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On the fluid mechanics of slotted liners in horizontal wells

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HIGHLIGHTS

- Slotted liners are commonly used in injection and production wells.
- Slot links inertial-pressure well flow to viscous-inertial-pressure reservoir flow.
- Results reveal that flow through slots is not uniform.
- Non-uniform flow through slots implies non-uniform conformance of flow along wells.

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ABSTRACT

Slotted liners are flow control devices widely used in both injection and production wells for thermal oil sands recovery operations such as Steam-Assisted Gravity Drainage. In these devices, slots are cut into the well at regular intervals around and along the well. The dimensions tend to be from fractions to several millimeters in gap and a few to about twenty centimeters long along the pipe. The key benefits offered by slotted liners are that they are among the most economical solutions for sand control and well bore stability as well as manufacturing. Slotted liners have several design parameters including the slot density, pattern, slot opening size and shape that must be chosen to provide optimum inflow and outflow performance in the reservoir. Due to the complexity in deriving these parameters analytically or experimentally, we have examined the impact of design parameters on steam injection by using a realizable k-ε turbulence computational fluid dynamic model of a 5 m slotted liner section coupled to a reservoir flow domain outside of the well governed by a modified Darcy's law that accounts for inertial effects. The results reveal that slot open area affects the flow distribution in the reservoir. The role of drive forces changes through the flow with viscous and pressure forces dominant in the slot and upstream area and inertial forces just downstream of the slot and pressure and viscous forces in the reservoir.

1. Introduction

Steam-Assisted Gravity Drainage (SAGD) is a thermal recovery process used in heavy oil and oil sands reservoirs. In SAGD, as shown in Fig. 1, steam is continuously injected through an upper horizontal well into the reservoir. The steam loses its latent heat to the cold oil sand at the edge of the depletion chamber which consequently raises the temperature of the bitumen which in turn lowers its viscosity from about 1 million cP to less than 10 cP. The mobilized oil then flows under the action of gravity to the base of the depletion chamber where a parallel horizontal well is located (Butler, 1985). SAGD wells are generally completed with horizontal sand control devices such as slotted liners or wire wrap screens, both illustrated schematically in Fig. 2 (Butler, 1985). Slotted liners are used as sand control devices in the oil industry for the production of heavy oil from long horizontal reservoirs with high permeability, unconsolidated sands (Kaiser et al., 2002; Kofoed et al., 2012; Bennion et al., 2007, 2008; Romanova and Ma, 2013). The advantage of slotted liners is that they are relatively inexpensive to manufacture and they have the strength to be placed in the reservoir. In unconsolidated rock reservoirs, in many cases, slotted liners filter more than 98% of the sand out while the well is being pumped (Bennion et al., 2009). Slotted liners, depending on the width of the slots, allow production of fine sand grains of a certain size which flow along with the mobilized oil.

The geometry of slotted liners is governed by the following factors: slot length, slot width, slot distribution, and slot density (Bennion et al., 2009; Mahmoudi et al., 2016). The specification of slot width depends on the sand size distribution – the narrower the slot width, the smaller the grain size that can flow through the slot. However, the greater is the pressure drop required to maintain a specified flow rate (or smaller is the flow rate at a given pressure drop across the liner). The slot density determines the open

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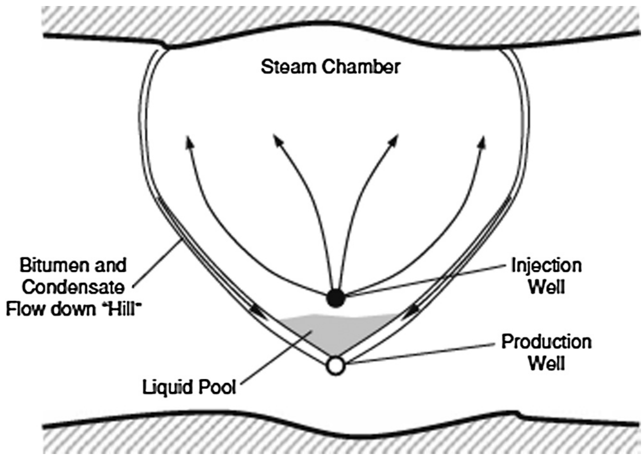

Fig. 1. Cross-section of a SAGD well pair. The injection and production wells are horizontal wells that go into the page.

