CI&CEQ
Chemical Industry & Chemical Engineering Quarterly
Available online at
Association of the Chemical Engineers of Serbia AChE
www.ache.org.rs/CICEQ
Chem. Ind. Chem. Eng. Q. 30 (1) 47−58 (2024) CI&CEQ

BENSABER BENSEBIA[1]
FATMA-ZOHRA CHAOUCHE[1]
OUAHIDA BENSEBIA[2]
SOUMIA KOUADRI MOUSTEFAÏ[3]

[1]Laboratory of Plant Chemistry-Water-Energy, Department of Process Engineering, Faculty of Technology, Hassiba Benbouali University, Chlef, Algeria

[2]Industrial Process Engineering Sciences Laboratory, Houari Boumediene University of Sciences and Technology, Bab Ezzouar, Algeria

[3]Department of Process Engineering, Faculty of Technology, Hassiba Benbouali University, Chlef, Algeria

SCIENTIFIC PAPER

UDC 66.096.5:51-7

BED EXPANSION IN TURBULENT BED CONTACTOR: EXPERIMENTS AND PREDICTION

Article Highlights

- Trends in bed expansion (Hd/Hst) evolution with operating variables
- A method for the prediction of bed expansion has been proposed
- The proposed calculation has been tested with experimental data, confirming its reliability
- The study determined the best correlations for predicting the expansion of the bed

Abstract

In this work, turbulent bed contractor (TBC) hydrodynamics have been studied in terms of bed expansion (Hd/Hst) using a particular approach to predict this important property for the design of such equipment. The study is based on 1604 sets of experimental data on the bed expansion, obtained by varying the operating variables (gas velocity, liquid spray, packing characteristics, static bed height, and free opening of the supporting grid). The prediction of the bed expansion necessitates the estimation of gas and liquid holdups. To achieve this, we employed a variety of correlations derived from existing literature, comprising six equations for gas holdup and twenty equations for liquid holdup estimation. Out of a total of 120 cases, bed expansion was estimated, and the accuracy of the model was evaluated by calculating the mean absolute error in percentage (MAPE), root mean square error (RMSE), correlation coefficient (ρ_{XY}), and explained variance (VE_{CV}). This study identified suitable correlations for gas and liquid holdups, leading to predictions with acceptable errors. Furthermore, statistical analysis was employed in a subsequent phase of the study to determine the most appropriate correlations for predicting bed expansion among those proposed by various authors.

Keywords: three-phase fluidization, turbulent bed contactor, bed expansion, gas holdup, liquid holdup.

The Turbulent Bed Contactor (TBC) is a three-phase fluidized bed of low-density spherical particles. The solid is fluidized by an upwardly flowing gas (continuous phase) and irrigated by a downwardly flowing liquid. Non-flooding grids, positioned at a sufficient distance to allow for bed expansion, support the bed. A turbulent and random motion of the packing enhances contact between the gas and liquid phases. This turbulent motion generates rapid interface renewal and a large interfacial area, increasing mass and heat transfer rates. The TBC presents several advantages over conventional contactors, including high capacity, high efficiency, and resistance to clogging.

In physical processing, the TBC is used in air-cooling humidification and dehumidification, particulate removal, and lactose granulation [1–3]. In chemical processing, it is employed in gas desulphurization, absorption, desorption, and distillation [4–7]. In biological processing, it is used for alcohol fermentation. Muroyama and Fan [8] discussed some

Correspondence: B. Bensebia, Laboratory of Plant Chemistry-Water-Energy, Department of Process Engineering, Faculty of Technology, Hassiba Benbouali University, B.P. 151, 02000 Chlef, Algeria.
E-mail: bensebiab@yahoo.fr; b.bensebia@univ-chlef.dz
Paper received: 4 March, 2023
Paper revised: 15 May, 2023
Paper accepted: 6 June, 2023

https://doi.org/10.2298/CICEQ230304010B

specific applications. In recent years, under the double constraint of the imperatives of environmental protection and pollution reduction and the rational use of energy, TBC has offered new opportunities, particularly in air pollution control [9].

Numerous published studies have focused on exploring the hydrodynamic parameters and performance of the Turbulent Bed Contactor (TBC), determining mass and heat transfer rates and associated parameters. Most of these studies have proposed empirical correlations for predicting the diverse hydrodynamic and mass and heat transfer parameters. In recent years, several authors have adopted the Computational Fluid Dynamics (CFD) approach for modeling the flow behavior in three-phase gas-liquid-solid systems, with specific emphasis on TBCs [10–12].

In 1972, O'Neill *et al.* [13] proposed a model for this three-phase fluidized bed based on the hydrodynamic behavior of a conventional packed column. They classified the TBC operation into two regimes: TBC Type 1 - Fluidization without "Incipient Flooding" and TBC Type 2 - Fluidization due to "Incipient Flooding." In Type I, fluidization started before flooding in the column, whereas in Type 2, fluidization started after flooding. All subsequent studies have referenced this model, which clarified several contradictions in previous findings and outcomes, constituting a significant contribution to comprehending the hydrodynamic behavior of the TBC process.

The bed expansion, which determines the fluidized bed height, is one of the key design parameters for the fluidized bed of TBC. Knowledge of this factor would allow calculation of the expanded volume of the bed and provide a basis for determining liquid and gas holdups. The work of Muroyama and Fan [8] comprehensively summarizes the experimental data of different authors on bed expansion in the Turbulent Bed Contactor (TBC).

According to many authors [14–18], the gas-distributing grid strongly affects the bed expansion behavior, resembling a bubble column with a high gas holdup. For grids having a small open area, a liquid layer formed above the grid causes an axial variation of the liquid holdup. Levsh *et al.* [15], which investigated the effects of the geometry of the supporting grid on the pressure drop and bed expansion of TBC, suggested a correlation between the dynamic bed height and the height of the liquid layer.

Chen and Douglas [19] showed that the bed height increased linearly with gas velocity and liquid velocities for low-density particles. Tichy and Douglas [20] reported that the bed expansion (H_d/H_{st}) is independent of both the static bed height (H_{st}) and particle density (ρ_p) for low particle density and that a rapid increase in dynamic bed height (H_d) has been observed for gas velocities approaching the true flooding point. Balabekov *et al.* [21,22], Ushida *et al.* [23], and Handl [24] noted the existence of two regions of bed expansion, while Vunjak-Novakovic *et al.* [14] observed, based on their experimental data, three regions of the curves in the expansion of the bed with the gas velocity.

The objective of this study, based on a large number of experimental data on the expansion of the bed in the turbulent bed contactor (Type II-TBC), is essentially oriented to the analysis of the evolution of the expansion with the operating variables, such as gas and liquid fluxes, static bed height, and opening of the supporting grid. The results of this analysis, as well as the experimental data, were used to develop a correlation allowing the prediction of the expansion of the bed in the turbulent bed contactor (Type II-TBC).

MATERIAL AND METHODS

Experimental procedure and apparatus

The experimental setup shown in Fig. 1 and previously described [25] consists of three main parts (Fig. 1a), including the fluidization column and the liquid (water) and gas (air) supply systems. The column comprises a plexiglass cylinder of 0.12 m internal diameter and 1.60 m height (1). The column is equipped, in its lower part, with a packing support grid with a variable free opening (2) and at the inlet of the gas distributor (3), ensuring a uniform gas flow through the whole section of the column. The top of the column is equipped with a liquid distributor (4) to ensure a uniform flow of liquid through the entire column section, especially at low flow rates. The liquid supplied to the distributor (Fig. 1b) comes from a reservoir (5) fed by tap water using a centrifugal pump (6). The air supplied to the gas distributor comes from the system's compressor tank (7) via a pressure reducer (8). The bed of particles (9) consists of hollow polypropylene spheres and lies in a static state on a supporting grid. The liquid and gas fluxes were controlled by valves (14, 15), and their flows were measured by rotameters (10 and 11). A U-tube water manometer measured the pressure across the column (12). To reduce pressure fluctuations, a particular device (13) has been designed to separate liquid droplets entrained by the gas at parietal connections.

