Pressure Drop in Randomly Packed Absorption Tower in Transient Flow Regime

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Abstract

In this work computational fluid dynamics is used to describe the fluid flow across a randomly packed absorption tower. The CFD simulation method is employed on a packed tower that is packed with 1cm Raschig rings. Tower is 175cm in height. Air flow rate range was 1.5 to 5 m/s. The measured pressure drops were in 1.5 to 12 Pascal per height of tower in meter. The Klerk's approach is examined to define the influence of confining walls on pressure drop in packed areas. It is concluded that CFD model that uses the Klerk's definition of radial porosity distribution is a successful way for pressure drop prediction in packed beds. Model prediction of dry pressure drop is about 4% lower than the experimental measurements. Ergun's pressure drop prediction is compared with that of Reichelt's using averaged and distributed porosity profiles. In both methods Ergun's approach in comparison with Reichelt's approach has %6 lesser error in dry pressure drop prediction.

Keywords: pressure drop, absorption packed tower, random packing, computational fluid dynamics.

1. INTRODUCTION

It is more than several decades that packed towers are widely used in chemical and petrochemical industries for gas absorption, distillation, and liquid-liquid extraction processes. In view of energy consumption pressure drop is an important parameter in packed tower design and selection of fluid flow equipment such as fans or blowers, compressors and pumps. Dry pressure drop is also an important design parameter in packed towers because it is required for wet pressure drop estimations and packing capacity evaluation [1].

Many pressure drop relations which are function of gas velocity and packed area properties are available in the literature [2-6]. The most famous one of them can be Ergun pressure drop relation for packed beds when just one phase flow through void spaces, which have been obtained experimentally [7]. Studies on the flow of Newtonian and non-Newtonian fluids through packed columns show the influence of confining walls on pressure drop prediction [8, 9]

Reichelt correlation [10] is one of the Ergun-type equations, which considered wall effect in pressure drop prediction equation by the terms A and B. Table 1 shows the pressure drop relations applied in this article. Eisfeld and Schnitzlein (2001) [11] compared the pressure drop correlations of Ergun's, Reichelt's, and the other approaches. Riechelt's approach was found more successful than others in small column diameter to packing diameter ratios (smaller than 10). Atmakidis and kenig (2009) [12] compared no-considering wall effect. Ergun's general approach with considering wall effect approaches such as Reichelt's in the CFD simulation of spherical packing in the packed bed with 1 and 7 column diameter to packing diameter ratios. Consideration of wall effects approaches were found more successful in pressure drop prediction than others in real geometry of packed bed simulation. In recent decades CFD is applied to solve complex calculations in packed towers. Numerical simulation solves engineering problems with an acceptable accuracy and reduces experimental costs, whilst makes available more local information which may not be attainable experimentally [13]. Packed towers simulation complexity is due to complex geometry of void spaces in randomly packed towers.

Two numerical approaches are applied to study transport phenomena in packed towers: first, considering exact geometry of packed bed which obtain by tomographic-based methods with high costs [12, 14]. In the second approach packed section is considered as porous media. Fluid flow governing equations and pressure drop correlations are applied to calculate fluid- solid interactions. Local phenomena is described as functions of radial and axial distribution of parameters [12]. Local voidage variation is one of the important parameters in simulation geometry description [15]. Most of the studies has resulted oscillatory damped behavior for radial porosity variation in packed sections [16, 17]. de Klerk [16] described radial porosity distribution by sinusoidal oscillatory damped function with exponential function near confining walls. Many researchers [18-23] applied second approach to model industrial packed towers with spherical and non-spherical packing such as Pall ring and Berl saddle in two dimensional (2D) and macro scale simulations. In this article, 3D CFD method in Eulerian-Eulerian frame is used to simulate a pilot scale tower that randomly packed with Raschig rings. Dry pressure drop is investigated

