THE IMPACT OF THERMAL AND CHEMICAL EFFECTS IN FRACTURE DEFORMATION

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Noordwijk, The Netherlands 27-30 September, 2009

ABSTRACT

Fractures are often the main conducting path for fluid flow during heavy oil production from carbonate reservoirs. The permeability of fractures is sensitive to changes in both temperature-induced stress changes and fluid chemistry during steam injection. The lack of a quantitative understanding of the impact of thermal and chemical processes on fracture permeability and fluid production increases uncertainty on production forecasts.

The main aim of this paper is to address the effects of thermal and chemical process on fracture permeability and fluid production. A detailed experimental program was carried out on fractured chalk to improve understanding of the controls on fracture permeability under constant confining pressure and flow rate. Due to the complexity of the combined thermal and chemical effects, different fluid types (oil and water) were re-circulated through the fracture at different temperatures, varying from ambient to 50 ^{o}C. Changes in the pressure drop across the fracture sample and X-ray CT imaging during flow were used to analyze thermo-chemical effects. The pore water chemistry was also monitored using electrical conductivity and inductively-coupled plasma (ICP) spectrometry to evaluate the extent of carbonate dissolution. The pressure drop across the fracture was found to be temperature dependent. The increase in differential pressure indicates continuous changes in fracture shape and aperture causing a significant permeability decrease. Analysis of produced water samples indicated an increase in the concentration of Ca^{+2} and Mg^{+2} during the course of the experiments. These results indicate that calcite dissolution (rock water interaction) is partly responsible for increasing the pressure difference. Furthermore, CT images show that fracture surface deformation has occurred during oil and water flow because thermal expansion, carbonate dissolution and rock strength weakening resulted in fracture deformation and closure. The current results show that both the thermal and chemical effects could have a significant impact on fracture permeability during steam assisted EOR operations in fractured carbonate reservoirs. Overall, the results indicate that chemical and well as geomechanical processes need to be incorporated into simulation models to improve predictions on the long-term productivity during thermally-assisted EOR operations in fractured carbonates.

INTRODUCTION

Fractures act as a main flow path in the reservoir allowing the fluid such as water and hydrocarbons to move easily because of its high permeability value that ranges in Darcy [1] and they significantly impact fluid production and injection. Moreover, fractures affect rock strength and deformability because they represent planes of weakness which damage more easily compare to surrounding rock[2]. In fractured reservoir rock mass permeability is a function of fracture geometry, aperture and distance between two adjacent fractures planes, roughness and contact area. These parameters are affected by natural or induced changes (fluid pressure and thermal load) that will eventually affect effective permeability [3]. During thermal recovery, hot steam is injected into the reservoir which dramatically reduces the oil viscosity thus increasing its mobility. On the other hand, heating may have a significant impact on fracture surface deformation. As well as changing the reservoir temperature, condensed water is formed when the steam front comes in contact with a cold rock/fluid [4-6]. Consequently, a low salinity water front will propagate through the reservoirs. In addition, water within the aquifer may also encroach into the reservoir as pressures decline. In a fractured reservoir, these processes may lead to chemical interaction between the water and fracture surface [7] Because fracture dominates the deformation, strength and permeability of the intact rock it is important to have a good understanding on fracture mechanical, geometrical and hydraulic properties and their effects on rock mechanics and petroleum engineering. The key aim of this paper is to address one of the major uncertainties, namely, "*how is steam injection likely to affect the long term oil production in fractured carbonate reservoir*?" A particular concern is whether thermal and chemical interaction will lead, over time, to a dramatic reduction in the fracture permeability. It is important to evaluate the details of fracture deformation, which is reduction in fracture aperture caused by stress, temperature and chemical changes applied to a rock system, effects on initial aperture, surface topographies (roughness and contact points), stiffness and rock strength. The objective of this paper is to address experimentally the impact of thermal and water interaction on fracture topology and permeability.

