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Parametric analysis of internal gas separation within an ebullated bed reactor

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ABSTRACT

Ebullated bed reactors are commonly found within resid hydroprocessors used to thermally crack and catalytically hydrogenate atmosphere and vacuum tower residue in heavy oil upgrading. These units have historically experienced very high solids-free gas holdups above 30%, displacing heavy feed and limiting product throughput, with significant focus placed on the effects of the internal recycle geometry on column performance. A fully functional 3D CFD framework for simulating the gas separation region is presented here, capable of capturing tangential and rotational fluid motion and transient gas separation dynamics. The model is applied to a first-generation recycle cup separator design and is used to explore operational parameters (fluid velocity, bubble size/holdup, recycle rate, and foam generation) and the choice of momentum coupling strategy on gas entrainment and separation efficiency. The results provide a framework for comparison and evaluation of future designs as well as fundamental insight in the separation dynamics in the freeboard region of this reactor, with efforts ongoing to compare and contrast fundamental operating modes of multiple separator designs.

1. Introduction

Athabasca Bitumen is a significant component of the Alberta oil sands reservoir and methods to improve its refinement to higher value products is important to the successful development of this resource. Thermal cracking processes are commonly used to convert the heavy components of bitumen to lighter hydrocarbons as part of the standard upgrading facilities present in many operations within Western Canada. A subset of these technologies uses hydrogen addition to increase both the value and volume of petroleum products produced, often within an ebullated-bed framework well suited to significant liquid recycle at high pressures. Consisting of a three phase (gas–liquid–solid) ebullated bed reactor with an internal recycle line, the efficient operation of these units is important for cost and emissions reduction to the overall upgrading process. High gas holdup (>30%) within the column has been identified by McKnight et al. (2008) as a limiting factor to the reactor's residue conversion, whereby the excess hydrogen and product vapors displace potential liquid inventory and reduce overall processing capacity. Methods and techniques to reduce circulating gas are thus of significant interest, with previous work exploring strategies to reduce gas holdup through operational and geometric modifications of the industrial and analogous cold-flow units (McKnight et al., 2008; Pjontek et al., 2014; Martínez et al., 2010; Grace and Zhu, 1992; Buttke and Frey, 1989; Ancheyta, 2013). While fundamental theory for gravity-based separators are thought to roughly describe the separation occurring within the system, the mechanisms governing gas–liquid separation within the ebullated bed are known to be complicated by foam formation, geometric deviation from a traditional "horizontal" separator, internal recycle rate, and other operational properties. As such, progressive generations of separators constructed

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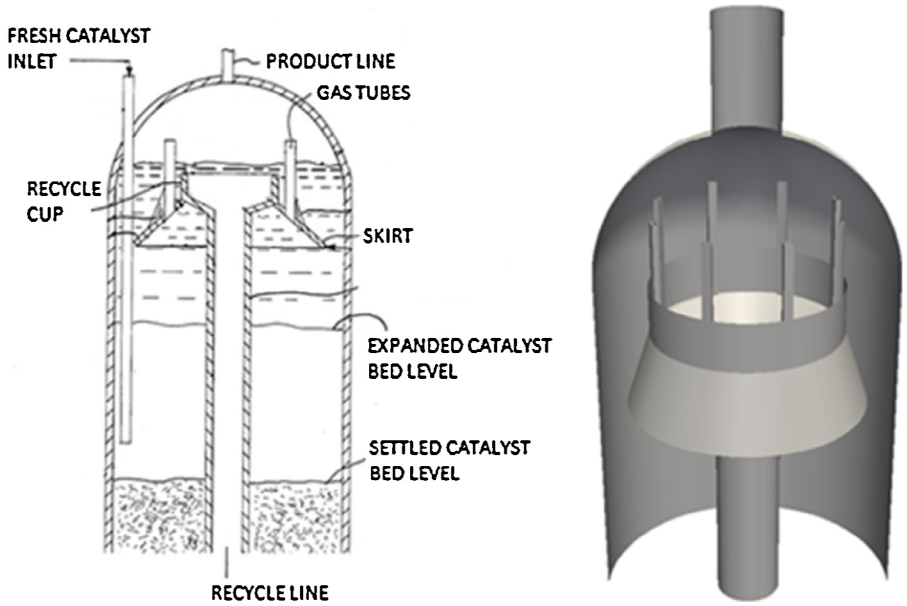