Table 1. Pressure drop predicting correlations

No	Correlation	Constants	Wall effect correction	Ref.
1	$\frac{\Delta p}{Z} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu}{(D_p\emptyset_S)^2} U + 1.75 \frac{(1-\varepsilon)\rho_g}{\varepsilon^3 D_p \emptyset_S} U^2$	-	No	Ergun[7]
2	$\frac{\Delta p}{z} = \frac{154A^2}{Re} \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{A}{B} \frac{(1-\varepsilon)}{\varepsilon^3}$	$A = 1 + \frac{2}{3\left(\frac{D}{dp}\right)(1-\varepsilon)}$ $B = \left[1.15\left(\frac{dp}{D}\right)^2 + 0.87\right]^2$	Yes	Reichelt [10]

In this study and validated experimentally. de Klerk's approach is applied to describe radial porosity distribution. Results has compared with simulation without wall effect consideration. In addition Ergun's approach is compared with Reichelt's approach in fluid flow resistance across the packed areas in tower diameter to packing effective diameter ratio approximately 17.

2. Experimental procedure

Figure 1 shows experimental set-up used in this research. The column is 1.75m in height and 0.05m in diameter. The column has two separated packed sections. Each packed with approximately 1cm Raschig rings. Tower diameter to packing effective diameter ratio is about 17. Voidage measurements carried out by sudden stop of water supply and measured collected water volume. Air supplied at the bottom of column. Manometer was used for column pressure drop measurements along the column. Air flow measured by calibrated rotameter. Effective diameter of packing element is used to apply packing shape effect of non-spherical packed beds on pressure drop correlation [24]. Eq.3 and 4 show effective packing diameter, d_p, relations with sphericity factor, $\emptyset_S$, spherical equivalent diameter of packing, D_p and specific surface of a packing a_v.

$$a_v = \frac{Sp}{Vp} \quad (3)$$

$$d_p = D_p \emptyset_S = \frac{6}{a_v} \quad (4)$$

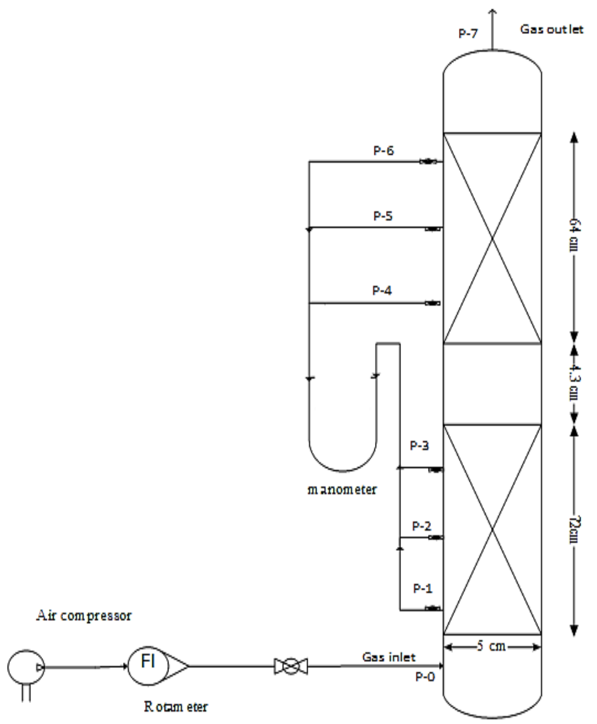


Figure 1. Schematic of experimental set up.