flow area to the reservoir – the greater the slot density, the larger is the flow rate at a given pressure drop across the liner. However, the greater the slot density, the lower is the mechanical strength of the slotted liner. There are two types of slot shapes cut into liners: straight cut and keystone cut (Kaiser et al., 2002). Straight cut liners are cut with equal width throughout the wall of the pipe. Keystone cut liners are narrow at the surface of the liner and gets wider towards the interior. Sand grain bridging at the slot is the deciding factor on the choice of the type of slot shape (Schwartz, 1969). The general rule is that the slot width should be equal to two to three times the diameter of the medium-sized sand particles. A typical particle size distribution, obtained by using a particle size analyzer (Analysette 28 Image Sizer, Fritsch), for a high grade Athabasca oil sands reservoir is shown in Fig. 3. The data reveals that the mean size of high grade (high oil saturation and permeability) Athabasca oil sand grains is 70 μm with a standard deviation of 20.03 μm, as listed in Table 4. For a medium grade (low oil saturation and moderate permeability) oil sands sample, the mean grain size is 86.3 μm with a standard deviation of 42.8 μm. The circularity plot in Fig. 3b shows that most of the oil sands particles, for these samples, are nearly circular in shape. As described by Fermaniuk (2013), for practical design of slot width in slotted liners, the one-seventh rule is often used to estimate the width of the slot; if the width is less than seven times the average particle size, sand arching occurs outside the slot and sand production is avoided. According to this rule, the slot width for the sand samples with average properties listed in Table 4 should be 0.49 and 0.60 mm, respectively, for the high and medium grade ores.

Depending on the requirement for the open flow area, the distribution of the slots is either staggered or un-staggered. The slotted liners aid in maintaining borehole integrity as the formation pressure depletes. Analysis and understanding of wellbore hydraulics involves several factors interacting with one another. Rheological properties and temperature-dependent properties of the injection and production fluids change with time and depth in wellbore operations. In SAGD wells, both vapor and liquid involve mass and heat transfer between phases. The flow states are complex with turbulence and different flow regimes e.g. annular mist, slug flow, etc. depending on the superficial velocities of the fluid phases (Wei and Gates, 2010; Winterfeld, 1989). Wellbore geometry is another important feature that establishes the cross-sectional flow area, fluid phase velocities, and hence heat transfer rates. Pressure drop is the significant factor for slotted liners as it is directly related to the slot open area and flow rates through the slots. The pressure distribution in the reservoir adjacent and along to the well determines the uniformity of flow along the well. The slot open area along the well can be modified to alter the pressure drop yielding a more uniform flow profile along the well. Although there are many papers in the literature on flow in and through slotted liners on production flows – that is, flow from the reservoir to the well often dealing with sand control (e.g. see Mahmoudi et al., 2016 and references within), there are nearly no papers in the area of flow through and out from slotted liners on injection flows – that is, flow from the well to the reservoir. There are no papers that focus on the velocity and pressure profiles that result from injection of fluid from a slotted liner into a reservoir.

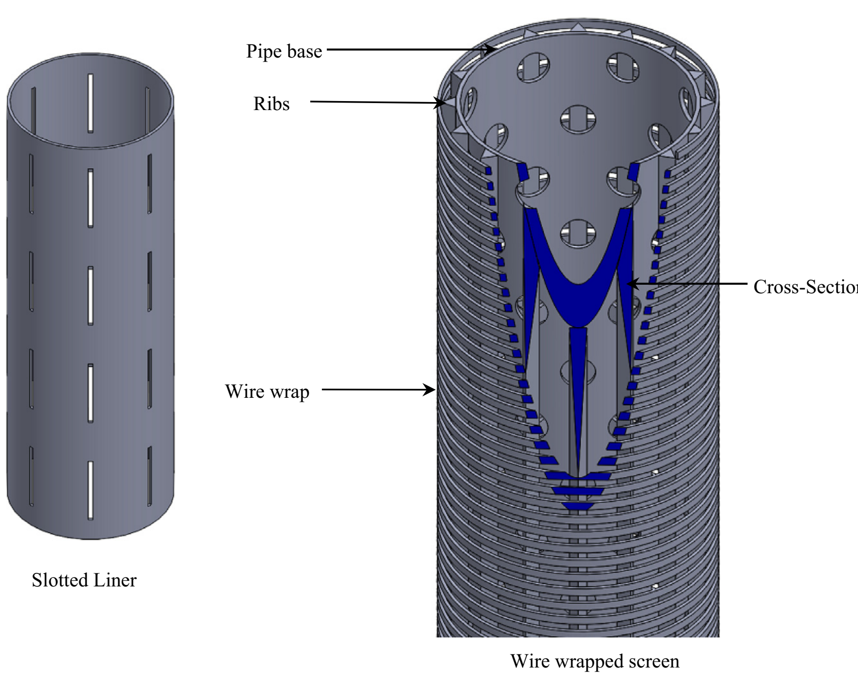

Fig. 2. Schematic diagrams of slotted liner and wire-wrapped screens.