EXPRIMENTAL PROCEDURE

Fluid flow experiments were performed on a chalk sample obtained from Flamborough Head located on the Yorkshire coast of England. It consists mainly of calcite with small fraction of quartz. Matrix porosity ranges between 18 to 20%. Axial fractures were created by applying compressive stress across a block of chalk placed between two sharp slides. Two fractured core plugs were used coded as FFA and FFC to address the effects of water interaction and heat separately. Matrix (non fractured) sample permeability determined by steady-state gas (nitrogen) method was 4.7 mD while effective permeability for FFA and FFC was 0.256 and 2.26 Darcy respectively at 1000 psi confining pressure. The sample was placed inside X-ray transparent core holder, within a Viton sleeve, and the fracture was parallel to the fluid flow direction. To image the fracture topology and aperture *in-situ* using X-ray computer tomography (CT) was used, which has a resolution of 250 micrometers.

In order to account the effects of chemical and thermal separately, different fluid types (oil and water) were re-circulated through the fracture. In one experiment oil was re-circulated at constant rate of 1.0 ml/min through FFC at temperatures varying from ambient to 50^{o}C. Temperature was controlled by internal and external heaters.

Hydrostatic confining pressure was applied on the fractured sample using and cycle of loading (between 1000 to 4000 psi) to remove hysteresis. Then, the confining pressure was maintained at 4000 Psi while the pressure drop was recorded. On a separate experiment, distilled water was re-circulated at 1 ml/min through FFA at room temperature and 1000 psi confining pressure. The electrical conductivity (EC) of the produced water was measured before being returned to the water supply container. Initially distilled water had an electrical conductivity of less than 10 µS/cm. Samples of produced water were collected for ICP-OES for analysis during the experiment. The samples were analyzed for dissolved Ca and Mg ions. Further details of the procedure can be found in [8]. Data (pressure drop, temperature and conductivity) were continuously logged on a computer and plotted on graphic screen using Lab View. At selected times, the flow was stopped and the core was CT scanned to determine any changes to the shape and size of the fracture.

RESULTS

Stress Effects:

The response of compression (loading) and decompression (unloading) was tested on the fractured (FFC) and non fractured sample. The confining pressure (hydrostatic stress) across the sample has increased from 1000 to 3500 psi. During the first loading cycle, as confining pressure was increased up to 3500 psi the permeability of the non fractured sample decreased by 10% while the fractured sample effective permeability reduced by 58% (Figure 1- Left). This is because as confining stress increases across the sample, fracture surface undergoes permanent deformation where the contact point crushes increasing its surface area. CT images confirmed the observed reduction in the permeability (Figure 1- Right).

Temperature Effects:

Constant confining pressure of 4000 psi was maintained across the sample FFC. Temperature was increased from 22 to 32 ^{o}C and dramatic reduction was observed in permeability. As the temperature was further increased to 51 ^{o}C the permeability was reduced and reached almost matrix permeability 4.7 mD. Figure (2) shows the reduction in permeability with increasing temperature and CT images give an evidence on further permeability reduction with temperature T =51 ^{o}C .

Chemical Effects:

During the distilled water re-circulation experiment, the pressure drop (ΔP) across the sample (FFA) rapidly increased up to 3.9 psi. Continuous recirculation of initially distilled water caused further increase in ΔP up to 8.6 psi after 15 days. Although the pressure drop was fluctuating for some time, the general trend showed an increase in pressure drop across the fractured sample. These observations are consistent with the fracture slowly closing during the experiments as shown in Figure (3). The increase in differential pressure indicated continuous reduction in fracture aperture and resulted in a decrease in permeability of up to 30 fold. Electrical conductivity measurements indicated an increasing number of ionic concentrations of the produced water sample. As conductivity measurements increased from 75 and 164 µS/cm, the concentration of Ca+2 and Mg+2 increased from 6.03 to 17.17 mg L-1 and from 0.763 to 2.46 mg L-1 respectively.