3. Mathematical models

3.1 Fluid dynamic equations

The governing equations describing the gas flow through the packed area are the volume averaged continuity and momentum equations:

Continuity Equation;

$$\frac{\partial}{\partial t}(\varepsilon\gamma\rho) + \nabla.\{\varepsilon(\gamma\rho U - \tau\nabla\gamma)\} = 0 \quad (5)$$

Momentum Equation;

$$\frac{\partial}{\partial t}(\varepsilon\gamma\rho U) + \nabla.\{\varepsilon\gamma(\rho UU - \mu(\nabla U + (\nabla U)^T))\} = \varepsilon\gamma(B - \nabla p) \tag{6}$$

Where:

The porosity of the packing area, ε, the volume fraction occupied by a phase, γ, the fluid density, ρ, the effective viscosity, μ , the dispersion coefficient, τ, the interstitial velocity vector, U, the body force (including the gravity and the flow resistance offered by the packing elements), B, the pressure, p complete continuity and momentum equations

3.2 Body force in packed area

Meandrous spaces in packed areas make resistance to fluid flowing. Body force includes the gravitational force ρg, In addition the resistance increased by the solid packing elements. In this equation (eq.7) $\boldsymbol{R}$ is resistance tensor. Resistance tensor is predictable from pressure drop By Darcy's low (eq.8).

$$B = \rho g + R.U \tag{7}$$

$$U = -R^{-1}.\nabla P \tag{8}$$

In this article, pressure drop correlations in Ergun's approach (eq.1) and Reichelt's approach (eq.2) is examined to define gas resistance flowing across the packed areas.

3.3 Porosity distribution

As explained in first section, the influence of confining walls on pressure drop of any packed area is the subject of many studies [11, 17]. Wall effect is defined as radial porosity distribution caused flow tendency near confining walls. Many studies carried out to define radial porosity distribution in packed beds [17], but there isn't any equation described this distribution for all kinds of packing. In this study, de Klerk's approach (eq.13) and packing effective diameter calculations are applied to define radial porosity distribution of packed column of Raschig rings.

$$a = \frac{R - r}{D} \tag{9a}$$

$$\varepsilon(r) = 2.14a^2 - 2.53a + 1 \ , a \leq 0.637 \tag{9b}$$

$$\varepsilon(r) = \varepsilon_b + 0.29\exp(-0.6a).\left[\cos\left(\frac{2}{3\pi(a - 0.16)}\right)\right] + 0.15\exp(-0.9\,a)\ , a > 0.637 \tag{9c}$$

4. CFD Simulation

Packed tower described in previous section is applied in simulation. Table 2 shows geometrical properties of packed areas in experimental set-up.

Table 2. Packed area properties.

Effective diameter of the packing element, cm	0.28
Porosity of upper packed area	0.6904
Porosity of lower packed area	0.8303

4.1 Geometry of packed tower

Fig. 2-(a) illustrates three dimensional (3D) geometry of absorption tower with two separated packed areas with exact geometry of gas inlet and outlet. In this simulation packed areas with Raschig rings have been modeled by porous media with fluid flow resistance. Averaged experimental data of porosity has been used in simulation without wall effect consideration.

4.2 Meshing

Figure 2-(b) shows meshed structure of packed absorption tower. Fine and distributed unstructured meshing has been applied specially in characteristic places such as near confining wall, fluid inlet, fluid outlet and distributer holes. The effect of the mesh number was examined on dry pressure drop results in four number of nodes 641908, 707764, 748879, 834808.

