The Effect of Low-Permeability Layers on Oil Production from Vertical and Horizontal Wells in the Troll Field

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The production of oil from the Troll Field in the North Sea has been studied numerically by Kossack, Kleppe and Aasen (1987). The reservoir description used in that study contained low-permeability layers of cemented sandstone at the gas-oil contact and below the water-oil contact. The lateral extent and continuity of these cemented layers and the exact value of their vertical permeability is unknown. As a result, the comparisons between the vertical and the horizontal well performance in the Troll Field as presented by Kossack et al. (1987) is only valid for the particular description used.

This contribution investigates the effect these calcite-cemented sandstone layers near horizontal and vertical wells have on the coning of gas and water, during oil production from thin oil zones. The vertical permeability of the calcite-cemented layers was varied from 0 mD (totally sealing) to 1800 mD (not present). The coning situation was studied at various oil production rates and with four different well configurations. Under certain conditions a secondary gas cap forms under the low-permeability layer at the gas-oil contact. At low and intermediate production rates the effect of this secondary gas cap on the coning result is surprising. A complicated interaction between gas coning from this secondary gas cap and the flow of primary gas cap gas through the layer was discovered as the production rate and vertical permeability of the layer were varied. An extensive analysis of these results explains the physical processes involved.

This phenomenon is of general interest in coning problems where low-permeability layers are present. The results can be applied to fields other than the Troll Field and to production situations involving both vertical and horizontal wells.

INTRODUCTION

The thin oil rim found in the Troll Field contains considerable amounts of oil, 5700 Mstb* (≈ 900 MSm³) owing to its large areal extent. The oil overlays an active aquifer, and is in contact with a large gas cap. Owing to a thickness of less than 92 ft (28 m), the critical rate to coning is low considering the offshore environment. Producing the field with conventional wells is most likely not economical because of the gas coning. Experiences with horizontal wells have shown good results in thin oil zones, particularly when coning is a problem (Chaperon, 1987; Darley et al., 1983; Ekran, 1987; Johansen, 1986; Karcher et al., 1986; Kossack et al., 1987; Reiss, 1985). The relatively lower pressure drawdown required to produce a certain rate from a horizontal well compared to a vertical will reduce the tendency to coning.

In the paper of Kossack et al. (1987), some reservoir-management aspects of oil production from the Troll Field are numerically investigated. Production from different well configurations of horizontal and vertical wells are compared.

Their reservoir description contained two thin, continuous low-permeability layers of cemented sandstone. Laboratory studies of these layers estimate the vertical permeability to be of the order of 0.1 mD, but their exact permeability and their lateral extent are unknown. This geological feature is a dominant factor in the well's performance, thus, the results calculated by Kossack et al. (1987) are valid only for the assumed description. Their results show that a horizontal well will perform better than 2 or 3 vertical wells when low-permeability layers \( k_v = 0.1 \text{ mD} \) exist at the gas–oil contact (GOC) and below the water–oil contact (WOC). This result is also dependent on the production rate and the length of the horizontal well.

This paper presents the results of evaluation of the effect
of these impermeable or low-permeability cemented layers on the near-well coning of gas and water into vertical and horizontal wells in Troll Field. Since the existence, lateral extent, and vertical permeability of these layers is uncertain, in the analysis the vertical permeability of the layers was given the values of 0 mD (totally sealing), 0.1 mD, 1.0 mD, and 1800 mD (not present).

REVIEW OF PREVIOUS STUDIES
OF HORIZONTAL WELLS IN
THE TROLL FIELD

An extensive study has been published recently by Kossack et al. (1987) that compares oil production from vertical and horizontal wells in the Troll Field. The reservoir model used in this study contained two thin (1.6 ft), low-permeability layers (LPL) \( k_H = 10 \text{ mD}, k_L = 0.1 \text{ mD} \). These cemented sandstone layers were located at the gas-oil contact and 6.6 ft (2 m) below the water-oil contact. The results of their study, summarized in this section, were highly dependent on the low vertical permeability of these two layers. This dependence is extensively investigated in the remainder of this paper. The basic rock properties, PVT data and reservoir description are given in their paper.

The basic objective of Kossack et al.'s (1987) study was to compare the oil production performance of 1, 2 and 3 vertical wells and a large-diameter horizontal well in a sector of a circular drainage area (full pattern). This configuration is most easily explained using Fig. 1, where six 60° sectors are shown in the full pattern. In their numerical study a 3-dimensional, finite-difference grid was constructed around 1, 2 or 3 vertical wells or a horizontal well in a symmetry element of the sector; see Fig. 2. In most of the simulations, the oil production rate for a sector was held constant with time. They investigated sector production rates from 4000 to 24 000 stb/d of oil per day. Note that the sector production rate is the sum of oil produced by all wells in a sector. The oil recovery results at shut-in gas-oil ratio (GOR) limit of 5000 scf/stb are summarized in Fig. 3. At low sector production rates, the 1500 ft (460 m) and 2000 ft (610 m) long horizontal wells produced much more oil than the 1, 2, or 3 vertical wells. As the sector production rate increased to 8000 stb/d, the recovery from the shorter horizontal well became less than from 3 vertical wells. Eventually, as the rate increased further, the performance of the shorter horizontal well equalled that of 2 vertical wells. The 2000 ft horizontal well performed much better than all the vertical well configurations for all production rates studied.

During these simulations the average water cut for all well configurations was between 0.36 and 0.40. The authors evaluated the sensitivity to the sector angle. The results are given in their paper. Economics, i.e. horizontal well drilling costs, operating costs, and oil price, would specify which sector angle has the highest present value.

In their final simulations Kossack et al. (1987) produced the horizontal wells (60° sector, 1500 ft length) in a more standard way, i.e. by reducing the required oil production rate by 50% every time the GOR rose above the solution gas value. These results are shown in Fig. 4, where schedule A is a vertical well producing 1000 stb/d of oil, schedule B is a horizontal well at 1000 stb/d, schedule C is a horizontal well producing in the sequence 8000, 4000, 2000, 1000 stb/d, and schedule D is a horizontal well with the sequence 4000, 2000, 1000 stb/d. Schedules B, C and D recover approximately 30% of the oil in the sector.

The conclusions of Kossack et al. (1987) were that a horizontal well in the Troll Field would replace 2 or 3 vertical wells, but the results are dependent on production rate and the horizontal well's length. Also, by a gradual reduction of production rate, a horizontal well can recover 30% of the initial oil in place.

EVALUATION OF EFFECT OF LOW-
PERMEABILITY LAYERS (LPL)
ON OIL PRODUCTION

The effect of the near-wellbore reservoir description on oil production can be evaluated by comparing the results of simulations from various scenarios. These scenarios should involve alterations in the reservoir description for the various well configurations. From these results, the importance of the LPL's permeability and extent will be shown in the differences in the fluid flow and the production GORs. To follow the lead given by Kossack et al. (1987), the numerical simulations were run with 1, 2 or 3 vertical wells or a large-diameter 1500 ft horizontal well.

The following two studies were performed and comparisons were made between these four well configurations.

(1) At a constant production rate and a constant vertical permeability of the calcite-cemented layers, the LPL at both the GOC and below the WOC were removed sequentially from the description. This yields four cases, which will be described in a later section.

(2) A sensitivity study of the vertical permeability of LPL at the GOC in the absence of the layer below the WOC was made. An additional parameter, the sector oil production rate, was varied from 4000 to 24 000 stb/day for all descriptions.

THE NUMERICAL MODELS

Reservoir description

In order to simulate both gas and water coning, the 3-dimensional, 3-phase black oil simulation model...