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# Formation adaptability of combining modified starch gel and nitrogen foam in profile modification and oil displacement

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Problems such as high permeability, serious heterogeneity, and unfruitful water flooding exist in developing offshore oil fields. Integrating modified starch gel as profile control agent and foam to displace oil was investigated to improve production problems. Physical models with in-layer and interlayer heterogeneity, as well as different permeability ratios, were used in the physical simulation experiments. The feasibility and mechanism of this combined technology were discussed in detail. Experimental results indicated that the viscoelastic-modified starch gel with high viscosity could effectively block the high permeability channels, making foam migrate uniformly in the medium, and mobilize the remaining oil in the low permeability layers. For inner heterogeneous models, starch gel blocked the high permeability layer, as well as improved the sweeping volume of nitrogen foam. In addition, at permeability ratios exceeding 40, the foam sweeping efficiency and oil displacement effect became less significant. For interlayer heterogeneous models, the starch gel effectively blocked the high permeability layer. Based on the experimental results and theoretical analysis, the sweeping volume and displacement mechanism of the synergistic effects were discussed. The laboratory results can provide reference for optimizing nitrogen foam flooding and improving oil displacement.



## 1. Introduction

Q3 Multiple layers, substantial thickness, high permeability, severe heterogeneity, and wide injector–producer spacing are the common geological complexities of China offshore reservoirs [1]. Vast investments in exploration, short work span of production platform, and high operating cost accelerate the development pace of reservoirs that are situated far from land. Intensive water injection and production are unfavorable but compelling methods used in numerous reservoirs. Therefore, water channels develop unavoidably due to chronic water washout. Invalid water displacement directly contributes to uneven injection and production profile, low sweep efficiency, surging water cut, and sharp reduction in oil production.

In recent years, many water shutoff agents have been studied [2–4]. Common practice in oil fields includes water injection following profile control operation to displace the remaining oil, but water channeling occurs because of huge permeability difference in offshore reservoirs. Zhao proposed the "2 + 3" oil displacement mode in 1999 [5], namely, confined chemical flooding based on thorough fluid profile control. Several studies and practices have been conducted on this subject, and numerous integrated profile control methods have been developed [6,7]. Modified starch gel is a high tensile gel that is produced with modified starch and acryl amide monomer through grafting copolymerization [8,9]. The favorable viscosity allows injecting the gel solution at relative low pressure on surface, and high tensity as well as cohesiveness with rock under formation conditions makes it possible to block the water production zone. Foam is a typical thermodynamically unstable dispersion system. Foams with high apparent viscosity and selective percolation were introduced to increase sweeping efficiency in low permeability reservoirs [10–13]. Nguyen et al. studied the effect of crossflow on foam-induced diversion in layered formations using computed tomography [14–16]. Hirasaki, Kovscek, and Rossen et al. studied the rheological properties of foam [17–20] from one single prospect, such as resistance factor or modified gas viscosity, not combined with another technique.

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**Table 1**
Components of modified starch gel.

| Components | Modified starch | Acrylamide monomer (AM) | Cross-linker | Initiator |
|---|---|---|---|---|
| Content (%) | 4 | 4 | 0.15 | 0.005 |

**Table 2**
Starch Gel Parameter.

| Gelling time (h) | Mean Storage Modulus (Pa) | Mean Loss Modulus (Pa) | Viscosity (mPa·s) |
|---|---|---|---|
| 7.5 | 336.3 | 24.0 | 77,166 |

This paper introduces an integrated profile control technique that combines the advantages of the modified starch gel and foam. A series of simulated experiments has been conducted to study the properties of agents, as well as the feasibility and formation adaptability of the compound technology. Oil displacement efficiency, as well as the sweeping scope in both in-layer and interlayer heterogeneous models with different permeability combinations and permeability range applicable for foam flooding, can be obtained to provide necessary experimental and theoretical guidance for reasonable oil field development.

## 2. Experiment

### 2.1. Experimental materials

The core flooding arrangements include a 2 PB00C constant flux pump manufactured by Beijing Satellite Manufacture Factory, thermotank manufactured by Haian Huada Petroleum Instrument Factory, fill and draw basin, pressure sensor, vacuum pump, and hand pump. In addition, the pressure acquisition module software from Beijing Kunlun Tongtai Automatic Software Technology Ltd., electronic balance, and stirrer are used as auxiliary tools.

The brine sample is BZ19-4-simulated formation water with a salinity of 5863.27 mg/L. The oil sample is a 1:2 mixture of degassed and dehydrated crude oil from SZ36-1 oil field and aviation kerosene. Viscosity of the mixture is 57 mPa s.

The cores for the experiment are 30 cm $\times$ 4.5 cm, square section and three-layered synthetic sandstones cemented with epoxy.

The profile control agent is the modified starch system composed of modified starch, AM, N-methylol acrylamide (Beijing Chemical Works, purity 98%) as cross-linker, and potassium peroxydisulfate (Beijing Modern Eastern Fine Chemicals, purity 98%) as triggering agent. The displacing plug is 4 wt.% modified starch resolution. Table 1 and Table 2 illustrate the content and parameters of the gel system respectively.

Gelling time refers to the static gelling time, which can be adjusted by the triggering agent content. The viscosity can reach as high as 77,166 mPa s after the solution turns into gel. Fig. 1 displays the state of the starch gel. The gel viscosity was measured by MCR-301 rheometer (Anton Paar, Austria). Fig. 1 indicates the favorable viscoelasticity of the gel.

Fig. 2 demonstrates the good blocking effect of the gel system in sand-packed tube ($K = 7000 \times 10^{-3}$ $\mu m^2$, 0.3 PV gel) since the inlet pressure rise drastically. The breakthrough pressure of subsequent water increases to 3550 KPa, and the effective permeability drops to $3.42 \times 10^{-3}$ $\mu m^2$ after gel injection. The residual resistance factor is 2020.97 with a 99.95% plugging perecentage. The result proves that starch gel can effectively block the high permeability sand-packed model.

In this experiment, α-olefine sulfonate (SD-1) serves as the active component in the surfactant, and a salt-resistant and hydrophobic associating polymer-HPAM acts as foam stabilizer. The foaming system include 0.5 wt.% surfactant as foaming agent and 0.2 wt.% foam stabilizer, pure nitrogen, and 0.5 wt.% surfactant solution as surfactant water. The performance of the foam system is tested according to the Waring blender method. About 100 mL foaming agent solution generates 410 mL foam, and the half-life of the bubble drainage is 198 min.

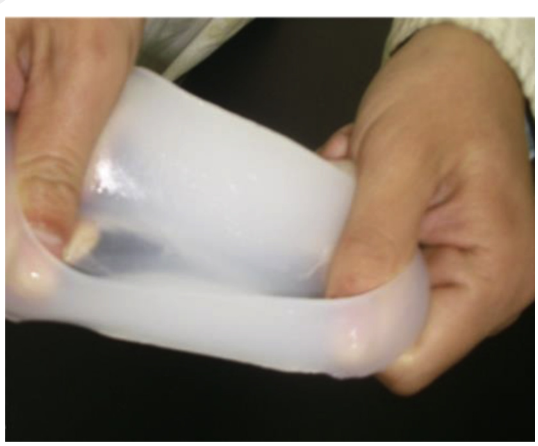

**Fig. 1.** Modified starch gel.