How much floating light nonaqueous phase liquid can a phreatic surface sustain? Riesenkampf's scheme revisited

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[1] Steady, Darcian, one-phase, phreatic surface flow of groundwater into a horizontal well with a pancake lens of light nonaqueous phase liquid (LNAPL) accumulated in the water table trough is studied by the method of complex analysis. A sharp interface model assumes groundwater capped by two isobaric limbs (groundwater–vadose zone interfaces) of a free surface with an in-between cambered segment of an immiscible LNAPL-water interface, along which pressure is hydrostatically increasing with the depth of the LNAPL "channel." The complex potential polygon is mapped onto an auxiliary half plane where the complex physical coordinate of the flow domain is represented in terms of singular integrals as a solution of the Keldysh-Sedov problem. The shapes of semi-infinite "wings" of the water table contacting the vadose zone gas and of a finite length LNAPL-groundwater interface are found from parametric equations that involve the sink strength and location with respect to the pancake surface, the ordinate of the lowest trough point, and the volume of LNAPL accreted in the lens. Critical conditions, corresponding to the lens contour cusping toward the sink, are found. The Riesenkampf solution contains a free parameter, which is fixed by specifying either a point on the free surface or the volume of the trough-intercepted LNAPL.

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1. Introduction

[2] Free-product hydrocarbons emerge in the water table of unconfined aquifers in several cases: pipeline spillovers, occasional filling station tank leaks, oil accumulated along highway flanks and, in arid zones like Oman, occasionally entrained by rare torrential rains as an infiltration pulse reaching a relatively deep water table, etc. Spatially localized lenses of light nonaqueous phase liquid (LNAPL) are observed and remediated [see, e.g., *Charbeneau et al.*, 2000]. A common cleanup utilizes horizontal and vertical wells, which attempt to skim LNAPL. Similarly, petroleum engineers try to skim a thin oil rim in gas-oil gravity drainage recovery [e.g., *Gallagher et al.*, 1993]. Occasional LNAPL contamination can jeopardize a water supply and drainage operation in groundwater hydrology and agricultural engineering, where potable and irrigation water is retrieved from horizontal wells (laterals) or waterlogging of cultivated areas is alleviated by tile drains.

[3] In environmental and reservoir engineering applications at mature stages of remediation and recovery, horizontal wells drive a wanted and unwanted fluid (water and brine) with residuals of an unwanted and desired liquid phase (LNAPL and crude). Theoretical and experimental studies of LNAPL-groundwater and mathematically equivalent groundwater–dense nonaqueous phase liquid (DNAPL) or groundwater-intruded sea water systems have been done by *Bear and Dagan* [1964], *Hocking and Zhang* [2009], *Nordbotten and Celia* [2006], and *Strack* [1989]. Reservoir engineers hunt for oil lenses (rims) with a small oil-to-water ratio in the bulk well production. The reduction of this ratio is bad and signifies reservoir depletion. In contaminant hydrology the objective of pumping is diametrically opposite to reservoir engineering: an LNAPL quantity that is as small as possible in the recovered water should be achieved. If so, this is considered as a success of remediation.

[4] Does, however, an abated LNAPL content in the abstracted water at a certain pumping rate guarantee that no significant quantity of a foreign LNAPL phase is left in the subsurface saturated with a denser background liquid? If a groundwater well pumps at a certain steady state rate an almost-pure water for a long time, does this mean that no significant LNAPL macrovolume is "sitting" near the well? If this "masked volume" is superjacent to the well, what will happen if the pumping rate is suddenly increased? Can the LNAPL volume (undetected in the normal-rate scenario) suddenly break through into the well at an increased pumping rate and ruin the very remediation effort, or does the "masked volume" simply drift a little toward the well by intensified pumping? In reservoir engineering, does an almost 100% water content in the production well mean that no oil rim or lens exists any longer in the formation and that the water flooding should be stopped (the formation abandoned)?

[5] The objective of this paper is to give mathematical answers to these questions and to show that "hydrodynamically suspended" volumes of LNAPL can be located straight above a well.

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