Flow Control Through a Non-Homogeneous Pellet Size Distribution in Catalytic Beds for a Low Reynolds Condition

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Highlights

- The proposed pellet size distribution may effectively control flow distribution.
- CFD agrees the model for low Reynolds. Experimental validation still required.
- Model's limitations at high Reynolds point to future research directions.

1. Introduction

In catalytic reactor design, controlling flow distribution is crucial for enhancing performance and preventing catalyst damage, especially in exothermic systems prone to hot spots, such as green hydrogen and captured CO2 conversion into methanol other value-added chemical species [1]. Recently, non-homogeneous cross-section substrates have been tested, showing potential for temperature control [2]. Building upon existing works on non-homogeneous substrates, this study introduces an analysis focused on pellet-based catalytic beds under a low Reynolds number condition. A distribution within the bed, where the central (core) region utilizes differently sized pellets compared to the peripheral (ring) area is investigated. This configuration results in a despair apparent permeability across the bed's regions, thus achieving controlled flow distribution and, consequently, a potentially more homogeneous temperature profile. The study develops a theoretical model to examine the effects of altering pellet sizes between the core and ring. The prediction from the model is then compared to CFD results. The proposed approach to predict flow distribution in core-ring catalytic beds, while successful in low Reynolds scenarios, has limitations at higher Reynolds numbers, setting the stage for future advancements in this domain.

2. Methods

The catalytic bed analyzed has a cylindric shape with two concentric regions. The center one is called core and the periphery one is the ring. Both regions differ in pellet size, as shown in Figure 1.

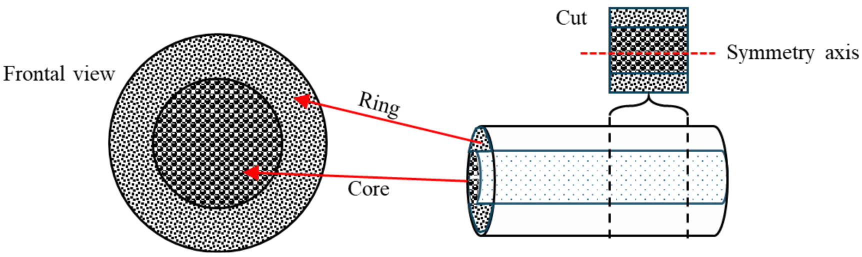

Figure 1: Schematic of the core-ring pellet bed

The fraction of the volume given to the core is the core size (λ_c). The analysis was conducted in non-dimensional units, hence, the specific values for bed length and diameter, and pellet sizes are not required. However, is noted that pellets are assumed to be spheric and well packed. Firstly, a low Reynolds is assumed ($\mathrm{Re_p} < 5$). If so, pressure drop is well approximated by Kozeny-Carma equation, which can be equated to Darcy law to obtain an apparent permeability (α), as follows [4]:

$$\alpha = \frac{D_p^2}{150} \cdot \frac{\phi^3}{(1-\phi)^2} \tag{1}$$

For spheres, sphericity (Φ) is one, and the void fraction (ϕ) is about 0.4 and is independent of the pellet size, as usual. Using Equation (1), provided that the core and ring differ in pellet diameter (D_p), the relative permeability, that is, the ratio of the core over the ring permeability (α_c/α_r), can be computed as D^2_{Pring}/D^2_{Pcore}. Adapting the equation in [2] for flow distribution in non-homogeneous permeability substrates to our case, the fraction of the flow passing through the core region (f_c) can be computed as:

$$f_c = \frac{\lambda_c}{\lambda_c + \left(D^2_{pring}/D^2_{pcore}\right)(1-\lambda_c)} \tag{2}$$

Equation (2) is only valid if backpressure equilibrium between the core and ring region is achieved. This assumption was tested by using a reactor scale CFD model implemented in ANSYS Fluent 2023R2. The model used the continuum approach and axial symmetry, assumes a substrate 150 mm long and 70 mm in diameter. The CFD model was validated against Ergun law by monitoring the pressure drop. Obtained f_c from Equation (2) were compared to those from CFD. Both are shown latter in the document.

3. Results and discussion

Core sizes from 0.25 to 0.75, together with relative pellet sizes from 0.5 to 1.5 were tested both using Equation (2) and the CFD model. Results are summarized in Figure 2.

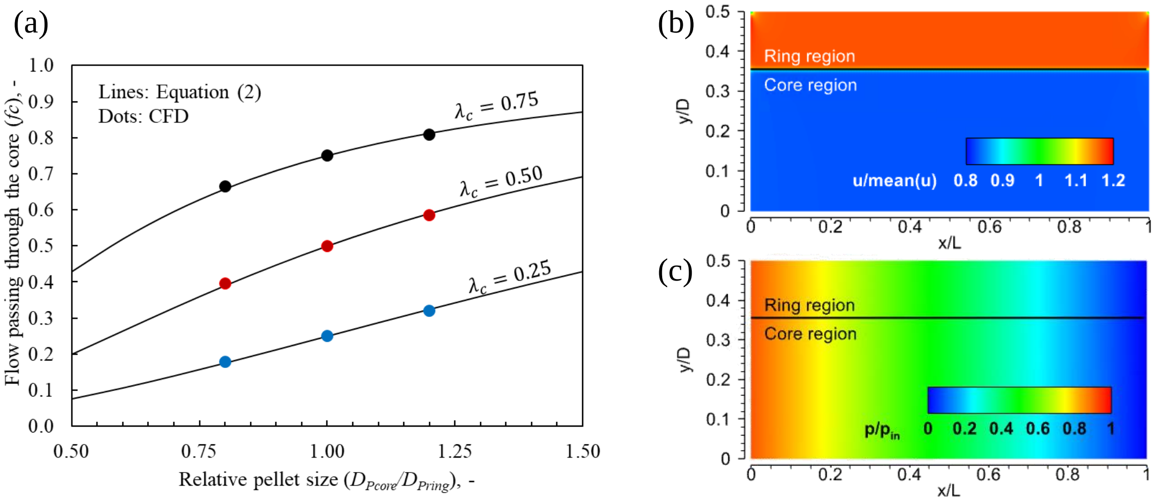

Figure 2. (a) flow distribution for the analyzed cases. (b) velocity and (c) pressure profile through the bed from CFD.

It can be seen from Figure 2(a) that, if the pellet size of both regions is identical, then, the fraction of the flow passing through the core is proportional to the core size. However, when changing the relative pellet size, significantly impacts the proportion of the flow passing through each region. The CFD simulations agree the flow distribution predicted by Equation (2), and also confirms backpressure equilibrium between core and ring. It can be seen from Figure 2(b) and 2(c) that core and ring velocities are significantly different, however, pressure drop is identical in both regions.

4. Conclusions

The study concludes that moderate size differences between the core and ring regions largely impacts the flow distribution; hence, offering opportunities for improving reactors design. Less flow through the core may prevent overheating the center of the bed and enhancing refrigeration in its periphery. However, changing the pellet size not only affects flow and heat. It also changes mass transfer; hence, applying the proposed approach must be deeply analyzed depending on each application case.

References

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Keywords
Flow Distribution; CFD; Dual Pellet Size; Pressure Drop