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Investigations about the effect of fractal distributors on the hydrodynamics of fractal packs of novel plate and frame designs

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HIGHLIGHTS

- A modular process equipment with a fractal distributor has been designed.
- Flow in such devices has been studied experimentally and computationally.
- Fractal distributor with equal flow path provides uniform residence time.
- Higher outlet density shows uniform outflow with lower pressure loss.
- Packed bed mal-distribution zones were reduced with higher outlet density.

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ABSTRACT

Flow distributors are extensively adopted by chemical industry to distribute process fluid for the downstream equipment. Conventional flow distributors in general have limited number of outlets. Their low outlet densities cannot distribute the incoming process stream uniformly and efficiently, which consequently undermine the overall equipment performance. In contrast, fractal distributors can achieve high outlet densities because of their inherent self-similarity feature. In this study, we fabricated two fractal packs of novel plate and frame designs. Each fractal pack was comprised of a fractal distributor, a resin bed and a fractal collector. The fractal distributors/collectors in these two fractal packs have 256 and 16 outlets/inlets, respectively. In this study, we carried out both CFD modeling and experiments to understand the effect of outlet density on the hydrodynamics of the downstream resin bed. By comparing the predicted velocity fields and the measured residence time distribution (RTD) curves, we noticed that a fractal distributor of high outlet density can distribute the process stream uniformly at a low pressure drop to the resin bed. The process streams entering the resin bed reach plug flow profile within a short bed depth. As a result of the uniform flow distribution, mal-distribution such as channeling and dead space are minimized, and the process streams have a uniform RTD in the fractal pack. In comparison, the fractal distributor of low outlet density, which mimics some aspects of a conventional distributor, is found to have severe mal-distribution in the resin bed and consequently poor RTD inside the fractal packs. In addition, the RTD analysis confirms that the fractal distributor of high outlet density shows consistently good distributing performance for a wide range of operating flow rates. This study confirms the advantages of fractal distributors over conventional ones and demonstrates the benefit of fractal distributors in improving the overall performance of chemical equipment, indicating that fractal distributors are promising to enable process intensification for the chemical industry.

1. Introduction

Since its emergence in 1970 s, process intensification, as one promising innovation path in the chemical process industry, has been attracting extensive research interests from both academic and industrial sectors (Charpentier, 2007; Hessel, 2009; Stankiewicz and Moulijn, 2000). Process intensification consists of the development of novel apparatuses and techniques that lead to drastic improvement in chemical processes by the reduction of equipment size and energy consumption as well as improved production efficiency. Such characteristics are highly desired as they make the chemical industry more sustainable and environment-friendly (Liu et al., 2010). One relevant topic of

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Nomenclature

α	permeability (m^2)
δ_{ij}	Kronecker delta function
ε	turbulence energy dissipation rate (m^2/s^2)
μ	dynamic viscosity (kg/m s)
μ_t	turbulent viscosity (kg/m s)
ρ	mass density (kg/m^3)
σ^2	second moment of RTD response (s^2)
C	tracer concentration (mol/m^3)
C_{R2}	inertial resistant coefficient
D_d	diffusivity of the tracer (m^2/s)
D_t	turbulence contribution to diffusion coefficient (m^2/s)
D_p	diameter of resin bead (m)
g	gravity (m/s^2)
G_k	generation of turbulent kinetic energy due to the mean velocity gradients (m^2/s^2)
G_b	generation of turbulent kinetic energy due to buoyance (m^2/s^2)
k	turbulent kinetic energy (m^2/s^2)
p	pressure (Pa)
R	resistance in the resin section (Pa/m)
Sc_t	turbulent Schmidt number
t_m	mean residence time (s)
u_i	velocity component in ith spatial component (m/s)
u_i'	fluctuating velocity component in ith spatial component (m/s)
x_i	ith spatial component (m)

process intensification is the innovation of flow distributors (Kochergin and Kearney, 2006). Flow distributors are extensively integrated into chemical equipment to distribute incoming feed streams uniformly prior to the subsequent chemical processes. The efficiency of the flow distributor plays a key role in determining the overall performance of the chemical equipment. When the distributors have low efficiencies, the chemical equipment has to be oversized as a compensation, resulting in the increased material and energy consumption and reduced efficiency. In order to achieve process intensification, innovative flow distributors that offer uniform flow distribution and close residence time distribution of the feed streams are in urgent need by the chemical industry.

