relative permeability curve mostly focused on temperature, pressure, physical properties of the reservoir, and permeation conditions, few of them concerned about the impact of core length on the measurement results of relative permeability curves. Dong et al. [13] mentioned in their study that using unsteady-state method to study relative permeability is not adaptable since the end effect is obvious and longer samples are required, however, the length of most samples is less than 6 cm, so the end effect cannot be eliminated. At present, in most laboratories, the cores used for the measurement of relative permeability curves have two types: small cores (diameter is about 2.5cm) and full-diameter cores (diameter is about 6cm), the length of the cores is generally about 5-10cm [14-16], and

very few researches use long cores to measure the relative permeability curves. Therefore, this paper selected the artificial long cores with similar characteristics as the outcrop cores of the Halfaya Oilfield for indoor simulation experiments. For core samples of different permeability and lengths, unsteady-state experiments were performed to measure and analyze the oil-water and gas-water relative permeability curves, in the hopes of providing a reference for similar experiments in subsequent research, and offering a theoretical basis and instructions to the numerical simulation of study areas and the formulation of development plans [17, 18]. This paper has four parts: experiment content; experiment principle, process and steps; experimental data processing and result analysis; and conclusions.

## 2. EXPERIMENT CONTENT

In the experiment, three permeability values (10 mD, 50 mD, 100 mD) were selected for the artificial core samples, and for each type of core samples, three lengths (10 cm, 20 cm, 30 cm) were selected, the core diameter was 2.5 cm, and the core experiments were arranged as shown in Table 1.

**Table 1.** Arrangement of the experiments

Experiment type	Experiment condition	Core length/cm	Permeability/mD	Core No.
Displacing oil with water	Constant speed	10	50	50-1
			100	100-1
		20	50	50-2
			100	100-2
		30	50	50-3
			100	100-3
	Constant pressure 0.1MPa	20	100	100-2
			50	50-3
		30	100	100-3
			50	50-3
		10	10	10-1
			50	50-1
Displacing water with gas	Constant pressure 0.2MPa	20	100	100-1
			10	10-2
		100	50	50-2
			100	100-2
		30	10	10-3
			50	50-3
	Constant pressure 0.3MPa	20	100	100-3
			10	10-2
		100	100	100-2
			50	50-3
		30	100	100-3
			10	10-2
Constant pressure 0.4MPa	20	50	50-2	
		100	100-2	
	30	100	100-2	
		10	10-3	

## 3. EXPERIMENT PRINCIPLE, PROCESS, AND STEPS

The measurement of oil-water relative permeability using the unsteady-state method is based on the Buckley-Leverett one-dimensional two-phase water-displaced oil front-advance theory. In the experiment, capillary pressure and gravity were ignored, and it's assumed that the two-phase immiscible fluids were incompressible, and the oil-water saturation in any cross section of the rock samples was uniform. In the experiment, the core samples were saturated with one fluid in advance and

then displaced with another fluid. In the process of displacing oil with water, the distribution of oil-water saturation in porous media is a function of distance and time. This process is an unsteady process. The principle for measuring the gas-water relative permeability using the unsteady-state method is the same.

### 3.1 Experiment process

The experiment equipment includes: core holder, pressure

sensor, liquid measuring cylinder, six-way valve, intermediate container, nitrogen gas cylinder, hand-operated confining pressure pump, constant-flux pump, valves, and wet gas flow meter. The experiment process is shown in Figure 1. Some artificial long core samples are shown in Figure 2.

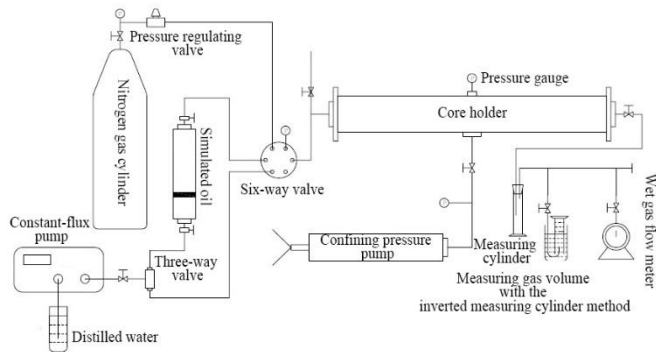


Figure 1. Experiment process



Figure 2. A photo of some artificial core samples

### 3.2 Experiment steps for measuring oil-water relative permeability using the unsteady-state method

The core samples used in the experiment were artificial and the oil was 5# white oil with a viscosity of 12.4 mPa·s and a density of 0.858g/cm<sup>3</sup>, the oil was subject to vacuum filtration before the experiment; to avoid core pollution, distilled water was used in the experiment, and the specific experiment steps are:

(1) The main material of the artificial core is quartz sand, organic materials were added in the quartz sand and cemented, and a certain amount of clay minerals were mixed, then, some silicone oil was added to adjust the wettability to neutral wet or weak water wet; after that, the materials were put into molds to shape, and then placed into a constant temperature oven to bake, later, they were cut into the length required for the experiment.

(2) The core samples were dried and weighed for their dry weight, and then measured for gas permeability.

(3) The core samples were vacuumed for 4 hours, then the formation water was sucked into the vacuum chamber and saturated for 3 hours, after that, the core samples were taken out and weighed for wet weight, and the pore volume and porosity were calculated;

(4) Distilled water was used to measure the permeability of the core with water flow at a certain flow rate;

(5) Oil was used to displace the distilled water in the cores to create irreducible water saturation. In the beginning, the displacement was at a low speed of 0.1ml/min, then the displacement speed was gradually increased until it reached

the displacement speed set for the experiment and no water had come out for a while, the displacement pressure difference and permeability with fluid flow were measured at this time (the state at this moment was that the water had been displaced by oil). After displacement, the core samples were immersed in simulated oil and aged in the constant temperature oven for some time.

(6) According to the experiment plan, the core displacement experiment was performed, time, displacement pressure difference, accumulated oil output, and accumulated fluid output were recorded; at the initial stage (when samples just contacted with water), the records were more frequent (in shorter time intervals), then with the decrease of the oil output, the record time intervals were longer, at last, the experimental results were calculated.

### 3.3 Experiment steps for measuring gas-water relative permeability using the unsteady-state method

(1) Core samples were installed in the core holder, then the constant-flux pump was used to perform water displacement on core samples at a certain flow rate, and the water-phase permeability was measured consecutively for 3 times (after the inlet-outlet pressure difference of the core samples and the outlet flow were stable), the relative error of the 3 measurements was less than 3%. The average permeability was taken as the basic value of gas-water relative permeability.

(2) According to the permeability measured with gas flow and water flow, an appropriate displacement pressure difference was selected, the initial pressure difference must be able to overcome the end effect and not produce turbulence. The initial gas displacement pressure was 0.1MPa~0.6MPa.

(3) The experiment of displacing water with gas was started, the displacement pressure, liquid output, and gas output were recorded at designed time intervals; at the initial stage (when samples just contacted with water), the data were recorded at shorter time intervals, then with the decrease of the liquid output, the record time intervals became longer, at last, the experimental results were calculated.

(4) The experiment of displacing water with gas was continued until there's only residual water, after the gas-phase effective permeability was measured, the experiment terminated.

(5) The gas-phase effective permeability was measured under the residual water states (the measurement was conducted under 1/2 and 1/4 displacement pressure respectively), and whether turbulence had occurred or not was judged (turbulence would occur when the effective permeability under low pressure exceeds 10% of the effective permeability under displacement pressure).

## 4. DATA PROCESSING AND RESULT ANALYSIS

### 4.1 Processing of experimental data

According to the *Petroleum and Natural Gas Industry Standard of the People's Republic of China SY/T5345-2007 Test Method for Two-Phase Relative Permeability in Rocks* [19], the experimental data were processed to get oil-water and gas-water relative permeability under different core permeability and core length conditions. After data processing, abnormal data points were eliminated and the curves of oil-water and gas-water relative permeability were plotted.

### 4.2 Analysis of experimental results of oil-water relative permeability curves measured by unsteady-state method

As shown in Figure 3, after the displacement started, with the increase of water saturation, the oil-phase relative permeability gets worse significantly, and the water-phase

relative permeability gets better significantly. As the core length grows, the iso-permeability points move to the right. But when the core length is greater than 20cm, the iso-permeability points are basically stable, indicating that the core length has an impact on the measurement results of the oil-water relative permeability curve.

