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Enhanced foam stability by adding comb polymer gel for in-depth profile control in high temperature reservoirs

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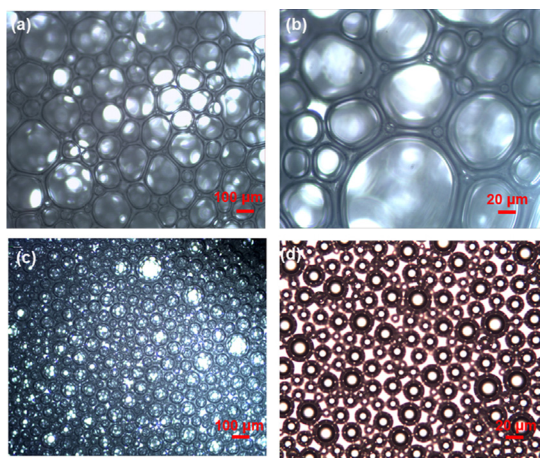
HIGHLIGHTS

- A long-term stability of gel enhanced foam was prepared for in-depth profile control in high temperature reservoirs.
- Stability mechanisms of gel enhanced foam by comb polymer gel were studied.
- Enhanced oil recovery mechanisms of gel enhanced foam were proposed.

GRAPHICAL ABSTRACT

(a) and (b): morphology of conventional aqueous foam; (c) and (d) morphology of gel enhanced foam.



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ABSTRACT

A long-term stability of gel enhanced foam as an in-depth profile control agent in high temperature reservoirs was successfully prepared by adding comb polymer gel. The increased viscosity of gel brings a negative effect on surface tension which reduces the gel enhanced foam volume. In turn, the increased viscosity could enhance the thickness and strength of foam film which increases foam stability and plugging capacity in porous media. The morphology results show that the gel enhanced foam has a thicker bubble film which enhances its foam stability. The effect of injection mode, gas–liquid ratio, gas injection velocity and formation permeability on the plugging capacity was investigated by single sand-pack experiments. When the gas–liquid ratio and gas injection velocity were respectively set at 1:1 and 0.5 ml/min, co-injection of gel enhanced foaming solution and gas could obtain a better plugging capacity in high permeability sand-packs. Parallel sand-pack experiments show that the profile improvement capacity of high formation permeability ratio is much better than that of low formation permeability ratio. The visual simulation experiment was also conducted to illustrate the flowing behavior of gel enhanced foam. By Jiamin effect or Jamin superimposed effect, directly plugging and bridging in the large pore space, the gel enhanced foam can effectively reduce the permeability of porous media in high

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permeability zones and divert fluid into low permeability zones, thus increases the swept volume. The treatment has been successfully used in Henan oilfield of China which provides a reference to water production control in other similar high temperature oilfields.

1. Introduction

Foam has been widely used for water production control in oil recovery operations [1–4]. When being injected into formation, the foam can increase apparent viscosity of gas and reduce gas mobility in high permeability zones. The present of foam could improve oil swept volume effectively by pluging throat pores in high permeability zones and diverting fluid into low permeability zones [5,6]. Additionally, foam is usually formed by surfactant which may decrease oil-water interfacial tension and improve oil displacement efficiency [7,8]. Thereby, the studies on the application of foam have attracted great attention in oilfield industry.

Aqueous foams are the initial conventional foams for oil recovery applications. However, the interfaces of aqueous foams are only stabilized with surfactants which can be easily collapsed when being transported through porous media in the formation. Therefore, aqueous foams are not applicable for long-term water production control treatments. To obtain the long-term stability of foam in high permeability zones, polymers and polymer gels have been used as the external phase to increase foam stability [9–13]. When polymers have been added into surfactant solution, the viscosity of liquid phase increases which decreases liquid drainage rate, thus enhances foam stability. Compared with aqueous foams, polymer enhanced foam obtains a better gas blocking capability, greater decay half-life, and larger residual resistance factor after defoaming [14–16]. However, the stability of polymer enhanced foam could be confined by the limited increased viscosity of polymers. As polymer enhanced foam flowing in porous media, the viscosity would gradually reduce due to shear degradation and dilution caused by contacting with reservoir minerals and fluids [17,18], especially after a long-term water flooding. In addition, the viscosity of polymers significantly reduces with increasing temperature [19], and polymers are usually degraded when reservoir temperature is higher than 85 °C. All above may result in instable foam and finally failed water production control treatments in high temperature reservoirs.