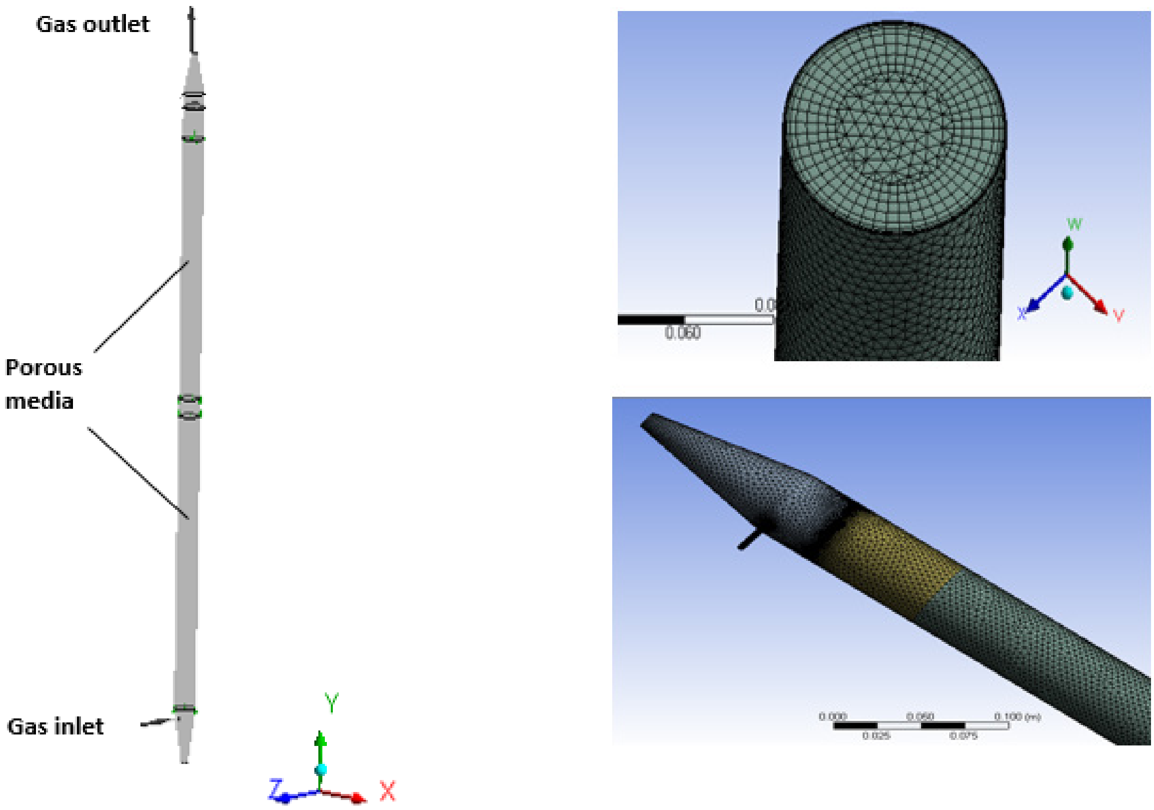


Figure 2. Packed column: (a) geometry and (b) mesh structure

4.3 Fluid flow regime and boundary conditions

Reynolds number calculations shows laminar and transient flow regimes along the tower. Turbulence effect is ignored in the simulation. Fluid velocity is used for inlet condition and constant pressure is used for outlet condition. No-slip condition is used for walls.

5. Result and discussion

5.1 Porosity Effect

In packed reactors it is accepted that radial porosity distribution, $\varepsilon(r)$, is a function of packing diameters but by changing diameter the average porosity remains a constant value at about 0.4. However, the average axial porosity, $\varepsilon(z)$ is varied by repacking in industrial towers with large diameters [20, 25]. Fig.3 illustrates 2D radial porosity distribution has been used by software in x-y coordination.