CONCLUSIONS

A series of flow experiments were performed on chalk core plugs in order to evaluate the effects of hydraulic thermo-chemical variations on fracture topology and aperture.. The effects of stress change on fracture have been widely studied in rock mechanics. Fracture aperture reduces with increasing stress and it reaches a maximum closure. The effects of temperature and chemicals induce changes in the hydraulic and mechanical properties of the fracture such as fracture topology and aperture, which are the main parameters that control fluid flow. Temperature effects on fracture behavior were evaluated by re-circulated oil at temperature varying from ambient to 51 ^oC. Dramatic reduction in fracture permeability was observed and confirm with CT images. During distilled water was re-circulation at ambient temperature Chemical effects show the same impact with evidence of calcite dissolution (rock fluid interaction) along the fracture surfaces. The pressure drop along the fracture and CT images confirm fracture surface deformation and fracture closure which indicates fracture aperture and permeability reduction. This could be associated with dissolution, precipitation or collapse of the contact points along fracture with time. Thus it can be shown that thermal and chemical effects by its own could have a significant impact on fracture behavior in carbonate reservoir. This behavior may need to be incorporated into production simulation models to provide more accurate forecasts of reservoir behavior during steam injection EOR projects. Further analysis of the CT images will be performed using Avizo Software to measure the mechanical aperture and its distribution to compare it with the hydraulic aperture and include this result in available mechanical models such as Barton-Bandis [9].

ACKNOWLEDGEMENTS

Ruqaiya Al Zadjali would like to thanks Petroleum Development of Oman (PDO) for sponsoring the study and to all our colleagues who participated in this work.

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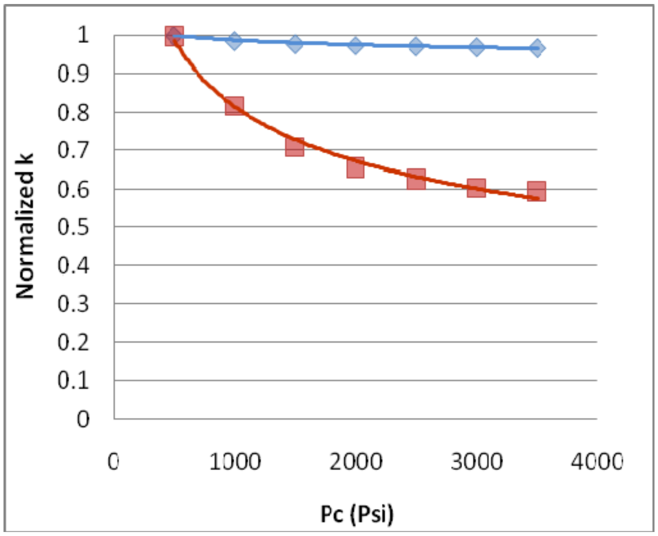


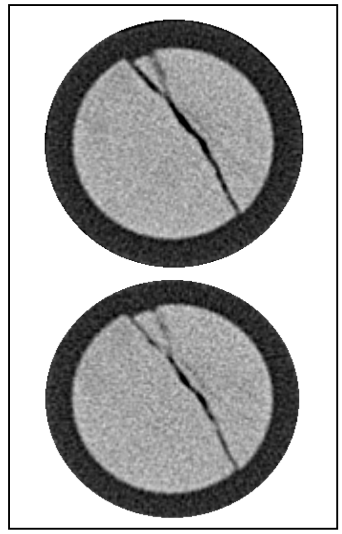
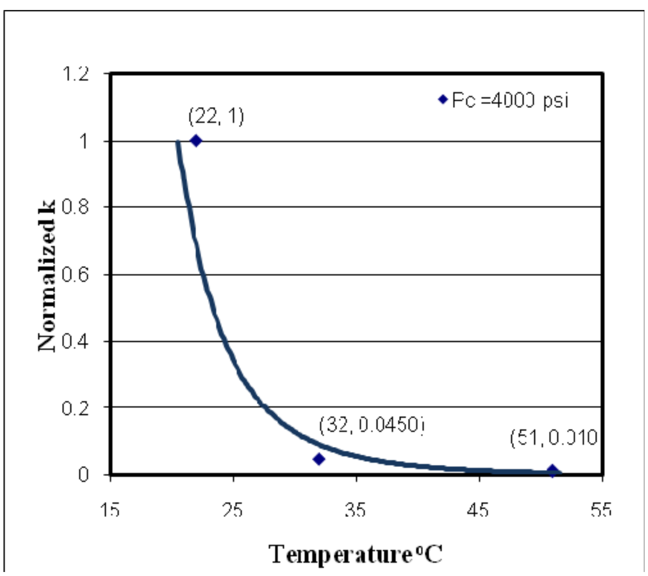


