



Research Article

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Research and Application of Microfluidic Control Technology for Functional Completion Screen



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Abstract

Conventional completion screens suffer from uneven inflow profile, severe water channeling, rapid productivity decline in high water-cut stages and low reservoir utilization efficiency in oilfield development. Aiming at the above technical problems, this paper carries out research on microfluidic control technology for functional completion screens. By optimizing the microscopic pore structure of the screen and constructing nano-micro scale precise flow control channels, differential regulation of oil and water is realized based on microfluidic hydrodynamic mechanisms. The proposed technology effectively inhibits formation water breakthrough, balances the inflow profile of horizontal well sections, reduces the comprehensive water cut, and improves single-well productivity and reservoir utilization efficiency. This study bridges the technical gap between microscopic flow control mechanism and macroscopic completion production, provides theoretical support and technical approaches for geologic-engineering integrated development, and supports the efficient, high-quality and long-term development of oil and gas wells.

Keywords: Completion Screen; Microfluidic Technology; Oil-Water Regulation; Water Control and Oil Enhancement; Geology-Engineering Integration; Productivity Improvement

Introduction

In the middle and late development stages of oil and gas fields, horizontal wells and deviated wells generally face problems such as edge and bottom water invasion, strong interlayer heterogeneity and severe local water channeling. Conventional screens only perform simple sand control and flow conduction without active fluid regulation capability, which cannot adapt to the heterogeneous seepage characteristics of reservoirs. This easily causes water channeling in high-permeability zones and insufficient reserve utilization in low-permeability zones, resulting in rapid water cut rise and continuous productivity decline, restricting the efficient development of oil and gas reservoirs.

Microfluidic technology can precisely regulate fluid migration laws through nano and micro-scale flow channels and realize differential shunting, throttling and flow stabilization of fluids with different viscosities and physical properties. By introducing

microfluidic flow control mechanisms into the structural optimization of completion screens, the single filtering function of traditional screens is upgraded, and a functional screen system with microscopic precise flow control and macroscopic balanced production is constructed. This technology fundamentally solves water channeling problems, realizes water control, oil stabilization and production enhancement, and provides a new technical support for fine geology-engineering integrated development.

Technical Theoretical System and Core Mechanism

Basic Theoretical System

Based on four basic theories including microscale fluid mechanics, two-phase seepage mechanics, interfacial physical chemistry and porous medium seepage theory, this technology breaks through the limitations of traditional macroscopic completion technology and establishes a new completion theoretical system of "nano-microscale microscopic regulation

and macroscopic productivity improvement". Different from the empirical design of conventional screens relying on single pore size filtration, the microfluidic water-control screen realizes differential and controllable seepage of oil and water based on quantitative theories of fluid viscosity difference, interfacial tension effect, scale confinement effect and channel shear effect, solving the theoretical bottleneck of water channeling control in heterogeneous reservoirs.

a) Microscale confined seepage theory: When the flow channel is reduced from conventional millimeter scale to nano-micro scale, the fluid no longer follows the traditional macroscopic Darcy seepage law and presents obvious scale confinement effects. The closer the channel size is to the fluid molecular interface scale, the more significant the changes in fluid viscosity, flow resistance and flow regime. Water has low viscosity and high interfacial activity, resulting in a sharp increase in resistance in microscale channels; crude oil has high viscosity and strong molecular agglomeration, and is slightly inhibited by microchannels, providing core theoretical support for adaptive oil-water separation and regulation.

b) Oil-water interfacial tension theory: A stable

interfacial tension exists at the oil-water interface. Special shaped microfluidic channels change the curvature of the fluid interface and generate additional capillary resistance. Formation water easily forms continuous water films in micropores and produces strong capillary plugging effects to restrain water breakthrough; crude oil can break through weak interfacial resistance and pass through channels smoothly, realizing the passive adaptive effect of "oil passage and water resistance".

c) Viscous shear differential resistance theory: The tortuous microfluidic channels produce strong shear effects on fluids. Low-viscosity water suffers severe velocity attenuation and sharp resistance increase under shear disturbance, while high-viscosity crude oil has stable flow performance and high flow efficiency. Automatic sorting and regulation are realized through viscous resistance differences.