Experimental conditions

Three relative static bed heights ((H_{st}/D_C) = 0.5;

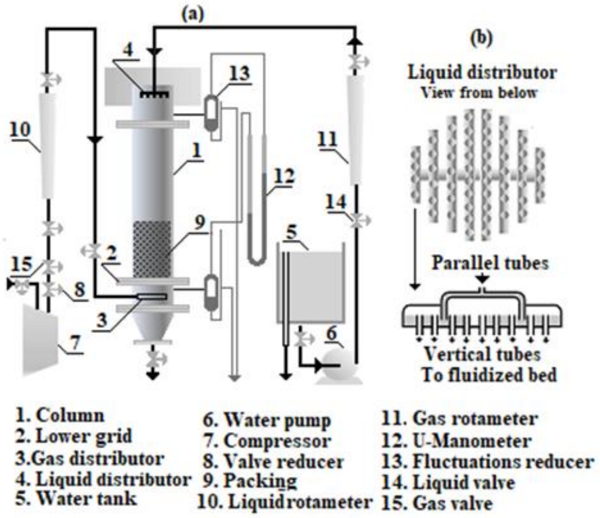

Figure 1. Experimental setup.

0.75 and 1.0)) were considered. For each static bed height, two different sets of packing were considered. For each packing (ρ_{PI}=868 kg m^{-3}, d_{PI}=0.01 m and ρ_{PII}=736 kg m^{-3}, d_{PII}=0.015 m), the opening of the lower grid (φ) was varied as (0.32; 0.56 and 0.82). Each support grid opening used five liquid fluxes (*L*=4.57; 10.23; 15.84; 20.94, and 27.90 kg m^{-2} s^{-1}). For each series thus defined (ρ_p, d_p, H_{st}, and *L*), the gas flux (*G*) was varied from 0 to 10 kg m^{-2} s^{-1}. Thus, for the 13 experimental series considered, 1604 sets of experimental data were measured. The pressure drop and the dynamic bed height were measured simultaneously. The full operating conditions are summarized in Supplementary material (Appendix A, Table A1.).

Methods

The fundamental dynamic bed height (H_d) equation is easy to obtain. Since the total volume of the fluidized bed (V_t) is the sum of the volumes of the different phases (V_s, V_l, and V_g), we can write in terms of fractions for each phase:

$$\varepsilon_S + \varepsilon_l + \varepsilon_g = 1 \quad (1)$$

We define, from the mass balance of the liquid phase and the solid phase, the solid and liquid holdup based on the static bed height ($\varepsilon_{s_{st}}$ and $\varepsilon_{l_{st}}$), as follows:

$$\varepsilon_{l_{st}} = \varepsilon_l \frac{H_d}{H_{st}} \quad (2)$$

$$\varepsilon_{S_{st}} = \varepsilon_S \frac{H_d}{H_{st}} \quad (3)$$

where H_d and H_{st} are the dynamic and static bed heights. If we write that ε_0 is the void fraction of the dry packing, we get:

$$\varepsilon_{S_{st}} = (1-\varepsilon_0) \quad (4)$$

The mass balance for the same amount of solid particles in a static and dynamic state gives:

$$\Omega H_{st}\rho_s(1-\varepsilon_0) = \Omega H_d \rho_s\left(1-\left(\varepsilon_l + \varepsilon_g\right)\right) \quad (5)$$

If we call (ε) the sum of liquid (ε_l) and gas holdup (ε_g):

$$\varepsilon = \varepsilon_l + \varepsilon_g \quad (6)$$

and combining Eqs. 1, 5, and 6, we obtain for ε_s :

$$\varepsilon_s = 1-\varepsilon = \frac{H_{st}}{H_d}(1-\varepsilon_0) \quad (7)$$

that becomes:

$$\frac{H_d}{H_{st}} = \frac{(1-\varepsilon_0)}{(1-\varepsilon)} \quad (8)$$

Rewriting Eq. 8, considering Eqs. 2 and 6 gives the fundamental relationship for the ratio H_d/H_{st}, which represents the bed expansion from liquid ($\varepsilon_{l_{st}}$) and gas (ε_g) holdups:

$$\frac{H_d}{H_{st}} = \frac{\varepsilon_{l_{st}} + (1-\varepsilon_0)}{\left(1-\varepsilon_g\right)} \quad (9)$$

RESULTS AND DISCUSSION

We have experimentally determined the expansion of the bed and the associated pressure drop. The effects of operating variables (gas and liquid fluxes (*G* and *L*), free supporting grid area (*φ*), static bed height (H_{st}), and packing characteristics (ρ_p, d_p) on bed expansion were determined. The experimental results consisted of 65 curves of the evolution of bed expansion. For brevity, we present only a few examples of experimental data.

Effect of gas and liquid velocities (u_g, u_l)

Fig. 2 shows that the bed expansion (H_d/H_{st}) increases sharply with the increase of the gas and liquid velocities (u_g and u_l), as has been observed earlier [15–17,19,20,26–28].

Effect of grid opening (φ) on bed expansion

Figure 3a clearly shows that a reduction in the opening of the lower supporting grid promoted the bed expansion and that this effect was enhanced by increasing the liquid velocity. It is illustrated in the inset figure in Fig. 3a, which represents the expansion's evolution for various support grid openings and liquid velocities of 0.00457, 0.01023, and 0.02094.m s^{-1}.

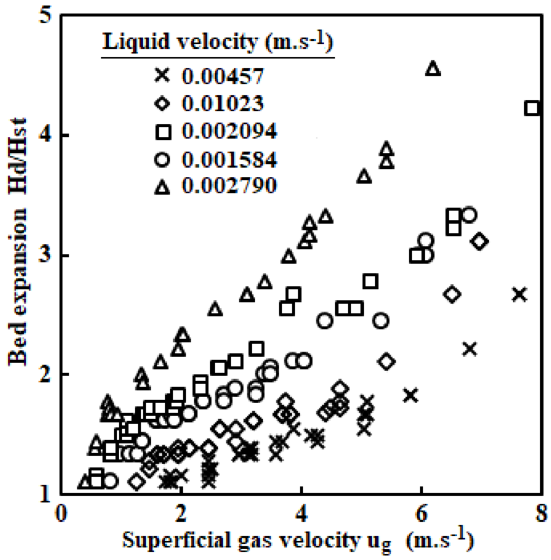

Figure 2. Variation of the bed expansion (H_d/H_{st}) with gas velocity (u_g) and liquid fluxes (L) for series II: (ρ_{PI}=868 kg m^{-3}, d_{PI}=0.010 m, φ=0.56, H_{st}=0.090 m).

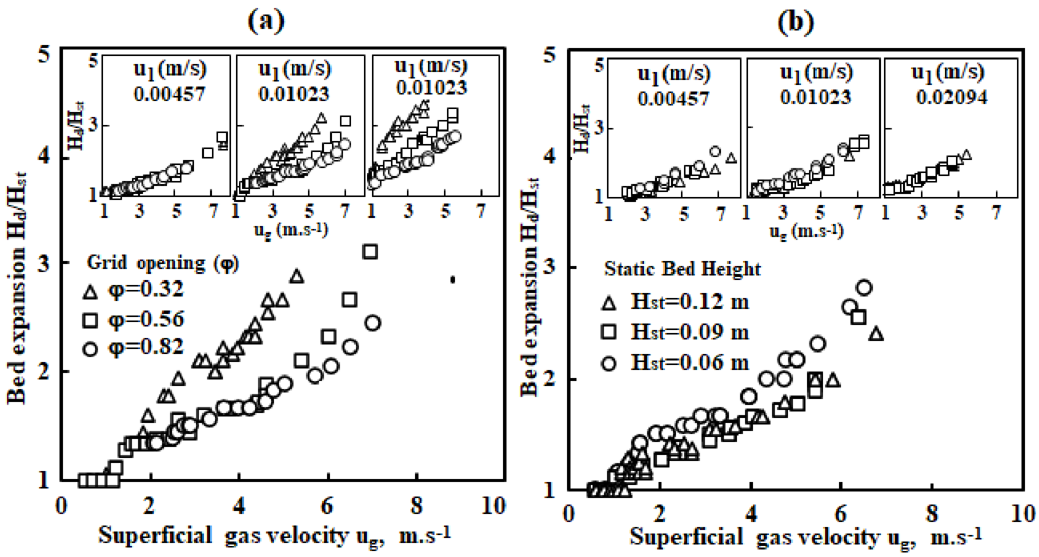

Figure 3. a) Effect of grid opening (φ) on bed expansion (H_d/H_{st}) for series I, II, and III (ρ_{PI}=868 kg m^{-3}, d_{PI}=0.010 m, H_{st}=0.090 m, L=10.23 kg m^{-2} s^{-1}. b) Effect of static bed height on bed expansion (H_d/H_{st}) for series VIII, XI, and XIV (ρ_{PII}=736 kg m^{-3}, d_{PII}=0.015 m, φ=0.56, L=15.84 kg m^{-2} s^{-1}).