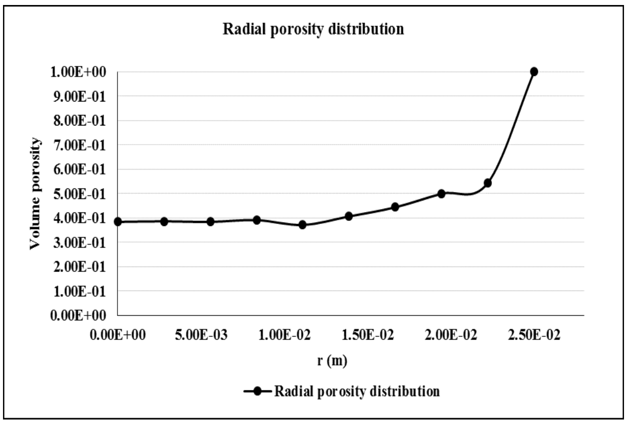
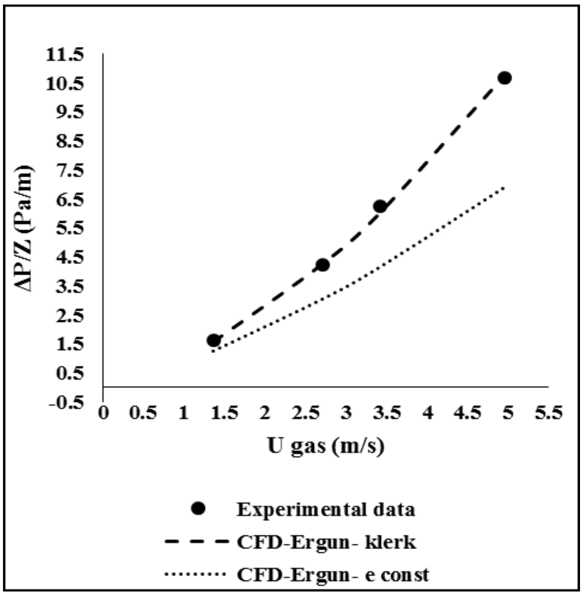


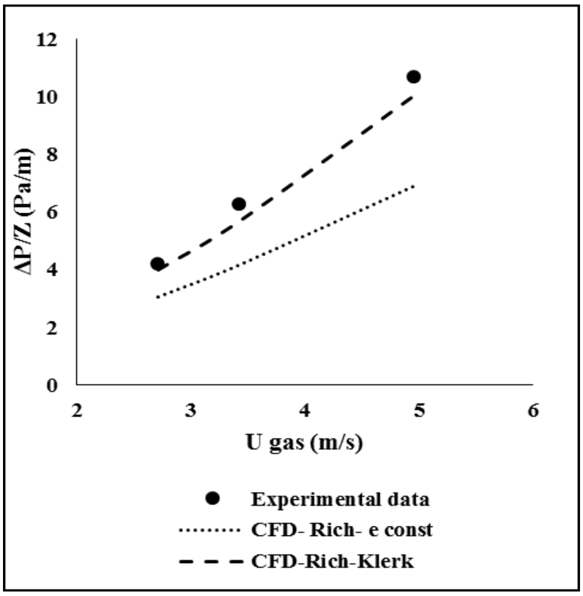
Figure 3. Porosity data generated by CFD model: radial

5.2 Wall Effect and pressure drop

CFD simulation was used to calculate pressure drop in the packed tower. The results compared with experimental data for the model validation in Fig. 4. Fig. 4 demonstrates with increasing gas velocity effects of transient behavior is more profound on the pressure drop. At low gas velocity the experimental data and predicted results are close to each other but the difference increases at higher gas flow rates; in other word wall effect becomes more characteristic by increase in fluid flow velocity in transient flow regime. Fig.4-(a) shows simulation results using Ergun's, Eq. 1, and de Klerk's, Eq. 13 and 14, equations. Fig.4-(b) shows simulation results using Reichelt's, Eq. 2, and de Klerk's, Eq. 13 and 14, equations. Experimental dry pressure drop is included as well. The figures show that using wall effect relations give a pressure drop estimation with a lesser difference from experimental data. It shows that combination of Ergun-Klerk relation gives more accurate data and therefore is more favorable.



(a)



(b)

Figure 4. Wall effect considering by de Klerk's approach study for simulations with pressure drop predicting equations: (a) Ergun (b) Reichelt

In Fig.5 CFD estimated pressure drop data has compared with experimental data. Ergun's approach in pressure drop prediction was more successful than Reichelt's approach in fluid flow resistance description in packed column with column diameter to effective diameter of packing ratio of 17.