Illustration: (Figure 1) The left side shows seepage of conventional macroscopic screens with simultaneous oil-water inflow and severe water channeling; the right side presents microfluidic channel seepage with blocked water flow and smooth oil flow, intuitively demonstrating the advantages of microscale water control theory.

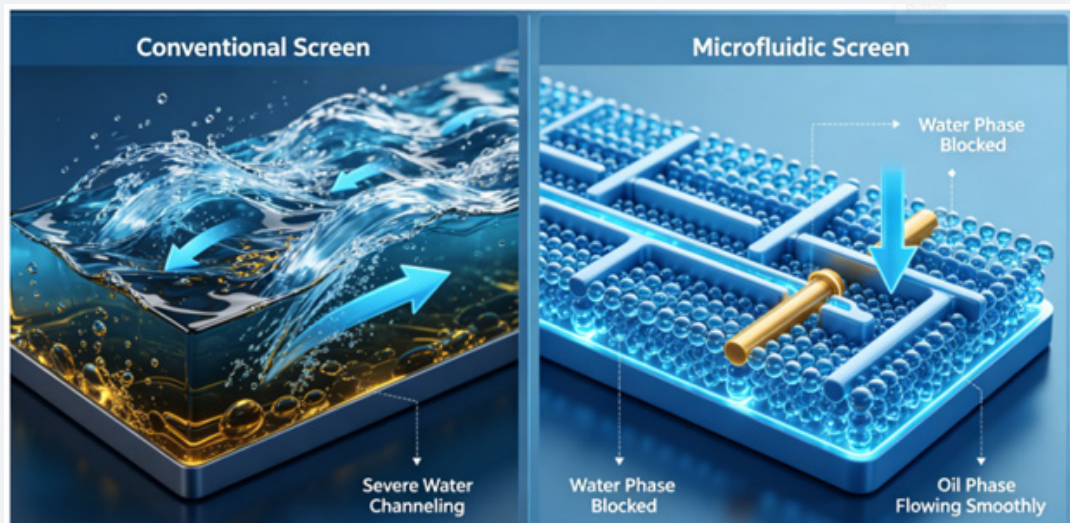


Figure 1: Schematic diagram of differential oil-water seepage mechanism in nano-microscale microfluidic channels.

Core Mechanism of Microfluidic Differential Water Control

Oil and water fluids exhibit significant seepage differences in nano-microscale channels. Crude oil has high viscosity and large flow resistance, while formation water has low viscosity and strong fluidity. Conventional screens have large channel

scales without differential constraints, causing water to rapidly break through along high-permeability channels and form water channeling. The functional microfluidic screen adopts multi-stage special microscale flow control structures, integrating scale effect, interfacial tension effect and viscous resistance effect to achieve adaptive regulation. High-fluidity formation water is throttled and inhibited, while crude oil seepage is promoted, realizing self-

adaptive dynamic regulation of “stable oil production and effective water control”. Relying purely on fluid physical differences, this technology requires no external energy or chemical intervention, with long-term stability and no reservoir damage.

Microstructure Upgrade and Gradient Seepage Mechanism

Different from the uniform millimeter-scale holes of traditional screens, the functional microfluidic screen reconstructs the surface sand-filtering network and internal flow guide channels, constructing a three-level composite microfluidic structure of “surface micron sand filtration + middle gradient flow guidance + inner nanometer water control”. Through the composite

matching design of micron diversion grooves and nano passivated pores, the near-well seepage field is completely improved while ensuring accurate sand control and anti-blocking performance. Conventional screens show centralized inflow and dominant water channeling in high-permeability zones, while microfluidic gradient structures disperse fluid pressure, balance seepage velocity in all directions, eliminate dominant water channeling pathways, and solve the problems of uneven near-well seepage and large interlayer utilization differences.

Illustration: (Figure 2) The diagram displays the surface sand-filtering layer, middle flow-guiding layer and inner water-control layer, marking micron and nanometer scale parameters to reflect the composite structural design principle.