Effect of static bed height (H_{st})

The results presented in Figure 3b show that the static head (H_{st}) had no significant effect on bed expansion for the different liquid flows.

Models' development

According to Vunjak-Novakovic *et al.* [14], three models for bed expansion in TBC have been proposed: Levsh *et al.* [15], Tichy and Douglas [29], and O'Neil *et al.* [30]. The first model of Levsh *et al.* [15] was considered incomplete [14] because it included the gas fraction in the bed for which no correlation was given. The second model of Tichy and Douglas [29] is based primarily on the analysis of experimental data [19,29], which shows a linear dependence between the bed expansion (H_d/H_{st}) and the gas flow rate, and the fact that the bed expands as a consequence of the pressure drop increase caused by the increase in the gas flow rate. There is, thus, a mutual relationship between the pressure drop and the expanded bed height. The shortcomings of this approach [14] are the use of an equivalent diameter of gas channels, somewhat fictitious for fluidized beds, and the use of correlations valid for fully fluidized beds at all gas velocities. According to their incipient flooding model [13] and using the Wallis equation for flooding in packed beds [31], O'Neil *et al.* [30] derived the third model based on Eq. 14 to predict bed expansion in TBC. However, as the expression (Eq. 14) was derived for incipient fluidization due to flooding, it could not be recommended for TBC type II.

In our opinion, adding the model based on Eq. 9 would also be necessary, which is considered the basic relationship to the definition of expansion. However, the implementation of this model requires reliable correlations for estimating gas and liquid holdups.

The study of different correlations for estimating the expansion (Table 1) identifies readily another model based on a relationship between the minimum fluidization velocity and expansion: those of Uysal [32], Khanna [33], and Blyakher *et al.* [28]. Other expressions are mainly based on the attempt to correlate experimental data and based on the operative variables affecting the bed expansion.

Table 1. Correlations for bed expansion (H_d/H_{st}) for TBC.

Authors	Correlations (S.I. Units)	Eq.
Levsh *et al.* [15]	$\frac{H_d}{H_{st}} = 4.4\, u_l^{0.43} u_g^{2}$ $for\ u_l < 0.0078\ m/s, \quad u_g < 2.5\ m/s$ $\frac{H_d}{H_{st}} = 2.2\, U_l^{0.35} u_g^{2}$ $for\ u_l > 0.0078\ m/s, \quad u_g > 2.5\ m/s$	(10)
Tichy & Douglas [20]	$\frac{H_d}{H_{st}} = 0.8849 + 0.3166\, G - 18.33\, d_P + 0.5852\, L^{0.6} d_P^{\ 0.5}$	(11)
Rama *et al.* [26]	$\frac{H_d}{H_{st}} = 2.132\, d_P^{\ 0.12} u_l^{0.31} + 1.02\, d_P^{\ -1.7} \rho_P^{\ -1.2} u_l^{0.2} U_g$	(12)
Blyakher *et al.* [28]	$\frac{H_d}{H_{st}} = 1.17 + (0.065 + 24.6\, u_l^{0.75})(\rho_g u_g - \rho_g u_{mf})$	(13)
O'Neil *et al.* [30]	$\frac{H_d}{H_{st}} = \frac{1-\varepsilon_0}{1-\varepsilon}, \varepsilon = \left[K\left(27 + \frac{4K}{108}\right)^{1/2} + \frac{K}{2}\right]^{1/3} - \left[K\left(27 + \frac{4K}{108}\right)^{1/2} - \frac{K}{2}\right]^{1/3}$ $K = \left[u_g^{\ 1/2} + u_l^{\ 1/2}(\rho_l/\rho_g)^{1/4}\right] / \left[0.775(g d_P \rho_l / 6\rho_g)^{1/4}\right]$	(14)
Uysal [32]	$\frac{H_d}{H_{st}} = 1 + \frac{0.147(\rho_g u_g - \rho_g u_{mf})}{H_{st}}, \qquad u_{mf} = \frac{10.86\, d_P^{\ 0.488} 10^{0.01985\, L}}{\rho_g}$	(15)
Khanna [33]	$\frac{H_d}{H_{st}} = 1 + 0.414(\rho_g u_g - \rho_g u_{mf})(\rho_g u_{mf})^{0.2}, u_{mf} = \frac{526.47 d_P^{\ 1.5} 10^{0.0117\, L}}{\rho_g}$	(16)
Lyashuk [34]	$\frac{H_d}{H_{st}} = 0.16 u_g^{\ 0.44} L^{0.27} H_{st}^{\ -0.71} \varphi^{-1.54}$	(17)
Shackley [35]	$\frac{H_d}{H_{st}} = 0.0833\,(-14.9\varphi^2 + 15.7\varphi - 2.1) H_{st}^{\ -0.34} L^{0.26} \rho_P^{\ -0.43} u_g^{\ 0.78} d_P^{\ -0.85}$	(18)
Gimenes & Handley [36]	$\frac{H_d}{H_{st}} = 1.862\, d_P^{\ 0.306} \left(1 - \frac{\varphi}{\psi_v}\right)^{1.37} L^{0.108} (10^3 \rho_P v_P)^{-0.107} exp(0.356\, u_g)$	(19)
Aksel'rod & Yakovenko [37]	$\frac{H_d}{H_{st}} = 0.933\, u_l^{0.3} H_{st}^{\ -0.4} \left(\frac{U_g}{\varphi}\right)^{0.93}$ $for\ \frac{u_g}{\varphi} \geq 6\ m/s$ $\frac{H_d}{H_{st}} = 2.16\, u_l^{0.3} H_{st}^{\ -0.4} \left(\frac{u_g}{\varphi}\right)^{0.43}$ $for\ \frac{u_g}{\varphi} < 6\ m/s$	(20)
Azhar-Ul Haq [38]	$\frac{H_d}{H_{st}} = 1.704\, u_l^{0.13} u_g^{\ 0.544}\, H_{st}^{\ -0.1055} \rho_p^{\ -0.2426} d_p^{\ -0.38}$	(21)

Proposed model

In this work, we proposed a model based on the basic theoretical equation of the fluidized bed expansion (Eq. 9) derived from the mass balance of the fixed and the fluidized bed. The model has an unquestionable theoretical consistency, and its application for predicting the fluidized bed expansion requires the estimation of the liquid and gas holdups ($\varepsilon_{l,st}$, ε_g). In the end, the prediction of the bed expansion depends only on the choice of the most appropriate correlations for the liquid and gas holdups. From the set of correlations for liquid and gas holdup in the literature, we had chosen those that gave the best predictions. These correlations are presented in Table 2.

The adopted procedure estimates the fluidized bed expansion (H_d/H_{st}) using Eq. 9, which requires the calculation of liquid (ε_{lst}) and gas (ε_g) holdups.

In this work which objective was to propose a prediction model of the fluidized bed expansion for the turbulent bed contactor, and to achieve this, we employed a variety of correlations derived from existing literature, comprising six equations for gas holdup (Eqs. 42–47) and 20 equations (Eqs. 22–41) for liquid holdup (Table 2). One hundred twenty pairs of correlations were obtained (Table 3) for liquid holdup ($\varepsilon_{l,st}$) and gas holdup (ε_g) that we used to estimate the expansion (H_d/H_{st}).

Table 2. Correlations for liquid and gas holdup ($\varepsilon_{l,st}$ and ε_g) for TBC.