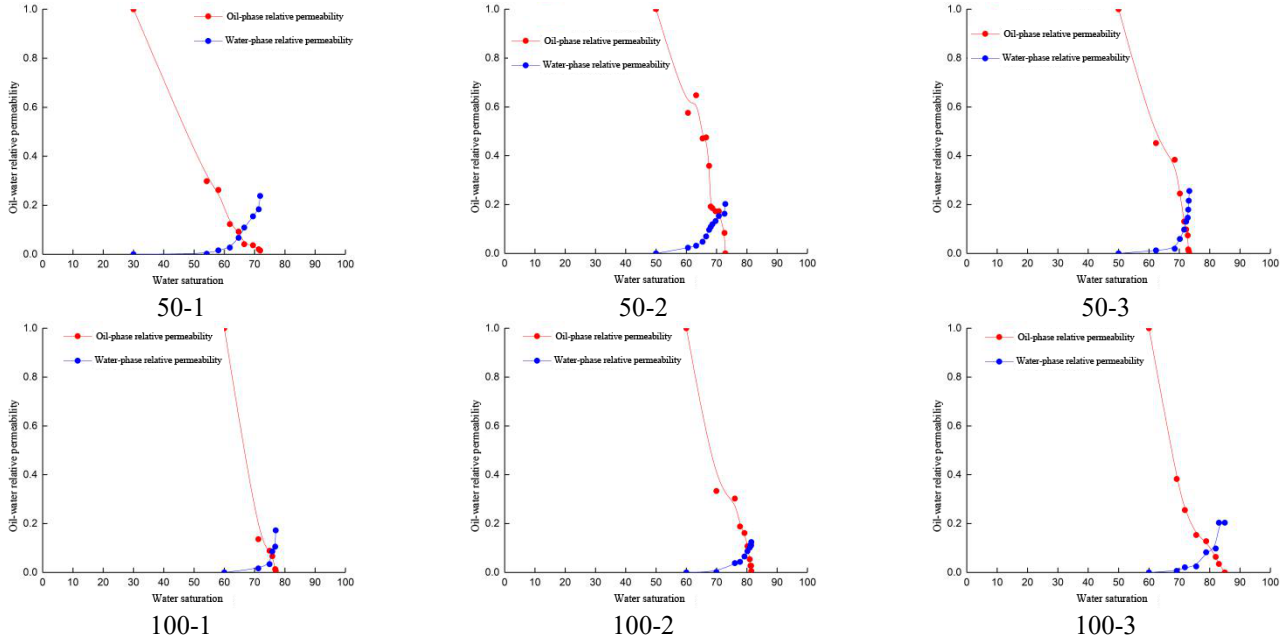


Figure 3. Oil-water relative permeability curves

### 4.3 Analysis of experimental results of gas-water relative permeability curves measured by unsteady-state method

Under a constant pressure of 0.1MPa, the results of the experiment of displacing water with gas at unsteady-state are shown in Figure 4.

Under a constant pressure of 0.2MPa, the results of the experiment of displacing water with gas at unsteady-state are shown in Figure 5.

Under a constant pressure of 0.3MPa, the results of the experiment of displacing water with gas at unsteady-state are shown in Figure 6.

Under a constant pressure of 0.4MPa, the results of the experiment of displacing water with gas at unsteady-state are shown in Figure 7.

According to Figure 4-7, under the conditions of different injection pressure, core permeability, and core length values,

after the displacement starts, with the increase of gas saturation, the water-phase relative permeability curves show a steep decline in the initial stage, and the decline gradually slows down in later stage. As shown in Figure 5, when injection pressure is constant and the core permeability is 10md and 50md, as the core length grows, the iso-permeability points and the co-permeation areas obviously move to the left, showing the characteristics of increased hydrophilicity, but such characteristics is not obvious when the core permeability is 100md, this indicates that during the measurement of relative permeability, for low-permeability cores, the core length has an impact on the measurement results of relative permeability curves; when the core length is about 20cm, the measurement results are relatively accurate. For high-permeability cores, the impact of core length on the measurement results of relative permeability curves is not obvious.