Conventional flow distributors utilize the pressure-based and trough-type designs, of which the typical diagrams are shown in Fig. 1(a) and (b), respectively. The pressure-based designs, *i.e.*, spray nozzle distributors as seen in Fig. 1(a), positions their outlets on the branches with certain intervals. The flow paths from the distributor inlet to each outlet are varying between each other. In order to achieve uniform flow distribution, each outlet has to be sized accordingly based on its flow path. Such design concept is associated with several inherent disadvantages. As the outlets are designed based on particular operating flow rates, the performance of such distributors are undermined significantly when the operating flow rates deviate from the designed value. For example, the process fluid may drip only from those center outlets when the operating flow rate is much lower than the designed one. In addition, the varying flow path results in different residence time for each stream. Furthermore, the scale-up of such distributors requires significant efforts as the design lacks symmetry. The outlet density, which is defined as the number of outlets per unit cross-sectional area, is usually limited below 250 openings per square meters (Inglezakis and Poulopoulos, 2006).

The trough-type distributors are composed of lateral troughs extended from a conventional splitter, *i.e.*, an open channel with weirs as shown in Fig. 1(b). After it overflows from the splitter, the incoming fluid flows laterally inside the troughs and maintains a constant height. The fluid is then discharged from orifices such as V-notches locating on the channel walls. The discharging flow rate from each orifice is determined by both the hydraulic head, which is the distance from the individual orifice to the free surface of process fluid, and the discharge coefficient of the orifice. In order to ensure uniform distributions, all troughs must have same width, and all orifices must have identical sizes. However, Yu et al. (2013) have observed that the lateral flows inside troughs influence the discharge coefficients of the orifices even though the orifices have identical sizes. Consequently, the flows discharged from the orifices are not uniform. In addition, the flow paths from the

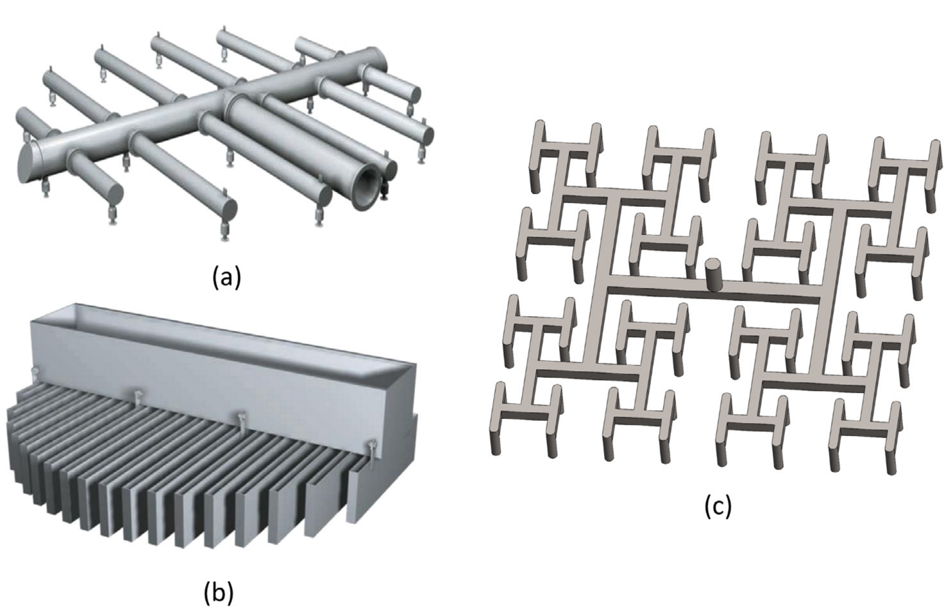

Fig. 1. (a) a conventional spray nozzle distributor (Sulzer Chemtech Ltd). (b) A trough-type liquid distributor (Sulzer Chemtech Ltd). (c) A fractal distributor.