Fig. 1 – Left—Schematic of an ebullated bed freeboard region modified from Buttke and Frey 5. Right—CFD Mesh rendering sectioned to illustrate the internal structure. The mesh is modeled as a 45 degree wedge geometry and is visualized by rotating the wedge about the vertical axis.

for the ebullated bed system have been based on extensive empirical testing and cold-flow optimizations. A better understanding of the fluid dynamic fundamentals for these units could identify the performance limit of current designs and lead to opportunities for reduced gas holdup within the column through the development of a next-generation designs.

Previous attempts to reduce gas hold-up originally led to the addition of a recycle pan at the top of the internal recycle line within the ebullated bed reactor (Fig. 1). This design was implemented in an attempt to enhance gas disengagement above the catalyst bed in the freeboard region of the reactor. Upon further testing, this first generation recycle pan was found to result in a stable, gas-rich effervescent foam region at the top of the reactor which extended down into the recycle line, increasing gas re-entrainment and increased gas holdup (McKnight et al., 2008). Industrial designs have since evolved to next generation separators capable of reducing the total gas holdup by a few percent, corresponding to significant increases in total liquid feed production capacities.

This work characterizes the separation process and fluid dynamics within the freeboard and separation region of the first-generation recycle pan, validating the computational framework through parametric analysis and exploring the effects of operating parameters and possibly foam generation on gas entrainment and recycle.

2. Computational methods and models

The recycle pan of the ebullated bed reactor was modeled using an Euler–Euler framework in OpenFOAM® modified to dynamically set boundary pressure conditions to meet a target liquid recycle rate. The computational domain was based on the unit description by McKnight et al. (2008) representative of the cold-flow unit approximately built to a 1:3 scale of the industrial column (~0.6 m radius). The cold-flow unit is a Kerosene–Nitrogen system operating at 20 psi and 20°C, while the industrial unit operates at significantly higher temperatures and pressures. These fluids have been shown to be good analogs for the industrial units operating conditions (Macchi et al., 2001). A Kerosene–Nitrogen system allows for a smaller mean bubble size (~1 mm) as well as a narrow bubble size distribution, and higher gas holds by better approximating the physical properties of the industrial fluids. This provides some confidence in the extension of hydrodynamic studies performed at the cold-flow facility to operational conditions. The resulting physical property values applied in this study are summarized in Table 1.

Fig. 1 illustrates the freeboard region of an ebullated-bed reactor (left) and the simulated geometry (right) consisting of a cup, skirt, and 8 riser pipes. The skirt's principle mechanism is to capture gas and divert it away from the recycle pan to the top of the unit though the riser pipes. The recycle pan draws liquid to the bottom of the unit to be recycled, ideally allowing gas bubbles to disengage and rise up to the product line. This geometry was modeled as a 45° wedge with symmetric boundary conditions about the central axis and rotated cyclic boundaries on surfaces through which tangential motion would occur. The risers are located at an angle of 22.5° within the wedge to mitigate asymmetric effects near the boundary surfaces. The inlet has flow entering from the annulus of the unit's freeboard region. The outlets, which will be referred to as the product line (top) and recycle line (bottom), remove fluid from the vessel and recycle fluid to the catalyst bed respectively. Both the product and recycle lines were assumed to be equal in diameter and have approximately 1/20th the cross-sectional area of the annulus. The velocity for

Table 1 – Physical properties employed within this study, representative of cold-flow conditions in a Kerosene–Nitrogen system.

Phase	Property	Value	Units
Gas	Density	1.61	$kg\,m^{-3}$
Gas	Viscosity	1.40E-05	$m^2\,s^{-1}$
Gas	Bubble diameter	0.001	m
Liquid	Density	819	$kg\,m^{-3}$
Liquid	Viscosity	4.00E-05	$m^2\,s^{-1}$