Authors	Correlations for liquid holdup ($\varepsilon_{l,st}$)	Eqs
Vunjak-Novakovic *et al.* [14]	$\varepsilon_{l_{st}} = 7.326\, Re_l^{-0.0591} Fr_l^{0.4354} \left(\frac{H_{st}}{D_C}\right)^{-0.4328} \left(\frac{\rho_p}{\rho_l}\right)^{0.0904} + 0.02\ (Type\ II)$	(22)
Chen & Douglas [19]	$\varepsilon_{l_{st}} = 0.02 + 2.369\ 10^{-3} U_L{}^{0.6} \rho_l{}^{0.6} d_P{}^{-0.5}$	(23)
Balabekov *et al.* [21]	$\varepsilon_{l_{st}} = c\left[\left(0.828\frac{L}{u_g}\right)\frac{\rho_g}{\rho_l}\right]^{k+1} (1-\varepsilon_0)\frac{\rho_P}{\rho_l}$ *For partial fluidization:* $c = 0.05\quad k = 0.8$ *For developed fluidization:* $c = (0.695/\varphi^3)(0.005/d_P)(\rho_P/\rho_l)^{-0.74}(L/10^2)^2,\quad k = (1.58/\varphi^{-0.16})(0.005/d_P)^{-0.1}$	(24)
Ushida *et al.*[23]	$\varepsilon_{l_{st}} = \frac{9.38\ 10^9}{g\rho_l}\ \mu_l{}^{2.3} \varphi^{-0.42} \left(\frac{d_0}{D_C}\right)^{-0.84} \rho_P{}^{0.18} L$	(25)
Handl [24]	$\varepsilon_{l_{st}} = 26.8\ \varepsilon_0\ Re_l{}^{-0.189}\ Fr_l{}^{0.474}$	(26)
Rama *et al.* [26]	$\varepsilon_{l_{st}} = 11\ Ga_l{}^{0.09}\ Fr_l{}^{1.66}\ Re_l{}^{-0.34}\ We_l{}^{-0.34} \left(\frac{H_{st}}{d_p}\right)^{-0.4} \left(\frac{\varphi d}{D}\right)^{-0.58} + 0.086$	(27)
Lyashuk [34]	$\varepsilon_{l_{st}} = 0.001648\ U_g{}^{0.16} L^{0.95} H_{st}{}^{-1.09} \varphi^{-2.02}$	(28)
Shackley [35]	$\varepsilon_{l_{st}} = 3.5\ 10^{-4}\ U_g{}^{0.75} L^{0.7} H_{st}{}^{-0.92} \varphi^{-2.5}$	(29)
Gimenes & Handley [36]	$\varepsilon_{l_{st}} = 9.75\ 10^3\ H_{st}{}^{-0.357} \left(\frac{d_p}{\psi_v}\right)^{-0.411} L^{0.616} exp(0.237 u_g)\ (Oblate\ spheres)$	(30)
Aksel,rod & Yakovenko [37]	$\varepsilon_{l_{st}} = 3.9\ 10^{-2} L\ \frac{\rho_P}{\rho_l}$	(31)
Kito *et al.* [39]	$\varepsilon_{l_{st}} = 12.8\ Ga_l{}^{0.090}\ Fr_l{}^{1.66}\ Re_l{}^{-0.34}\ We_l{}^{-0.34} \left(\frac{H_{st}}{d_p}\right)^{-0.4} \left(\frac{\varphi d}{D}\right)^{-0.58}$	32)
Paterson & Clift [40]	$\varepsilon_{l_{st}} = 2.29\ U_g{}^{-0.07} U_L{}^{0.71} H_{st}{}^{-0.52} \varphi^{-0.874}$	(33)
Petrov & Tassaev [41]	$\varepsilon_{l_{st}} = 8.9\ 10^{-4} U_g^{0.13} L^{0.4} H_{st}{}^{-0.7} d_p^{-0.6} \varphi^{-0.5} \rho_p^{0.02}$ *for partial fluidization* $\varepsilon_{l_{st}} = 1.9\ 10^{-4} U_g^{1.3} L^{0.5} d_p^{-0.6} \varphi^{-0.6} \rho_p^{0.02}$ *for full fluidization*	(34)
Soundarajan & Krishnaiah [42]	$\varepsilon_{l_{st}} = 7.7\ Ga_l{}^{0.090}\ Fr_l{}^{1.66}\ Re_l{}^{-0.34}\ We_l{}^{-0.34} \left(\frac{H_{st}}{d_p}\right)^{-0.4} \left(\frac{\varphi d}{D}\right)^{-0.58} U_g{}^{0.57}\ Type\ II$	(35)
Gel'perin *et al.* [43]	$\varepsilon_{l_{st}} = 0.001369\ U_L{}^{0.5} \rho_l{}^{0.6} d_P{}^{-0.5}$	(36)
	$\varepsilon_{l_{st}} = 4.36\ 10^{-3}\ L^{0.5} H_{st}{}^{-0.25} d_P{}^{-0.6}$	(37)
Gel'perin *et al.* [44]	$\varepsilon_{l_{st}} = 5.47\ 10^{-2}\ u_g{}^{0.24} L^{0.14} H_{st}{}^{-0.08} \rho_l{}^{-1} \rho_P{}^{-0.1}$	(38)
Bruce & Krishnaiah [45]	$\varepsilon_{l_{st}} = 1.36\ Fr_l{}^{1.44}\ Re_l{}^{-0.927} \left(\frac{H_{st}}{d_p}\right)^{-0.593} \left(\frac{\varphi d}{D}\right)^{-0.213} (Type\ II)$	(39)
Barile & Meyer [46]	$\varepsilon_{l_{st}} = 1160\ Fr_l{}^{0.78}\ Re_l{}^{-0.51} H_{st}{}^{-0.36} d_p{}^{0.36}$	(40)
Tarat *et al.* [47]	$\varepsilon_{l_{st}} = 8.38\ 10^{-2}\ H_{st}{}^{-1} L^{0.96} u_g{}^{1.04} \rho_g{}^{1.04}$	(41)
	Correlations for gas holdup (ε_g)	
Kito *et al.* [17]	$\varepsilon_g = 0.19 \left(\frac{d_p U_g{}^2 \rho_l}{\sigma}\right)^{0.11} \left(\frac{U_g}{\sqrt{g D_C}}\right)^{0.20}$	(42)
Bensebia *et al.* [25]	$\varepsilon_g = 0.276\ Fr_g{}^{0.325} \left(\frac{L}{G}\right)^{-0.014} \varphi^{-0.137}$	(43)
Kito *et al.* [39]	$\varepsilon_g = 0.417\ U_g{}^{0.44}$	(44)
Gel'perin *et al.* [43]	$\varepsilon_g = 0.93 \left(\frac{d_p U_g{}^* \rho_g}{\mu_g}\right)^{0.4} \left(\frac{d_p{}^3(\rho_p - \rho_g)\rho_g}{\mu_g{}^2}\right)^{-0.2} \left(U_g{}^* = \frac{U_g}{1 - \varepsilon_{l_{st}}(H_{st}/H_d)}\right)$	(45)
Soundarajan & Krishnaiah [48]	$\varepsilon_g = 0.322\ Fr_g{}^{*0.22}\quad \left(Fr_g^* = (U_g/\varphi)/\sqrt{g d_p}\right)$	(46)
Vunjak-Novakovic *et al.*[49]	$\varepsilon_g = \frac{U_g}{U_{g_{mf}}} \varepsilon_0 - 4.43\ 10^{-3} \left(\frac{H_{st}}{D_C}\right)^{0.433} d_P^{-0.494} L^{0.812} \left(\frac{\rho_p}{\rho_l}\right)^{0.090} - 0.02\ (partial\ fluidization\ type\ II)$ $\varepsilon_g = 0.628 U_g{}^{0.237}\ (Fully\ fluidization\ types\ II)$	(47)

Table 3. Pairs ($\varepsilon_{l,st}$, ε_g) used for predicting bed expansion according to Eq. 9.