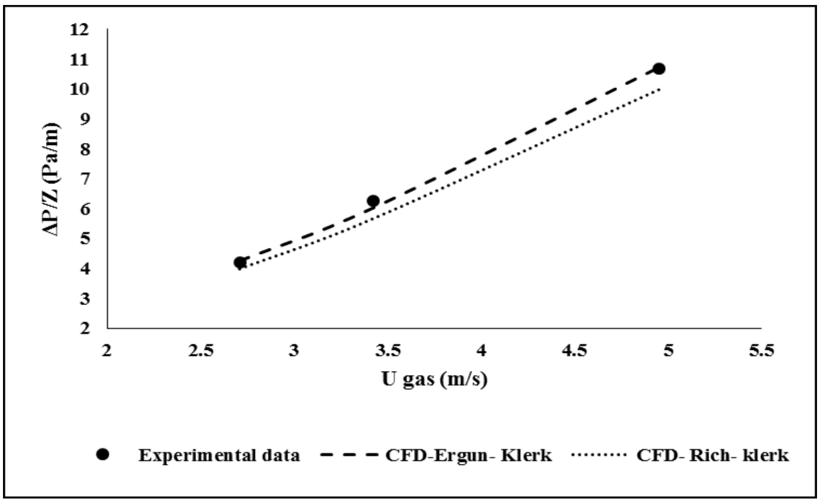


Figure 5. Comparison between Ergun's and Reichelt's approaches in fluid flow resistance description for packed column with Raschig rings

The CFD models errors prediction is illustrated in Fig 6. The de Klerk's approach is about 56% more successful in predicting experimental data regardless of not using wall effect. The de Klerk's description of packed bed geometry has just 4% error (Fig.6 a and b). Using Reichelt's approach to describe fluid flow resistance with wall effect consideration become about 50% more successful in experimental data prediction but has about 10% error yet (Fig.6 c and d). Fig.6 b and d demonstrate simulation by general Ergun's approach in resistance description is 6% more successful than Reichelt's approach in pressure drop prediction.