Figure 1: Left) A plot of normalized permeability values for chalk sample FFC at different confining pressure Pc ranging between 500 to 3500 psi for fractured and non fractured sample. Right) CT images; Top) fracture aperture at 1000 psi confining. Bottom) fracture aperture reduction after applying confining pressure of 4000 psi



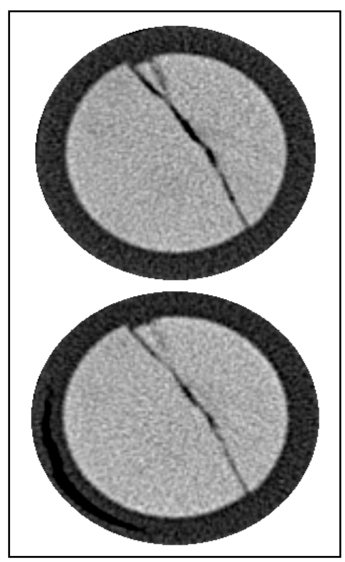


Figure 2: Left) Plot of normalized permeability reduction with temperature increase for fracture chalk sample FFC at 4000 psi confining. Right) CT image showing reduction in fracture aperture after increasing temperature to 51 °C.

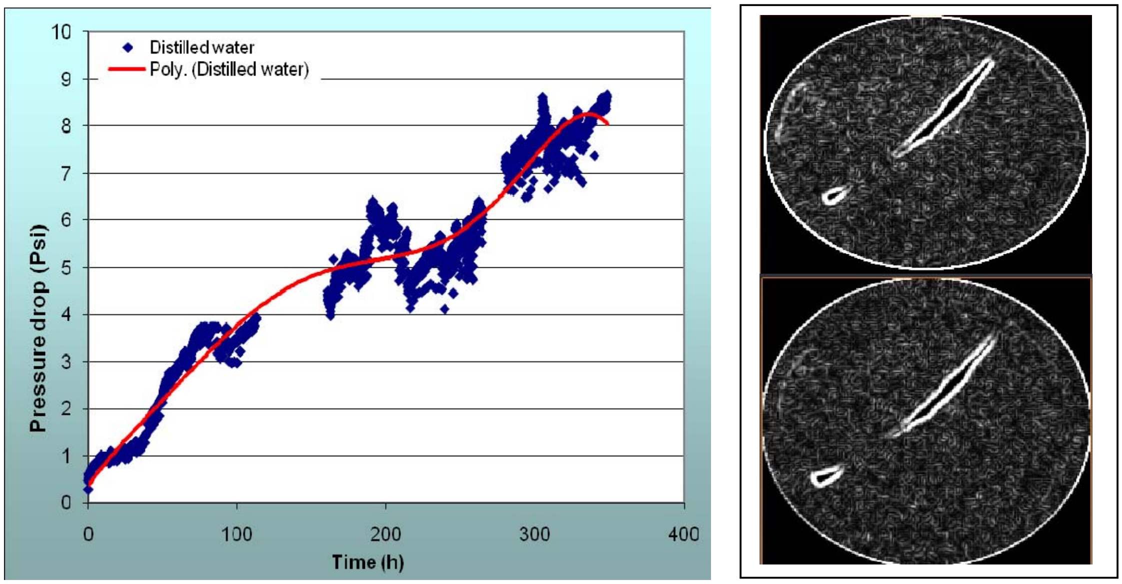


Figure 3: Left) General trend showing an increase in pressure drop along fracture sample during distilled water recirculation at 1 cm^3/min for 15 days. Right) CT image. Bottom) fracture aperture reduction after one month of recirculation with distilled water comparing with the image at top (before the experiments.)