	Authors	ε_g					
		Kito *et al.*[17]	Bensebia *et al.* [25]	Kito *et al.* [39]	Gel'Perin *et al.* [43]	Soundarajan & Krishnaiah [48]	Vunjak-Novakovic *et al.* [49]
ε_{lst}	Vunjak-Novakovic *et al.*[14]	Eqs. (22, 42)	Eqs. (22, 43)	Eqs. (22, 44)	Eqs. (22, 45)	Eq. (22, 46)	Eq. (22, 47)
	Chen and Douglas [19]	Eqs. (23, 42)	Eqs. (23, 43)	Eqs. (23, 44)	Eqs. (23, 45)	Eq. (23, 46)	Eq. (23, 47)
	Balabekov *et al.* [21]	Eqs. (24, 42)	Eqs. (24, 43)	Eqs. (24, 44)	Eqs. (24, 45)	Eq. (24, 46)	Eq. (24, 47)
	Ushida *et al.* [23]	Eqs. (25, 42)	Eqs. (25, 43)	Eqs. (25, 44)	Eqs. (25, 45)	Eq. (25, 46)	Eq. (25, 47)
	Handl [24]	Eqs. (26, 42)	Eqs. (26, 43)	Eqs. (26, 44)	Eqs. (26, 45)	Eq. (26, 46)	Eq. (26, 47)
	Rama *et al.* [26]	Eqs. (27, 42)	Eqs. (27, 43)	Eqs. (27, 44)	Eqs. (27, 45)	Eq. (27, 46)	Eq. (27, 47)
	Lyashuk [34]	Eqs. (28, 42)	Eqs. (28, 43)	Eqs. (28, 44)	Eqs. (28, 45)	Eq. (28, 46)	Eq. (28, 47)
	Shackley [35]	Eqs. (29, 42)	Eqs. (29, 43)	Eqs. (29, 44)	Eqs. (29, 45)	Eq. (29, 46)	Eq. (29, 47)
	Gimenes & Handley [36]	Eqs. (30, 42)	Eqs. (30, 43)	Eqs. (30, 44)	Eqs. (30, 45)	Eq. (30, 46)	Eq. (30, 47)
	Aksel,rod & Yakovenko [37]	Eqs. (31, 42)	Eqs. (31, 43)	Eqs. (31, 44)	Eqs. (31, 45)	Eq. (31, 46)	Eq. (31, 47)
	Kito *et al.* [39]	Eqs. (32, 42)	Eqs. (32, 43)	Eqs. (32, 44)	Eqs. (32, 45)	Eq. (32, 46)	Eq. (32, 47)
	Paterson and Clift [40]	Eqs. (33, 42)	Eqs. (33, 43)	Eqs. (33, 44)	Eqs. (33, 45)	Eq. (33, 46)	Eq. (33, 47)
	Petrov & Tassaev [41]	Eqs. (34, 42)	Eqs. (34, 43)	Eqs. (34, 44)	Eqs. (34, 45)	Eq. (34, 46)	Eq. (34, 47)
	Soundarajan & Krishnaiah [42]	Eqs. (35, 42)	Eqs. (35, 43)	Eqs. (35, 44)	Eqs. (35, 45)	Eq. (35, 46)	Eq. (35, 47)
	Gel'perin *et al.* [43]	Eqs. (36, 42)	Eqs. (36, 43)	Eqs. (36, 44)	Eqs. (36, 45)	Eq. (36, 46)	Eq. (36, 47)
	Gel'perin *et al.* [43]	Eqs. (37, 42)	Eqs. (37, 43)	Eqs. (37, 44)	Eqs. (37, 45)	Eq. (37, 46)	Eq. (37, 47)
	Gel'perin *et al.* [44]	Eqs. (38, 42)	Eqs. (38, 43)	Eqs. (38, 44)	Eqs. (38, 45)	Eq. (38, 46)	Eq. (38, 47)
	Bruce and Krishnaiah [45]	Eqs. (39, 42)	Eqs. (39, 43)	Eqs. (39, 44)	Eqs. (39, 45)	Eq. (39, 46)	Eq. (39, 47)
	Barile and Meyer [46]	Eqs. (40, 42)	Eqs. (40, 43)	Eqs. (40, 44)	Eqs. 40,45)	Eq. (40, 46)	Eq. (40, 47)
	Tarat *et al.* [47]	Eqs. (41, 42)	Eqs. (41, 43)	Eqs. (41, 44)	Eqs. (41, 45)	Eq. (41, 46)	Eq. (41, 47)

Model evaluation

In addition to having a consistent theoretical basis, the quality of a predictive model is closely linked to the results of evaluating the precision, accuracy, and reliability of the correlation deduced from this model. The evaluation of the discrepancies between the experimental data and the predictions, according to the proposed approach, was estimated using the mean absolute error in percentage (MAPE), the root mean square error (RMSE), the coefficient of correlation (ρ_{XY}) and explained variance (VE_{CV}). The statistical indicators used were defined as follows:

$$MAPE\,(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|(H_d/H_{st})_{(\mathrm{exp})_i} - (H_d/H_{st})_{(\mathrm{pred})_i}\right|}{(H_d/H_{st})_{(\mathrm{exp})_i}} \tag{48}$$

$$RMSE\,(\%) = \sqrt{\sum_{i=1}^{n}\frac{1}{n}\left((H_d/H_{st})_{(\mathrm{exp})_i} - (H_d/H_{st})_{(\mathrm{pred})_i}\right)^2} \tag{49}$$

$$\rho_{XY} = \frac{\sum_{i=1}^{n}\left((H_d/H_{st})_{(\mathrm{exp})_i} - \overline{(H_d/H_{st})_{(\mathrm{exp})}}\right)\left((H_d/H_{st})_{(\mathrm{pred})_i} - \overline{(H_d/H_{st})_{(pred)}}\right)}{\sqrt{\sum_{i=1}^{n}\left((H_d/H_{st})_{(\mathrm{exp})_i} - \overline{(H_d/H_{st})_{(\mathrm{exp})}}^{\,2}\right)\left((H_d/H_{st})_{(\mathrm{pred})_i} - \overline{(H_d/H_{st})_{(pred)}}\right)^2}} \tag{50}$$

$$VE_{CV} = \left[1 - \frac{\sum_{i=1}^{n}\left((H_d/H_{st})_{(\mathrm{exp})_i} - (H_d/H_{st})_{(\mathrm{pred})_i}\right)^2}{\sum_{i=1}^{n}\left((H_d/H_{st})_{(\mathrm{exp})_i} - \overline{(H_d/H_{st})_{(\mathrm{exp})}}\right)^2}\right]100\% \tag{51}$$

where $\left(\frac{H_d}{H_{st}}\right)_{(\mathrm{exp})_i}$ and $\left(\frac{H_d}{H_{st}}\right)_{(\mathrm{pred})_i}$ are respectively, the i^th^ experimental data and predicted values of bed expansion, among the n data, and $\overline{\left(\frac{H_d}{H_{st}}\right)_{(\mathrm{exp})}}$ and $\overline{\left(\frac{H_d}{H_{st}}\right)_{(\mathrm{pred})}}$ are, respectively, the mean of the experimental data and predicted values.

Two different ways have been used for bed expansion prediction: i) with the different correlations presented in Table 1, ii) using the model based on Eq.9

and the correlations of liquid and gas holdups presented in Table 2.

Evaluation of the correlations of the different authors

All the bed expansion correlations presented in Table 1 were tested with the experimental values obtained under the experimental conditions of the present work. In Fig. 4, where an example of a given experimental system is presented, it is easy to notice that Eqs. 10, 13, 15, 18, 20, and 21 overestimate the bed expansion compared to the experimental data, while Eqs. 14, 17, and 19 underestimate the expansion to different degrees. Remarkably, the best estimate is given by Eq. 11 of Tichy and Douglas [20], which is one of the simplest and among the first.