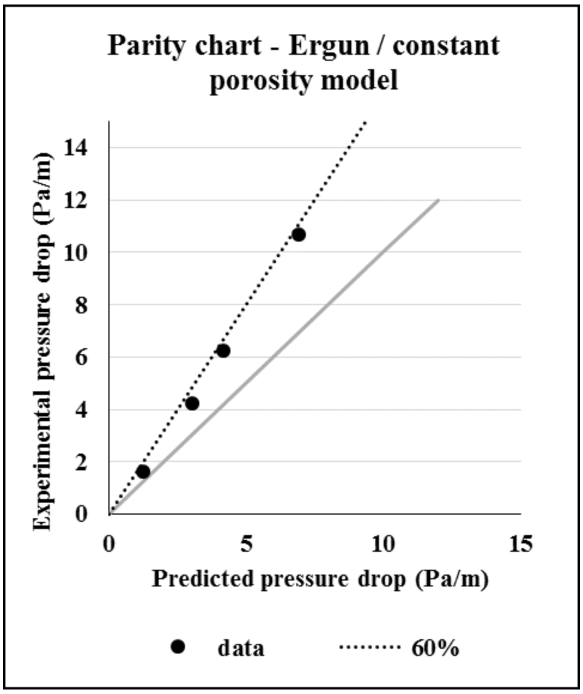


Figure. 6a

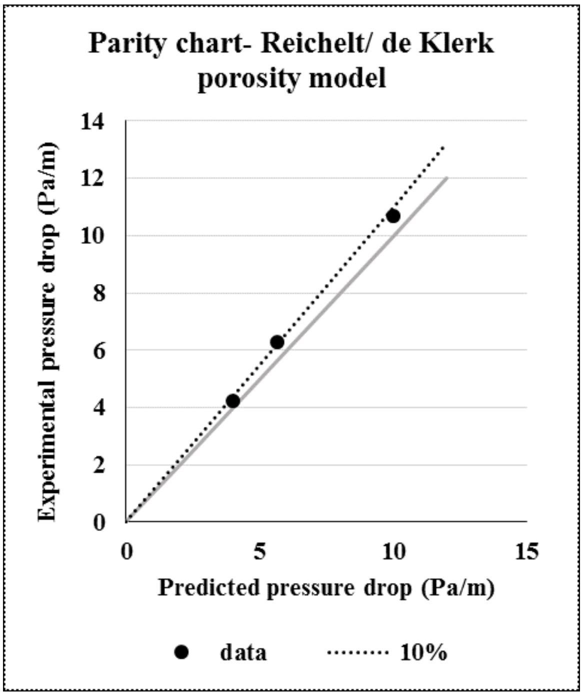


Figure. 6c

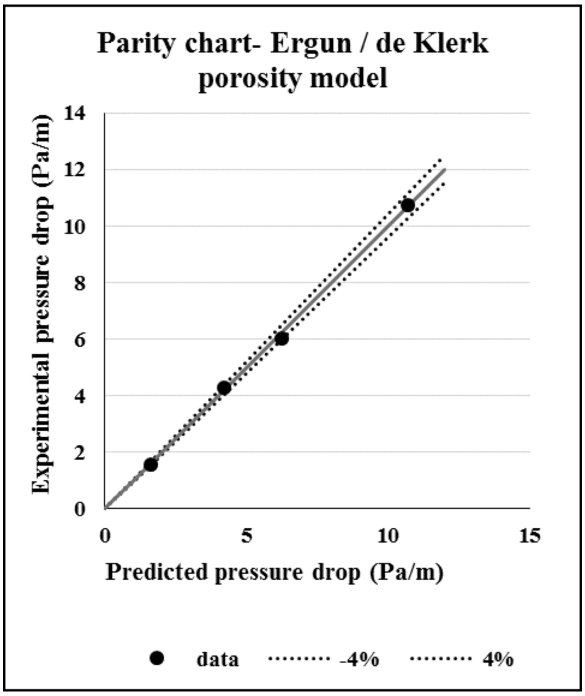


Figure. 6b

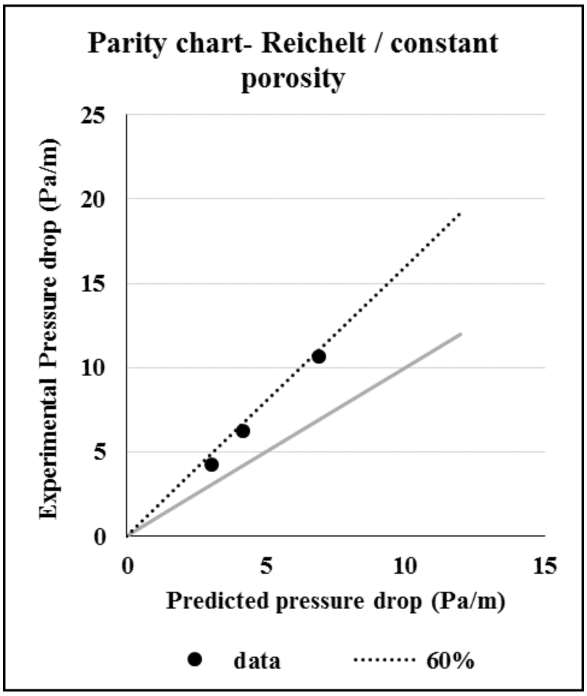


Figure. 6d

Figure 6. The CFD model prediction validation study: (a) and (b) Ergun's approach in resistance description with and without wall effect consideration, respectively. (c) and (d) Reichelt's approach in resistance description with and without wall effect consideration, respectively.

6. Conclusion

In this article packed tower with Raschig rings in pilot scale has been simulated by using porous with resistance model. Wall effect phenomena is examined by de Klerk's approach for effective diameter of packing element. In addition, Ergun's and Reichelt's approaches are examined to describe flow resistance across the packed area. Simulation and modeling validated for dry pressure drop experimentally.