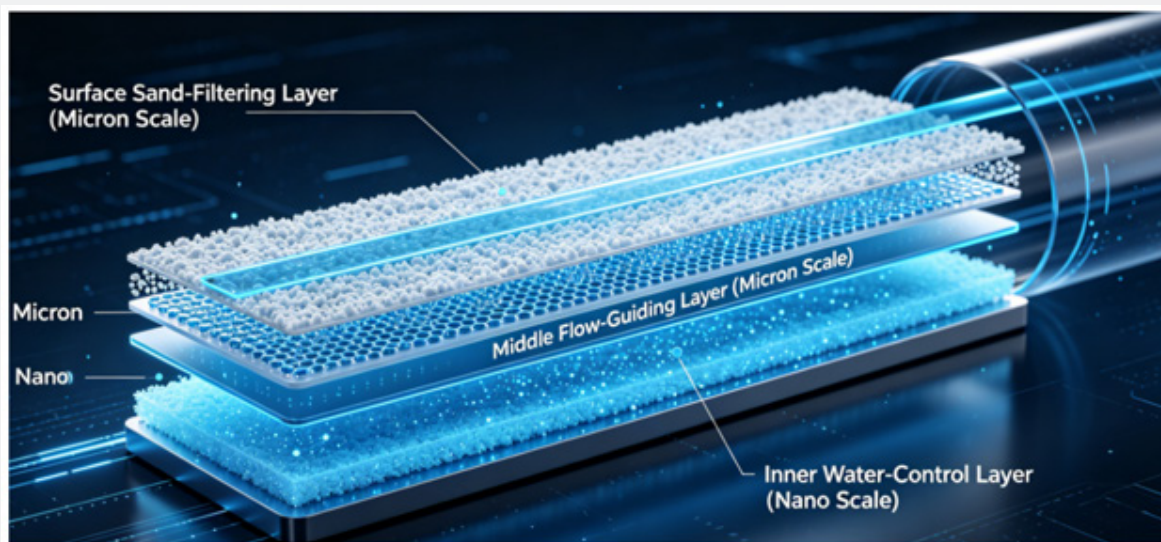


Figure 2: Schematic diagram of microscopic hierarchical structure of functional microfluidic screen.

Illustration: (Figure 3) The left figure shows concentrated seepage and obvious local water channeling of conventional screens; the right figure presents uniform seepage without dominant water flow channels of microfluidic screens, intuitively reflecting the technical advantages.

Theoretical Formula System of Microfluidic Flow Control

Different from traditional macroscopic Darcy seepage, the microfluidic control technology for functional completion screens realizes adaptive oil-water differential regulation based on three core theoretical formulas: microscale capillary resistance formula, viscous pressure drop formula, and oil-water throttling resistance difference formula, which constitute the mathematical basis for water control and oil stabilization.

a) Microscale capillary resistance formula

The nano-microscale pores of microfluidic screens are equivalent to special capillaries, and the additional capillary resistance during oil-water flow is the key to realizing “water

resistance and oil passage”.

$$\Delta P_c = \frac{4\sigma \cos f_0 \theta}{d}$$

Parameter definition:

ΔP_c — Additional capillary resistance, Pa;

σ — Oil-water interfacial tension, N/m;

θ — Wetting contact angle between fluid and pore wall, °;

d — Equivalent diameter of microfluidic channel, m.

Mechanism analysis: Formation water is a water-wet phase with an extremely small contact angle and $\cos f_0 \theta$ close to 1. In nano-microscale pores, the capillary resistance of water increases sharply and achieves effective throttling and interception. Crude oil is an oil-wet phase with a large contact angle and much lower capillary resistance, enabling smooth passage. The smaller the pore size, the more significant the scale effect and oil-water resistance difference, resulting in better water control performance.