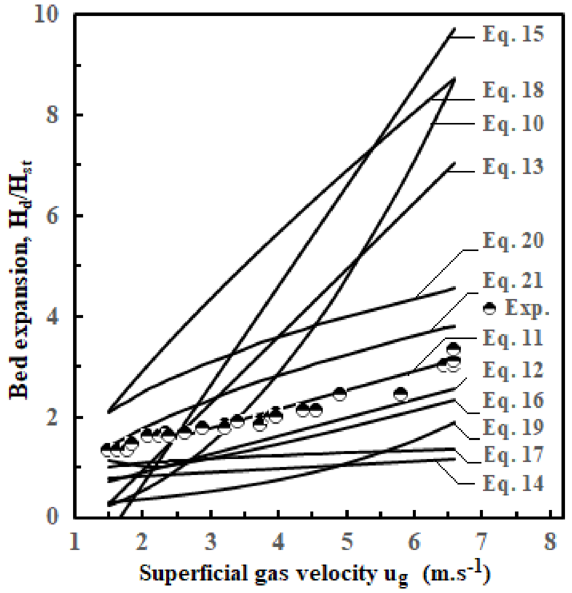

Figure 4. Comparison of experimental bed expansion (H_d/H_{st}) data and predictions by different bed expansion correlations (Eqs. 10–21) for system II.3 (ρ_{Pl}=868 kg m^{-3}, d_{Pl}=0.010 m, H_{st}=0.090 m, φ=0.56, L=15.84 kg m^{-2} s^{-1}).

Fig. 4 compares experimental results obtained from a specific system (System II.3 with L = 15.84 kg m^{-2} s^{-1}) with those of the 13 experimental systems investigated in the present study. To conduct a comprehensive analysis of the comparison results, encompassing all correlations (Eqs. 10–21) and the entirety of the experimental data (i.e., the 13 systems representing the various experimental conditions), the percent mean absolute error (MAPE), root mean square error (RMSE), correlation coefficient (ρ_{XY}), and variance explained (VE_{CV}) were determined.

The results for the experimental data set (1604 data) confirm that Eq. 11 of Tichy and Douglas [20] and Eq. 16 of Khanna [33] gave the best predictions for the expansion of the fluidized bed in TBC.

Table B1 in Appendix B presents the prediction results for all the correlations studied.

Evaluation of the predictions according to Eq. 9 and correlations for $\varepsilon_{l,st}$ and ε_g

The bed expansion prediction results (H_d/H_{st}) were obtained for all the systems using the evaluation criteria: MAPE, RMSE, ρ_{XY}, and VE_{CV}. For presentation, Table 4 shows only the results of systems with a MAPE error of less than 25%. Fig. 5a shows the experimental data of bed expansion for all experimental points (1604 points) with the proposed correlations (Eqs. 26 and 43).

The results in Table 4 show that among the 120 pairs studied, 15 pairs (correlations for $\varepsilon_{l,st}$, ε_g) gave predictions with MAPE errors lower than 25%.

Among the correlations for estimating gas holdup (ε_g), Eqs 42, 43, and 46 gave the best results for bed expansion (H_d/H_{st}). It should be noted that these Eqs

Table 3. Statistical results of comparison of bed expansion (H_d/H_{st}) data and predictions based on Eq. 9 and correlations of $\varepsilon_{l,st}$ (Eqs. 23, 26, 34, 36, and 37) and ε_g (Eqs. 42, 43, and 46).

Eqs. for ε_g		Statistical functions	Eqs. for $\varepsilon_{l,st}$				
N° Eq.	Authors		Eq. 23 Chen & Douglas [19]	Eq. 26 Handl [24]	Eq. 34 Petrov & Tassaev [41]	Eq. 36 Gel'perin *et al.* [43]	Eq. 25 Ushida *et al.* [23]
Eq. 42	Kito *et al.* [17]	MAPE (%)	20.26	15.33	24.75	22.68	33.04
		RMSE	0.70	0.55	0.72	0.75	0.73
		$\rho_{(x,y)}$	0.97	0.83	0.97	0.98	0.95
		VEcv (%)	49.95	64.86	55.88	42.31	40.69
Eq. 43	Bensebia *et al.* [25]	MAPE (%)	16.86	18.57	20.00	17.31	16.07
		RMSE	0.52	0.45	0.56	0.56	0.53
		$\rho_{(x,y)}$	0.86	0.65	0.83	0.86	0.84
		VEcv (%)	55.76	67.42	49.03	49.09	54.81
Eq. 46	Soundarajan & Krishnaiah [48]	MAPE (%)	15.66	16.46	17.05	16.47	15.79
		RMSE	0.52	0.41	0.53	0.57	0.55
		$\rho_{(x,y)}$	0.71	0.40	0.75	0.72	0.67
		VEcv (%)	56.02	73.24	54.24	47.49	51.31

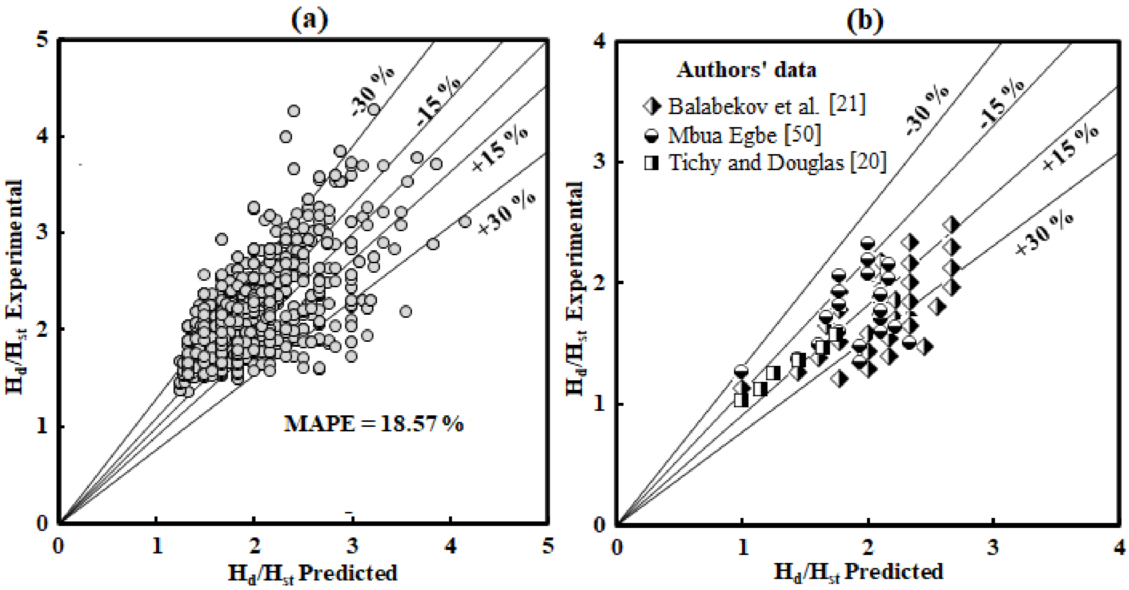

Figure 5. a) Comparison of experimental data of bed expansion (H_d/H_{st}) with predictions calculated by Eq. 9 with Eqs. 26 and 43 for all series (ρ_{PI}=868 k m^{-3}, d_{PI}=0.010 m, ρ_{PII}=736 kg m^{-3}, d_{PII}=0.015 m, Hst=0.06, 0.09, 0.12 m, φ=0.32, 0.56, 0.82). b) Comparison of experimental bed expansion (H_d/H_{st}) data with the predictions of Balabekov et al. [21], Tichy and Douglas [20], and Mbua Egbe [50].