Simulation of packed bed geometry in packed tower with Raschig rings illustrates that wall effect has characteristic role in pressure drop prediction in packed column with column diameter to effective diameter of packing ratio 17. Tomographic experiments is costly and calculation the exact meandrous spaces of packed areas requests advance computation power. de Klerk's approach and effective diameter of a packing calculation was successful in description of Raschig rings packed bed geometry. Although approved Reichelt equation is successful to predict pressure drop in low column diameter to effective diameter of packing ratios, this study demonstrates general Ergun's approach is more successful than Reichelt's approach to describe fluid flow resistance across the packed area in high column diameter to effective diameter of packing ratio 17.

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Nomenclature

A, B	Coefficients of pressure drop equations (-)
a	Nondimensional distance from the wall (-)
a_v	Specific surface of a particle (m^{-1})
$\mathbf{B}$	Body force (N)
D	Column diameter (m)
D_p	Equivalent spherical diameter (m)
d_p	Particle diameter (m)
G	Gas flow rate (Kg/ m^2. s)
g	Acceleration due to gravity (m/s^2)
Δp	Pressure drop across packed bed (Pa)
R	Resistance tensor kg $s^{-1}m^{-3}$
R	Column radius (m)
r	Radial position relative to the column center line (m)
Sp	Surface area of particle (m^2)
U	Superficial gas velocity (m/s)
us	Superficial fluid velocity (m/s)
Vp	Volume of particle (m^3)
Z	Height of packed bed (m)

Greek letters

μ	Dynamic viscosity (N s/m^2)
ε	Porosity (-)
εb	Porosity in the absence of wall effects (-)
γ	Volume fraction(-)
ρ	Density (kg/m^3)
ρg	Gas density (kg/m^3)
$\emptyset_S$	Sphericity coefficient (-)
ε	Dispersion coefficient vector, $kgm^{-1}s^{-1}$

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افت فشار برج جذب آکنده نامنظم در رژیم جریان گذرا

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چکیـــــده

در این پژوهش از روش دینامیک سیالات محاسباتی برای توصیف جریان در بستر آکنده برج جذب با آکنه های نامنظم پرداخته شده است. در این بررسی برجی در مقیاس نیمه صنعتی با آکنه های راشیگ ۱ سانتیمتری بوسیله دینامیک سیالات محاسباتی مورد شبیه سازی در مقیاس ماکرو قرار گرفته است. ارتفاع برج در حدود ۱۷۵ سانتیمتر است. محدوده سرعت هوا ۱/۵ الی ۵ متربرثانیه و افت فشار اندازه گیری شده ۱/۵ الی ۱۲ پاسکال بر واحد متر است. پدیده اثر دیواره که منجر به توزیع تخلخل شعاعی در ناحیه آکنده میشود با دیدگاه کلرک بیان شده است. تعریف توزیع تخلخل شعاعی کلرک در مدل CFD در پیش بینی افت فشار حاصل از محیط آکنده با آکنه های راشیگ موفق بوده است.پیش بینی افت فشار خشک توسط مدل تنها در حدود ۴٪ با نتایج آزمایشگاهی اختلاف دارد. دیدگاه پیش بینی افت فشار ارگان، در دو حالت بررسی با تخلخل متوسط و توزیع تخلخل شعاعی، با دیدگاه رایکلت مورد مقایسه قرار گرفته است. در این بررسی دیدگاه پیش بینی افت فشار براساس رابطه ارگان در هر دو روش به نسبت دیدگاه رایکلت در پیش بینی داده های آزمایشگاهی دقیق تر بوده و تنها ۶٪ از نتایج آزمایشگاهی اختلاف داشت.

واژگان کلیدی: افت فشار، برج جذب آکنده ، آکنه نامنظم، دینامیک سیالات محاسباتی