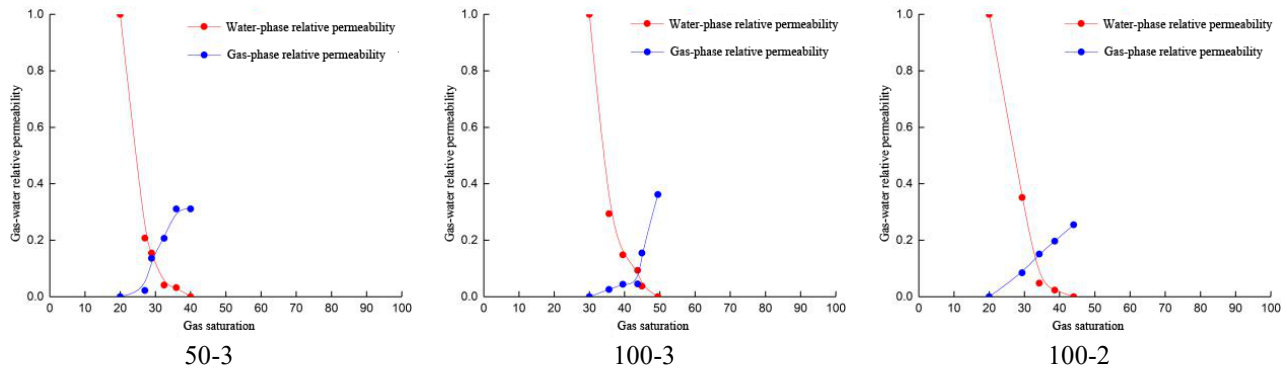


Figure 4. Unsteady-state gas-water relative permeability curves under a constant pressure of 0.1MPa