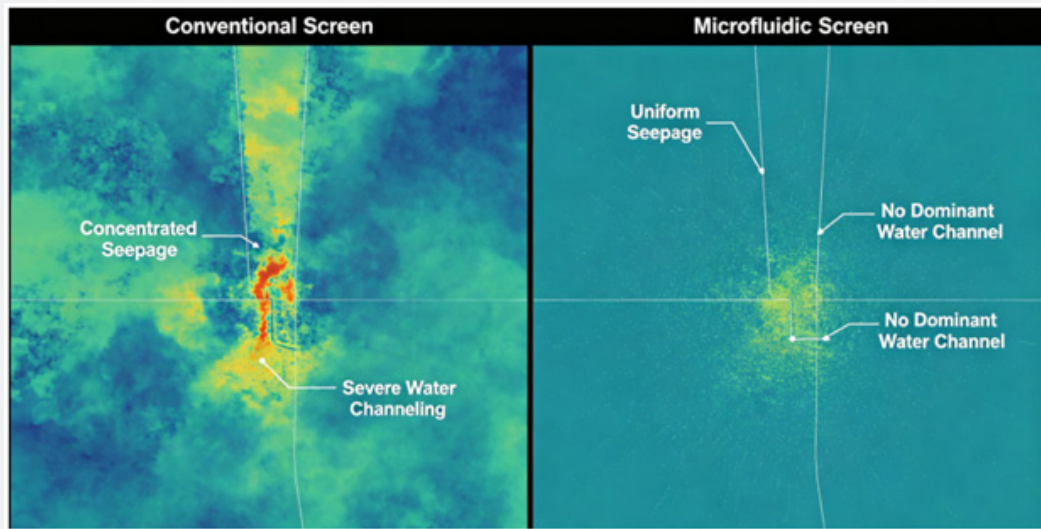


Figure 3: Comparison of downhole seepage field distribution between conventional screen and microfluidic screen.

b) Microchannel viscous pressure drop formula

Fluid flowing in tortuous microfluidic channels produces viscous pressure drop following microscale laminar flow rules.

$$\Delta P = \frac{32\mu Lv}{d^2}$$

Parameter definition:

ΔP — Viscous pressure drop, Pa;

μ — Fluid dynamic viscosity, Pa·s;

L — Effective length of microfluidic channel, m;

v — Fluid seepage velocity, m/s;

d — Equivalent channel diameter, m.

Mechanism analysis: Although water viscosity is lower than crude oil, water flows faster in microchannels and produces a quadratic increase in viscous pressure drop under high velocity, leading to significantly increased flow resistance. Crude oil flows stably with low pressure drop and high flow efficiency. The formula quantitatively verifies that microfluidic structures realize passive adaptive water control based on fluid physical differences.

c) Modified microscale Darcy seepage formula

Traditional Darcy formula is not applicable to nano-microscale seepage. A modified microscale Darcy formula is adopted:

$$Q = \frac{KA\Delta P}{\mu L} \cdot \eta$$

Parameter definition:

Q — Fluid seepage flow rate, m³/s;

K — Equivalent permeability of microstructure, m²;

A — Flow cross-sectional area, m²;

ΔP — Driving pressure difference, Pa;

η — Microscale correction coefficient (smaller pore size corresponds to larger correction coefficient).

Mechanism analysis: For conventional screens, $\eta \approx 1$, and oil-water flow is only affected by pressure difference, causing easy water channeling. For microfluidic channels, the correction coefficient of water increases significantly to inhibit water flow, while oil seepage is barely affected, realizing differential seepage of high oil permeability and low water permeability.

d) Oil-water flow regulation evaluation formula

The oil-water resistance ratio λ is defined to quantitatively evaluate the water control and production enhancement performance:

$$\lambda = \frac{\Delta P_w}{\Delta P_o}$$

Definition: ΔP_w is water-phase flow resistance; ΔP_o is oil-phase flow resistance.

Evaluation criteria:

a) Conventional screen: $\lambda \approx 1$, similar oil-water resistance with no water control capability;

b) Microfluidic functional screen: $\lambda \gg 1$, water resistance is far greater than oil resistance with excellent water control performance.

Formula summary: The above theoretical formulas systematically explain the mathematical mechanism of microfluidic screen water control from capillary force, viscous resistance, seepage law and flow differentiation. The nano-micro structural design amplifies the flow resistance difference between

oil and water, fundamentally inhibits water channeling and balances production performance, providing accurate theoretical and quantitative support for structural optimization, parameter design and field application of functional completion screens.

Technical Innovation and Functional Advantages

Microscale Precise Flow Control and Water Cut Reduction

Relying on nano and microscale microfluidic structures, the technology blocks water channeling pathways from the seepage source, restrains rapid edge and bottom water advance, solves local water channeling at the heel and toe of horizontal wells, effectively reduces comprehensive water cut, delays water cut rising trend, and extends the stable production period.