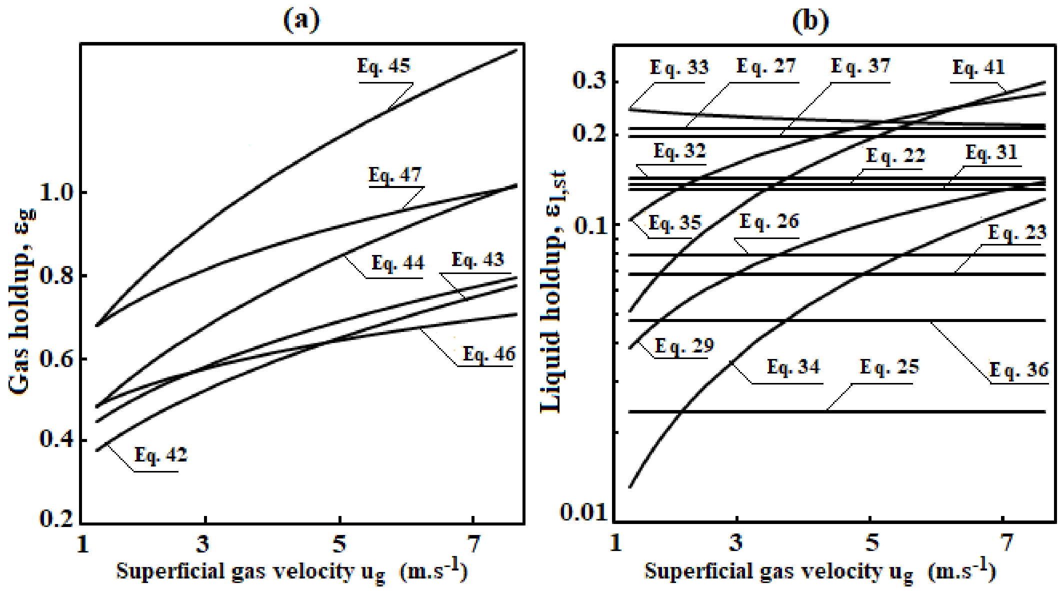

Figure 6. a) Gas holdup (ε_g) predictions with different correlations (Eqs. 42–47) for (ρ_{PII}=736 kg m^{-3}, d_{PII}=0.015 m, H_{st}=0.12 m, φ=0.56, L=4.57 kg m^{-2} s^{-1}). b) Liquid holdup predictions ($\varepsilon_{l,st}$) with different correlations for (ρ_{PII}=736 kg m^{-3}, d_{PII}=0.015 m, H_{st}=0.12 m, φ=0.56, L=4.57 kg m^{-2} s^{-1}).

equations gave substantially similar predictions of gas holdup (ε_g) with lower values than those given by the other equations (44, 45, and 47). This feature is well shown in Fig. 6a, which presents an example of the results of gas holdup predictions (ε_g) for a given experimental case.

Eqs. 42, 43, and 46, which gave the best predictions for bed expansion, gave significantly lower values of gas holdup (ε_g) than those given by Eqs 44, 45, and 47. Regarding the liquid holdup ($\varepsilon_{l,st}$), it was noticed that the correlations that give the lowest predictions for the liquid holdup (Eqs. 23, 25, 26, 34, and 36) gave the best estimates of the fluidized bed expansion.

Fig. 6b, which illustrates the evolution of the liquid holdup with the superficial velocity, using the different correlations of Table 2, highlights this peculiar where it is illustrated that Eqs. 23, 25, 26, 34, and 36 gave the lowest predictions for the liquid holdup.

The complete results of the comparison of experimental data obtained from the 13 series of bed expansion with predictions made using Eq. 9 and correlations for liquid holdup (Eqs. 22–41) and gas holdup (Eqs. 43–47) have been presented in Table B.2 within Appendix B.

Comparison of predictions with experimental values from other authors

The bed expansion prediction procedure developed in this work and based on Eq. 9 was tested using experimental data from different authors. The use of the correlations proposed in this work (Eqs. (26, 43), Eqs. (35, 43), Eqs. (36, 43)) to correlate the data of Tichy and Douglas [20], Balabekov *et al.* [21], and Mbua Egbe [50], gave satisfactory results as shown in Fig 5b. In Fig 5b, the comparison of the experimental and predicted values of Tichy and Douglas [20], Balabekov *et al.* [21], and Mbua Egbe [50], using the approach proposed in this work is presented. The experimental conditions used by the authors of the considered works are presented in Table C1, Appendix C.

CONCLUSION

The analysis of the experimental data showed that the bed expansion (H_d/H_{st}) increased with the gas velocity and the liquid flux. It was also observed that the bed expansion is favored by the decrease of the free surface of the support grid and that the static bed height did not affect the bed expansion.

The second part of this work, analyzing the results of expansion prediction using correlations from different authors, allowed the selection of the most suitable expressions based on a systematic evaluation using appropriate statistical indicators. Among the correlations for the prediction of H_d/H_{st}, the equations of Tichy and Douglas [20] and Khanna [33] gave the best predictions. It should be noted that these correlations involve the gas and liquid fluxes and the particle diameter without including the static bed height.

Analysis of the predictions using the model based on the basic theoretical fluidized bed expansion Eq. 9 yielded the best predictions using Eqs. 42, 43, and 46 for gas holdup estimation and Eqs. 23, 25, 26, 34, and 36 for liquid holdup estimation. Specifically, combinations of Eqs. 46 and 23 and Eqs. 42 and 26 yielded the best-fluidized bed expansion prediction.

NOMENCLATURE

D_C	Column inside diameter, m
d_p	Packing diameter, m
g	Acceleration due to the gravity, m s^{-2}
G	Mass flow rate of gas per unit area, kg m^{-2} s^{-1}
H_d	Expanded bed height, m
H_{st}	Static bed height, m
L	Liquid mass flow rate per unit area, kg m^{-2} s^{-1}
$-\Delta P_c$	Total pressure drop across the entire column, Pa
u_g	Superficial gas velocity, m s^{-1}
u_{gmf}	Minimum fluidization velocity, m s^{-1}
u_l	Liquid velocity, m s^{-1}
V_d	Volume of the expanded bed, m^3
V_g	Volume of the gas in the bed, m^3
V_l	Volume of the liquid in the bed, m^3
V_p	Volume of the packing in the bed, m^3
v_p	Volume of the individual particle of packing, m^3
ε_0	Voidage of the static bed without gas-liquid flow, m^3 m^{-3}
ε_g	Gas holdup ($V_g/\Omega H_d$), m^3 m^{-3}
ε_l	Liquid holdup based on expanded bed height (V_l/V_d), m^3 m^{-3}
$\varepsilon_{l,st}$	Liquid holdup based on static bed height (V_l/V_d), m^3 m^{-3}
ε_p	Packing holdup based on expanded bed height(V_p/V_d),m^{3}m^{-3}
$\varepsilon_{s,st}$	Packing holdup based on static bed height (V_p/V_d), m^3 m^{-3}
φ	Free-open area of the supporting grid
Ω	Cross-sectional area of the column ($\pi D_C^2/4$), m²
ρ_g	Gas density, kg m^{-3}
ρ_l	Liquid density, kg m^{-3}
ρ_p	Packing density, kg m^{-3}
ψ_v	Sphericity

REFERENCES

[1] Z. Arsenijević, T. K. Radoičić, M. Đuriš, Z. Grbavcic, Chem. Ind. Chem. Eng. Q. 21 (4) (2015) 519–526. https://core.ac.uk/download/pdf/299291518.pdf.

[2] S. J. Kulkarni, A. K. Goswami, Int. Res. J. Eng. Tech, 02 (05) (2015) 279–282. https://www.irjet.net/archives/V2/i5/IRJET-V2I551.pdf.

[3] M. L. Gimenes, D. Handley, M. G. C. Silva, Braz. J. Chem. Eng. 24 (1) (2007) 37–45. https://doi.org/10.1590/S0104-66322007000100004.

[4] S. Deagan, Rev. Chim., 70 (11) (2019) 4040–4046. https://doi.org/10.37358/RC.70.19.11.7698.

[5] F.-M. Ilea, A-M. Cormos, S. Dragan, C.-C. Cormos, Chem. Eng. J. 449 (1) (2022) 137674. https://doi.org/10.1016/j.cej.2022.137674.

[6] K. Muroyama, L.-S. Fan, AIChE 31 (1) (1985) 1–34. https://doi.org/10.1002/aic.690310102.

[7] S. Durga Jeevitha, A. Annam Renita, K. Soundarajan, K. Krishnaiah, J. Abbas Mohaideen, Int. J. Appl. Bioeng. 2 (1) (2008) 77–79. https://doi.org/10.18000/ijabeg.10028.

[8] H. A. Khalifeh, M. Alkhedher, S. Fernandes, 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO) (2019) 1–4. https://dspace.adu.ac.ae/handle/1/2777.

[9] S. S. J. Gillani, A. Ullah, M. Zaman, I. R. Chugtai, M. H Inayat, Particuology, 35 (2017) 51–67. https://doi.org/10.1016/j.partic.2016.10.008.