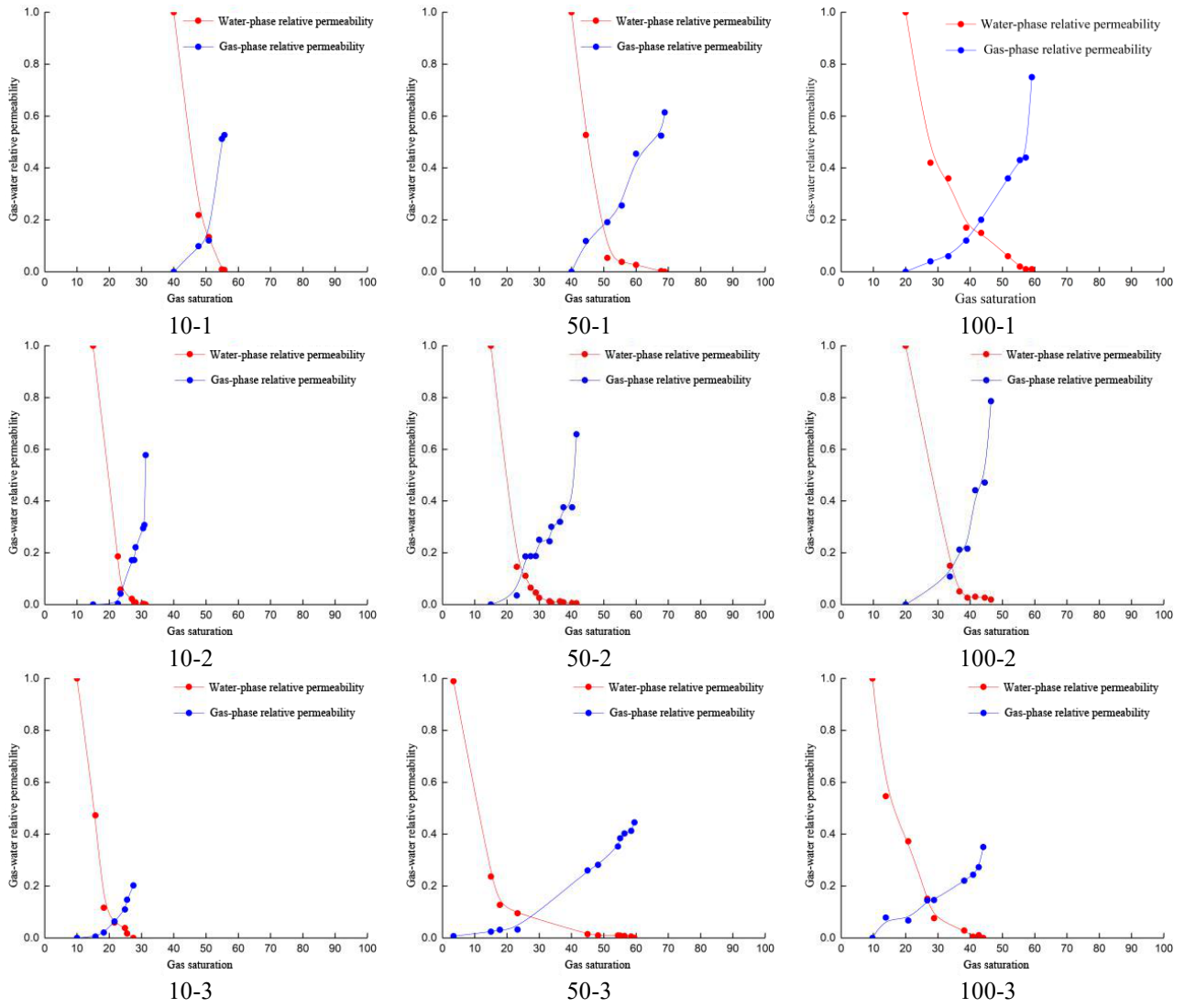


Figure 5. Unsteady-state gas-water relative permeability curves under a constant pressure of 0.2MPa

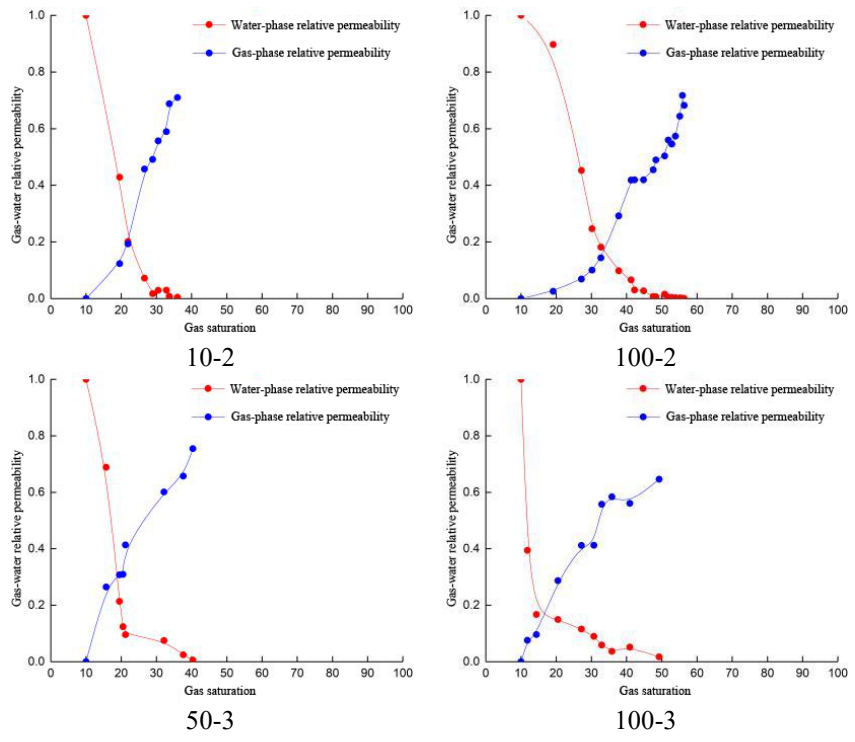


Figure 6. Unsteady-state gas-water relative permeability curves under a constant pressure of 0.3MPa

As shown in Figure 8, when injection pressure and core length are constant, as the core permeability increases, the gas-liquid relative permeability increases as well, the iso-permeability points tend to move to the right, and the gas-liquid co-permeation areas increase.

As shown in Figure 9, when core permeability and core length are constant, for low-permeability cores, as the

injection pressure grows, the gas-water co-permeation areas increase, the gas-water relative permeability increases, and the curves move to the right. As for high-permeability cores, within a certain pressure range, the gas-water co-permeation areas increase; when the pressure continues to grow, the gas-water co-permeation areas do not change much.