Balanced Inflow Profile and Improved Reservoir Utilization

Conventional screens cause excessive liquid production in high-permeability zones and insufficient reserve utilization in low-permeability zones. Microfluidic screens adaptively adjust flow distribution of different well sections, suppress water production in high-permeability layers, activate productivity of low-permeability oil layers, balance the production profile of horizontal sections, and greatly improve the utilization efficiency of thin and heterogeneous reservoirs.

Integrated Sand Control and Flow Control for Long-Term Production

This technology integrates precise micron-scale sand control and microfluidic water control, avoiding sand plugging and failure. It maintains stable long-term flow control performance and overcomes the defects of easy scaling, blockage and short service life of conventional water control tools, meeting the requirements of long-term continuous oil and gas production.

Support for High-Quality Geology-Engineering Integrated Development

The technology realizes accurate matching between reservoir heterogeneity and completion engineering regulation. Targeted microchannel parameters can be optimized according to reservoir physical properties and oil-water distribution characteristics of different blocks, forming personalized water control completion schemes. It builds an integrated technical chain of geological cognition, engineering design and field development, supporting refined and intelligent oilfield development.

Technical Implementation Scheme

Accurate Reservoir Parameter Evaluation

Based on block geological data, reservoir porosity, permeability, oil-water viscosity ratio, edge-bottom water energy and heterogeneity are analyzed to identify dominant water

channeling pathways and low-efficiency production intervals, and determine core parameters including microchannel scale, pore gradient and layout position of microfluidic screens.

Structural Optimization and Design of Functional Microfluidic Screen

According to reservoir fluid physical properties, composite gradient microfluidic structures are designed. The matching ratio of nano passivated pores and micron diversion channels is optimized to balance sand control accuracy, oil flow capacity and water throttling effect, realizing integrated integration of water control, oil stabilization and sand control.

Field Completion Construction

According to horizontal well characteristics, functional microfluidic screens are precisely deployed in intervals with high water channeling risk and strong heterogeneity, combined with conventional screens to optimize the string structure, realize adaptive fluid regulation in the entire wellbore, and ensure balanced utilization of all reservoir layers.

Dynamic Monitoring and Effect Optimization

After production, real-time monitoring of liquid production, water cut, and productivity variation is carried out. Dynamic production data are used to reversely optimize microchannel structural parameters, continuously improve the block-adaptive microfluidic water control completion system and achieve sustained development performance improvement.

Field Application Effect and Value

Field applications show that the microfluidic control technology for functional completion screens can effectively balance horizontal well inflow profiles and significantly inhibit formation water breakthrough. Compared with conventional screen completion, the comprehensive water cut is reduced by 15%~25%, the stable production period is extended by more than 30%, and reservoir utilization efficiency is increased by about 20%, achieving remarkable single-well production enhancement. Relying on pure physical flow control mechanism, the technology requires no chemical agents, causes no reservoir damage, features simple construction, strong scaling and blockage resistance and long service life, and solves the industry bottlenecks of poor pertinence, insufficient oil stabilization effect and high maintenance cost of conventional water control technologies.

Meanwhile, this technology constructs an integrated development model of "accurate geological evaluation + microscopic flow regulation + precise engineering implementation", provides a new technical approach for the efficient development of deep, heterogeneous and high water-cut reservoirs, promotes refined and high-quality oilfield development, and realizes high-efficiency oil and gas production [1-4].

Conclusion and Prospect

Based on microscale fluid mechanics and two-phase seepage theory, the microfluidic control technology for functional completion screens breaks through the technical limitation of single filtering function of traditional screens. Through nano-microscale differential fluid regulation, it fundamentally solves the problems of water channeling, rapid productivity decline and uneven reservoir utilization, effectively reducing water cut, stabilizing oil productivity and improving reservoir utilization efficiency. The technology is suitable for horizontal well development of various heterogeneous, high water-cut and edge-bottom water developed reservoirs, with complete theoretical system, stable technical performance and wide field adaptability.

In the future, intelligent monitoring and numerical simulation technology will be combined to further optimize microchannel

structural parameters and develop self-adaptive intelligent microfluidic screens. The geology-engineering integrated water control completion system will be continuously improved to provide solid technical support for long-term stable and high-quality development of oil and gas fields.

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