Arrest Mechanisms of Buoyant Hydraulic Fractures

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Massive hydraulic fracturing (HF) treatments can form widespread fractures. Understanding their containment - or its lack - at depth is critical given the positive buoyancy contrast between the fracturing fluid and the surrounding rock, promoting upward growth [1]. Different containment mechanisms exist, such as fluid leak-off, stress barriers, or lithology changes. They can act either before the HF becomes buoyant or when interacting with a buoyant HF. In the context of planar three-dimensional (3D) HFs, these two mechanisms have recently obtained attention in the literature [2, 3, 1]. We study several possible arrest mechanisms for the case of a fully established buoyant HF propagating either in the toughness- (see Fig. 1 (a)) or viscosity-dominated regime (see Fig. 1 (b)). We restrict our investigation to fractures remaining planar during their entire propagation.

The first investigated mechanism consists of changes in the fracture energy $G_c = K_{Ic}^2(1-\nu^2)/E$ of the solid media. We restrict here to changes in the material fracture toughness (K_{Ic}) without consideration of possible concurrent changes in elastic material properties (E, ν). However, we distinguish between two types of variable fracture toughness, a fracture scale-dependent variation and a jump (sudden change). For the former, we follow the observation in [4] and assume that the fracture energy increases, at most, linearly with the largest dimension of the propagating fracture front. If we consider a toughness-dominated buoyant HF, this dimension corresponds to the breadth of the blade-like fracture (e.g. $K_{Ic} \propto \sqrt{b}$, see Fig. 1 (a)). We demonstrate that the size dependence of fracture toughness does not represent an actual mechanism capable of arresting an already buoyant HF. For the latter variation, we consider a sudden jump in fracture toughness, likely due to a lithology change (see Fig. 1 (c)). We discuss whether or not a positive jump (e.g. $K_{Ic\text{-}2}/K_{Ic\text{-}1} > 1$) can temporally or definitively arrest the upward HF movement.

The second mechanism investigated relates to a variation in normal stress (see Fig. 1 (d)). Similar to the toughness jump, this so-called stress barrier must be positive (e.g. $\sigma_{o\text{-}2}(z)/\sigma_{o\text{-}1}(z) > 1$) to constrain the upward fracture advancement. Under certain conditions, this limit is mathematically equivalent to a local increase in fracture toughness. Despite this possible link, the two mechanisms are fundamentally different. A phenomenon observable when comparing Figs. 1 (c) and (d). Without penetrating the more resistant layer, the HF can feel the toughness jump at the interface (Fig. 1 (c)). Differently, the fracture adjusts to normal stress changes only once propagation is in the higher stress layer (Fig. 1 (d)).

As a final arrest mechanism considered in our work, we investigate the impact of fluid leak-off on upward growth. Leak-off can not only slow down the propagation of a buoyant HF but also efficiently arrest the fracture propagation, even in the case of an ongoing release.

We investigate these arrest mechanisms using numerical simulations and scaling arguments and showcase relevant parameter combinations for industrial HF applications.

References

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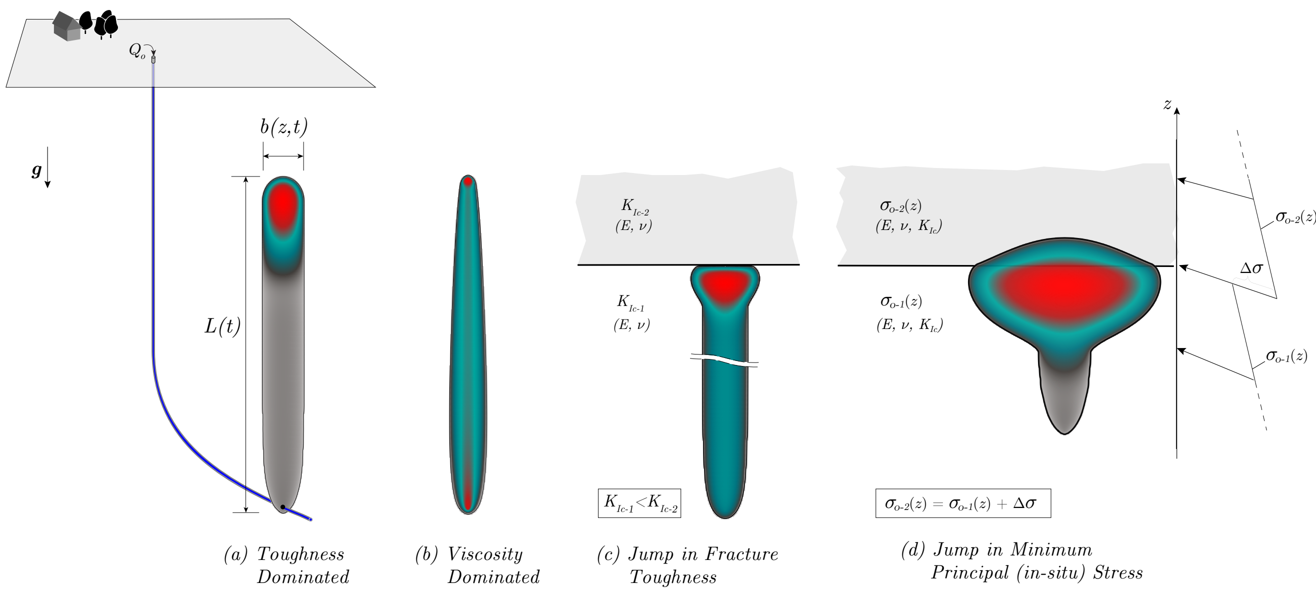

Figure 1: Characteristic footprints in different limiting regimes ((a) and (b)) and considered arrest mechanisms ((c) and (d)) of buoyant hydraulic fractures. The color code represents the fracture opening. The sequence from lower to higher values is in the order gray-green-red.