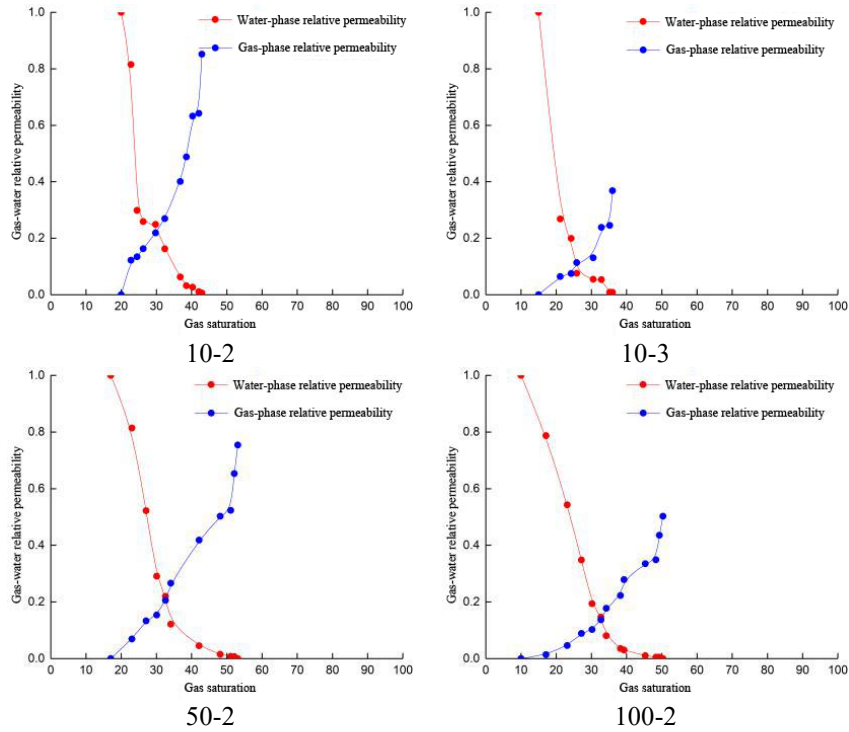


Figure 7. Unsteady-state gas-water relative permeability curves under a constant pressure of 0.4MPa

