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Effects of compressibility factor on fluid catalytic cracking unit riser hydrodynamics

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ABSTRACT

A detailed steady state FCC riser process model is simulated for the first time with different compressibility (Z) factor correlations using gPROMS software. A 4-lump kinetic model is used where gas oil cracks to form gasoline, coke and gases. The usual practice has been the assumption that the FCC riser gas phase is an ideal gas at every point under any condition (varying C/O ratio, riser diameter, operating temperature and pressure, etc.). This work found that the Z factor varies at every point across the riser height depending on riser operating pressure and temperature, diameter and C/O ratio. It also shows that the magnitude of deviation of a gas phase from ideal gas behaviour can be measured over the riser height. The Z factor correlation of Heidaryan et al. (2010a) is found to be suitable for predicting the Z factor distribution in the riser.

1. Introduction

1.1. Background

The fluid catalytic cracking (FCC) operation is central to effective performance of a refinery. It converts refinery residues such as vacuum and atmospheric gas oil into the two important fuels; gasoline and diesel. The conversion is achieved in a pneumatic vessel called a riser. The pneumatic movement is caused by the riser-regenerator pressure gradient, which in turn determines the resident time of both gas oil and catalyst in the riser, and ultimately the yield of products. This process is effective if the riser hydrodynamics is efficient. Maintaining an efficient pressure gradient in the riser is a measure of good riser hydrodynamics that tends to improve product yield. A detailed model of the FCC can capture all the aspects of the unit that improves on the prediction of the performance of FCC risers [26]. As the feed meets the catalysts at the vaporization section, it vaporizes into the riser forming gas and catalyst phases that flows in a fluid-like manner to the top where it exits. The volume of the products, which is the gas phase, increases as cracking of the feed proceeds bringing about changes in the density, molecular weight, temperature and pressure of the system along the riser height. All of the changes in those process variables depend on the type and nature of catalyst and feed. Due to this, properties like the crude oil American Petroleum Institute (API) gravity, density or specific gravity of feed and catalyst properties are specified in most FCC riser simulation. One of the process variables not always specified is the compressibility factor. Some authors [4,16,32,23] have treated the gas compressibility of the vaporised fluid in the riser as unity. Others have assumed that the compressibility or Z factor can be a dimensionless value of one due to the fact that the riser operates at low pressure and high temperature [4,15], even though, at low pressure, 2–3% error is prevalent [2]. There is also an assumption that the density relationship of the gas phase model in the riser behaves as an ideal gas at any position in the riser even for a heavy oil feedstock [32]. Another researcher treated the gas phase in the riser as ideal gas with the assumption of constant enthalpy [28]. However, enthalpy is not constant in the riser [17].

The Z-Factor is very significant in characterising the fluid flow of oil and gas in the upstream and downstream sector of the petroleum industries [19,20]. The process that the fluid undergo describes whether it is compressible or non-compressible, and if there is a density change, as is possible in the riser, then the compressibility factor changes. Hence, treating the gaseous phase as an ideal gas in the case of changing density system will not be accurate. Also, as velocity increases, the density of the fluid varies and can be a compressible fluid [7]. Some process variables such as density [30], viscosity and the void fraction would vary when change in mass (or moles) occur due to cracking reactions and when operating conditions such as temperature, mass flowrate and/or pressure (a function of gas compressibility) are altered. Since these changes in the operating conditions of the riser are taken into account when modelling risers [26], the variation in the compressibility factor of the fluid needs to be considered too. One major operating determinant of the FCC unit is the catalyst circulation between the riser and regenerator, and it accomplishes two simple