Currently, using polymer gels as an external phase is another important method to improve foam stability. The gel enhanced foam behaves as polymer enhanced foams at the initial of injection stage. But the viscosity of gel enhanced foaming solution gradually increases when transporting in porous media. The increased viscosity will form a viscoelastic shell which improves the flowing resistance of water on foam film and reduces liquid drainage rate, then enhances foam stability. After gelation, bubbles are firmly trapped within the high viscosity gel film in porous media which improves plugging capacity in high permeability zones. Due to the high viscosity, the gel enhanced foam still behaves as a viscoelastic gel even after the bubble defoaming which ensures a high plugging capacity [20,21]. It can be an effective method for stabilizing the foam and controlling water production. In this paper, a gel enhanced foam system based on comb polymer was studied for in-depth profile control in high temperature reservoirs. There are few reports about foaming properties and in-depth profile control capacity of this gel enhanced foam systems in high temperature reservoir. So in this research, the foaming performance, the effect of injection mode, gas–liquid ratio, gas injection velocity and formation permeability on the plugging capacity, formation permeability ratio on profile improvement capacity, and the flowing behavior of gel enhanced foam in porous media are systematically studied. In addition, oilfield test is also conducted to confirm that using gel enhanced foam is an effective in-depth profile control technology for water production control in high temperature reservoirs. Through the laboratory experiments and oilfield tests, we hope the work can be a further promotion and application for water production control in other similar mature oilfields.

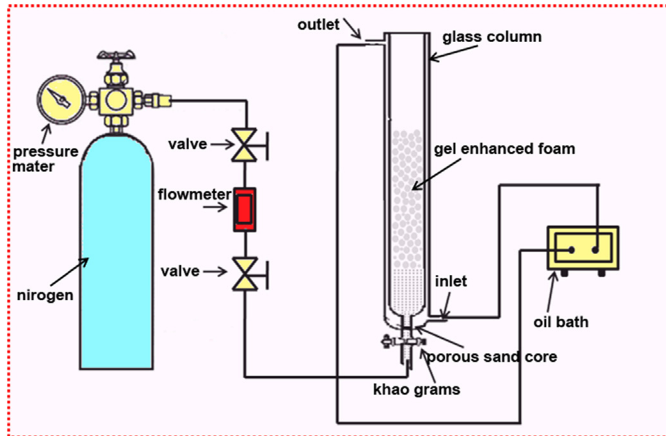

Fig. 1. Schematic of foam generation apparatus.

2. Materials and methods

2.1. Materials

Comb polymer with a hydrolysis degree of 26.8% and an average molecular weight of 23,000,000 g/mol was provided by Hengju Co. Ltd., China. The phenolic resin cross-linker was purchased from Yuguang Co. Ltd., China. A high temperature surfactant HN-1 used to generate foam was provided by Henan oilfield, China. Nitrogen gas with a purity of 99.98% was provided by Tianyuan Co. Ltd., China. The crude oil was provided by Henan oilfield of China, and the viscosity is 125 mPa s at 70 °C. The salinity of brine is 2380 mg/L, and used in all experiments.

2.2. Experimental methods

2.2.1. Performance of gel enhanced foam experiments

A modification of Ross-mile method was used to evaluate the performance of gel enhanced foam. The foam generation device is consisted of conventional glass column with a length of 55.0 cm and inner diameter of 4.0 cm, which is fitted with a porous sand core placed at the base of the column (Fig. 1). 20 ml of foam solution was injected into the glass column. To generate foam, nitrogen was sparged through the foam solution via the porous sand core. After the foam was formed, the initial foam volume was immediately recorded, which was used to describe foaming capacity. Generally, the foam stability was characterized by the defoaming time (decay half-life), which is defined as a time required for obtaining half of the solution surface free of bubbles. All the foam tests were performed at 100 °C.