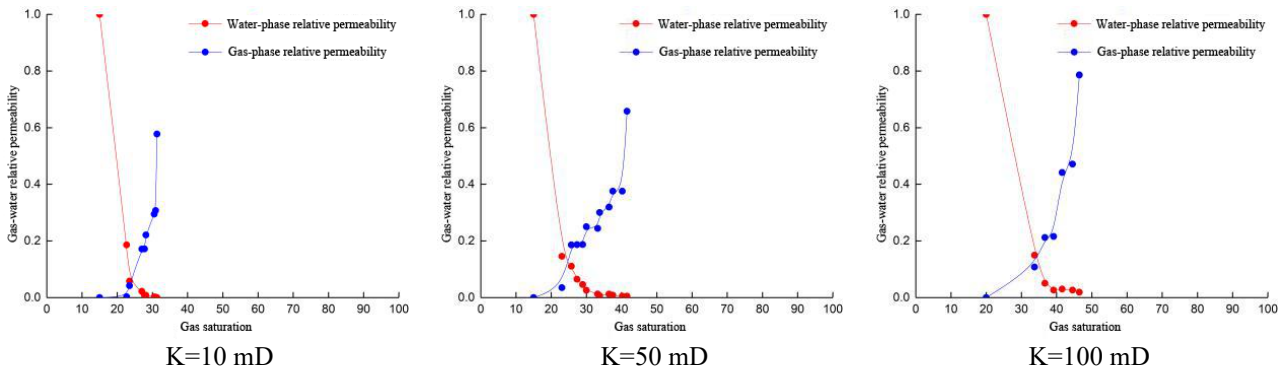
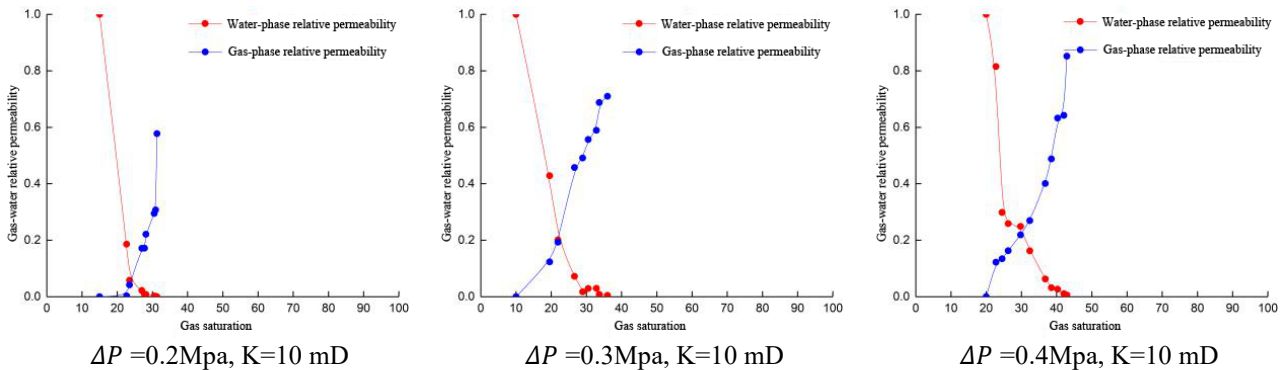
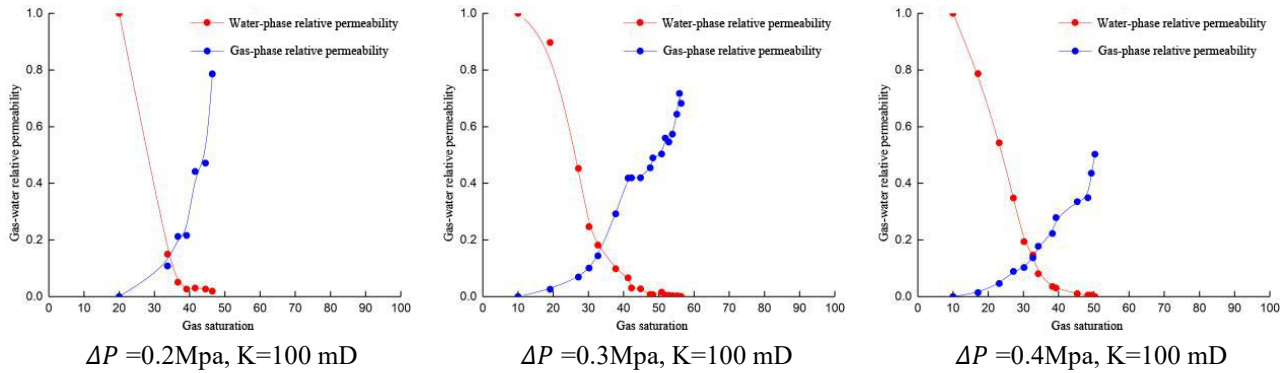


Figure 8. Comparison of relative permeability curves under an injection pressure of 0.2MPa and a core length of 20cm





**Figure 9.** Comparison of relative permeability curves under a core length of 20cm

## 5. CONCLUSIONS

(1) In the measurement of oil-water relative permeability curves, as the core length grows, the iso-permeability points move to the right. When the core length is greater than 20cm, the iso-permeability points are basically stable, indicating that the core length has an impact on the measurement results of the oil-water relative permeability curves.

(2) In the measurement of gas-water relative permeability curves, under the conditions of different injection pressure, core permeability, and core length values, after the displacement starts, with the increase of gas saturation, the water-phase relative permeability curves show a steep decline in the initial stage, and the decline gradually slows down in later stage.

For low-permeability cores, when the injection pressure is constant, as the core length grows, the iso-permeability points and the iso-permeation areas show an obvious tendency of moving to the left, but such tendency is not obvious when the core length is greater than 20cm, and high-permeability cores do not have such characteristics, indicating that the core length has an impact on the measurement results of relative permeability curves, and the measurement results are relatively accurate when the core length is about 20cm. For high-permeability cores, the impact of core length on the measurement results of the gas-water relative permeability curves is not obvious.

When core permeability and core length are constant, for low permeability cores, as the injection pressure grows, the gas-water co-permeation areas increase as well, the gas-water relative permeability increases, and the curves move to the right. As for high-permeability cores, within a certain pressure range, the gas-water co-permeation areas increase; when the pressure continues to grow, the gas-water co-permeation areas do not change much.

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