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Notation

A	Surface area, m^2
A_{ptc}	Effective interface heat transfer area per unit volume, m^2/m^3
C	Mole concentration, kg mole/m^3
C_{p_g}	Gas heat capacity, kJ/kg K
C_{p_s}	Solid heat capacity, kJ/kg K
D	Diameter, m
d_c	Catalyst average diameter, m
E	Activation energy, kJ/kg mole
F	Mass flow rate, kg/s
H	Specific enthalpy, kJ/kg
ΔH	Heat of reaction kJ/kg
ΔH_{vlg}	heat of vaporization of liquid feedstock in the feed vaporization section, kJ/kg
h	Enthalpy of reaction kJ/kg
h_p	Interface heat transfer coefficient between the catalyst and gas phases
h_T	Interface heat transfer coefficient, kJ/m^2 s K
k_{i0}	Frequency factor in the Arrhenius expression, 1/s
K_i	Rate coefficient of the four-lump cracking reaction, 1/s
K_g	Thermal conductivity of hydrocarbons
L	Length, m
M_w	Molecular weight
P	Pressure, kPa
Q_{react}	Rate of heat generation or heat removal by reaction, kJ/s
R	Ideal gas constant, 8.3143 kPa m^3/-kg mole K or kJ/kg mole K
RAN	Aromatics-to-naphthenes ratio in liquid feedstock
S_c	Average sphericity of catalyst particles
S_g	Total mass interchange rate between the emulsion and bubble phases, 1/s
T	Temperature, K
u	superficial velocity, m/s
V	Volume, m^3
y	Weight fraction
Z	Gas compressibility factor or Z factor

Greek

Ω	Cross-sectional area
ρ	Density, kg/m^3
∅	Catalyst deactivation function
ε	Voidage
α	Catalyst deactivation coefficient
α_C^*	exponent for representing α
μ_g	viscosity, kg/m s

Subscript

Cc	Coke on catalyst
CL1	Cyclone 1
ck	Coke
ds	Disperse steam
FS	Feed vaporization section
g	Acceleration m/s^2
gl	gasoline
go	Gas oil
gs	gases
MABP	Molal average boiling temperature, K
MeABP	Mean average boiling temperature, K
pc	pseudo-critical
pr	pseudo-reduced
Rs	Riser
RT	Disengager-stripping section

purposes: preserving the regenerated catalyst activity via regeneration and upholding the heat balance by the endothermic reactions in the riser and other forms of heat removal. The catalyst circulation in the FCC is possible by the overall pressure balance, which also has a relationship with the gas compressibility factor. To get this pressure balance right, accurate conditions of the catalyst, feed and auxiliary equipment must synchronise with proper design of the FCC unit. In this work, the impact of the gas compressibility on the riser pressure, a major hydrodynamic parameter of the riser will be studied. This will identify the adequate compressibility factor at every point in the riser, which may give an accurate estimate of pressure drop and pressure balance in the riser and of the entire FCC unit. This will also determine the need for considering adequate gas compressibility factor to be used in plant design and not the outright assumption that the fluid phase is an ideal gas.

1.2. Motivation

One of the most unspecified quantities in the simulation, design and development of many process equipment for gas/solid handling is the compressibility factor because of the assumption that many gases behave like ideal gas. For the FCC riser reactor, the compressibility factor has always been assumed to be that of ideal gas. In reality, ideal gas is just an assumption and with all the assumptions made on how close the compressibility factor in the riser is to that of the ideal gas, there is no measured data in the literature to corroborate this. Of great interest in this work, is the accurate representation of gas Z-factor of the fluid in the riser. The accurate Z-factor will help to give an accurate estimate of hydrodynamic process variables such as pressure drop and pressure balance in the riser, and ensure effective process plant design.

1.3. Novel contributions of this study

This is the first study on compressibility factor of the riser where correlations are used through modelling as there is no such publication in the open literature. Some of the novel aspects of this paper are: (a) It is demonstrated that different Z factors produce different riser pressure and temperature responses, hence affect the product distribution of the riser (b) Once a catalyst-to-oil (C/O) ratio is known, a correlation was obtained that can provide the pressure drop values across the riser height (c) A correlation is obtained for the varying Z factor as a function of C/O ratio. Once the C/O ratio of the riser is known, the change in Z can be obtained, which shows the extent in numerical terms how the real gas phase in the riser varies from the ideal gas phase (d) The Heidaryan et al. [19] Z factor correlation is found to be suitable for representing the Z factor across the riser. It affects the pressure regime in the riser.

2. Gas compressibility factor

The gas compressibility factor (Z-Factor) is a vital process variable in upstream and downstream calculations in petroleum industries [20], and its root equation is:

$$PV = ZnRT \tag{1}$$

The equation is suitable for real gases, and for ideal gas, Z is unity. An ideal gas does not exist in practice. Hence, an accurate gas compressibility factor needs to be used in some processes that handle gaseous phase flow or reactions. The compressibility factor is defined as the ratio of the actual volume of gas to the ideal volume of gas, meaning that it is a measure of the extent of deviation from perfect behaviour