[10] M. Imran, A. Ullah, S. W Ahmad, H. G. Qutab, M. Hameed, Arab. J. Sci. Eng., 45 (2020) 7477–7485. https://doi.org/10.1007/s13369-020-04605-4.

[11] A. Ullah, A. Amanat, M. Imran, S. S. J. Gillani, M. Kilic, A. Khan, Chem. Eng. Process., 156 (2020) 108101. https://doi.org/10.1016/j.cep.2020.108101.

[12] A. Ullah, K. Hong, S. Chilton, W. Nimmo, Powder Technol., 281 (2015) 129–137. https://doi.org/10.1016/j.powtec.2015.03.016.

[13] B. K. O'Neill, D. J. Nicklin, N. J. Morgan, L. S. Leung, Can. J. Chem. Eng. 50 (1972) 595–601. https://doi.org/10.1002/cjce.5450500507.

[14] G. V. Vunjak-Novakovic, D. V. Vukovic, H. Littman, Ind. Eng. Chem. Res. 26 (5) (1987b) 958–966. https://doi.org/10.1021/ie00065a019.

[15] I. P. Levsh, N. I. Krainev, M. I. Niyazov, Int. Chem. Eng. 8 (2) (1968a) 311–312. https://archive.org/details/sim_international-chemical-engineering_1968_8_index-contents/page/n5/mode/2up.

[16] M. Kito, M. Shimada, T. Sakai, S. Sugiyama, C. Y. Wen, in Fluidization Technology, D. L. Kearns (ed.), Hemisphere Publishing Co Washington, (1976b), p. 411–429. ISBN: 089116006X, 9780891160069.

[17] M. Kito, T. Monma, Y. Kayama, T. Sakai, S. Sugiyama, Kagaku Kogaku Ronbunshu 2 (5) (1976a) 476–478. https://doi.org/10.1252/kakoronbunshu.2.476.

[18] M. Kito, K. Tabei, K. Murata, Ind. Eng. Chem. Proc. Design Develop. 17 (4) (1978) 568–571. https://doi.org/10.1021/i260068a030.

[19] B. H. Chen, W. J. M. Douglas, Can. J. Chem. Eng. 46 (1968) 245–249. https://doi.org/10.1002/cjce.5450460406.

[20] J. Tichy, A. Wong, W. J. M Douglas, Can. J. Chem. Eng. 50 (1972) 215–220. https://doi.org/10.1002/cjce.5450500213.

[21] O.S. Balabekov, P.G. Ramankov, E.Ya. Tarat, M.F. Mikhalev, J. Appl. Chem. U.S.S.R. (Engl. Transl.) 42 (1969) 1454–1458. https://searchworks.stanford.edu/view/365872.

[22] O.S. Balabekov, E.Ya. Tarat, P.G. Romankov, M.F. Mikhalev, J. Appl. Chem. USSR 42 (1969a) 1068–1074. Translated from Zhurnal Prikladnoi Khimii 44 (5) (1969) 1061–1068.

[23] S. Ushida, C.S. Wong, C. Y. Wen, Can. J. Chem. Eng. 55 (4) (1977) 392–396. https://doi.org/10.1002/cjce.5450550405.

[24] R. Handl, Ph.D. Thesis, Technischen Universitat Clausthal, R.R.G. (1976).

[25] B. Bensebia, F-Z. Chaouche, S. Kouadri Moustefaï, Kem. Ind. 71 (9–10) (2022) 557–567. https://doi.org/10.15255/KUI.2021.094.

[26] O. P Rama, D.P. Rao, V.S. Rao, Can. J. Chem. Eng. 61 (1983) 863–868. https://doi.org/10.1002/cjce.5450610614.

[27] K. Soundarajan, K. Krishnaiah, Can. J. Chem. Eng. 72 (4) (1994) 569–575. https://doi.org/10.1002/cjce.5450720403.

[28] I. G. Blyakher, L.Ya. Zhivaikin, N.A. Yurovskaya, Chem. Eng. 7 (3) (1967) 485–490. https://doi.org/10.1007/bf01150061.

[29] J. Tichy, W.J.M Douglas, Can. J. Chem. Eng., 50 (1972) 702–706. https://doi.org/10.1002/cjce.5450500604.

[30] B.K. O'Neill, D.J. Nicklin, L.S. Leung, Fluidization and its Applications, Ed. by H. Angelo, J.P. Couderc, H. Gilbert, C. Laguerie, (Ed.), Cepadues-Editions-Toulouse. (1973), 365–371.

[31] G.B. Wallis, One Dimensional Two-Phase Flow. McGraw-Hill Book Company, New York. 1969, 408. https://doi.org/10.1017/S0022112070211362.

[32] B.Z. Uysal, Ph.D. Thesis, McGill, Montreal, 1978. https://escholarship.mcgill.ca/downloads/2227ms35b.pdf.

[33] R.T. Khanna, Ph.D. Dissertation, McGill University. PhD:198, Montreal 1971. https://escholarship.mcgill.ca/downloads/41687j305.pdf.

[34] A. Lyashuk, Research, J. Chem. Pet. Eng. 37 (3–4) (2001) 125–133. https://doi.org/10.1023/A:1017607026104.

[35] I. Shackley, Ph.D. Thesis, Department of Chemical and Process Engineering, University of Sheffield 2000. http://prr.hec.gov.pk/jspui/bitstream/123456789/1974/1/1439S.pdf.

[36] M.L. Gimenes, D.A. Handley, Chem. Eng. Res. Des. 76 (A7): (1998) 855–863. https://doi.org/10.1205/026387698525478.

[37] L.A. Aksel'rod, M.M. Yakovenko, Theor. Found. Chem. Eng. 3 (1969) 124–126. https://link.springer.com/article/10.1023/A:1017607026104.

[38] A. Ul-Haq, Ph.D. Thesis, Pakistan Institute of Engineering and Applied Sciences Nilore Islamabad, Pakistan, 2012. http://prr.hec.gov.pk/jspui/handle/123456789/1974 (accessed 31 May 2014).

[39] M. Kito, M. Sawada, M. Shimada, M. Takada, T. Sakai, S. Sugiyama, Int. Chem. Eng. 16 (2) (1976c) 701. https://doi.org/10.1252/kakoronbunshu.2.12.

[40] A.H.J. Paterson, R. Clift, Canadian Journal of Chemical Engineering. 65 (1987) 10–17. https://doi.org/10.1002/cjce.5450650103.

[41] P. Petrov, Sh. Tassaev, Chem. Ing. Tech. 50 (11) 887–888 (1978). https://doi.org/10.1002/cite.330501118.

[42] K. Soundarajan, K. Krishnaiah, Indian. J. of Chem. Technol. 5 (4) (1998) 179–186. http://nopr.niscpr.res.in/bitstream/123456789/30839/1/IJCT%205%284%29%20179-186.pdf (accessed 22 January 2023).

[43] N.I. Gel'Perin, V.I. Savshenko, V.Z. Grishko, Theor. Chem. Eng. 2 (1) (1968) 65–71. https://istina.msu.ru/workers/39330694/.

[44] N.I. Gelperin, V.A. Liferenko, ,V.Z. Grishko, V.I. Sokolov. Prom. Sanit. Ochistka Gazov (1976) 3 14.

[45] A.E.R. Bruce, P.S.T. Sai, K. Krishnaiah, Chem. Eng. J., 99 (3) (2004) 203–212. https://doi.org/10.1016/j.cej.2003.10.004.

[46] R.G. Barile, D.W. Meyer, Chem. Eng. Prog. Symp. Ser. No 119, Vol. 67, (1971) 134–141. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20014PYW.TXT.

[47] E.Y. Tarat, V.S. Burkat, V.S. Durodova, Journal of Applied Chemistry USSR 47 105–108 (1974). https://searchworks.stanford.edu/view/365872.

[48] K. Soundarajan, K. Krishnaiah, Ind. J. Chem. Technol. 6 (3) (1999) 152–160.

http://nopr.niscpr.res.in/handle/123456789/16916.

[49] G.V. Vunjak-Novakovic, D.V. Vukovic, H. Littman, Ind. Eng. Chem. Res. 26 (5) (1987a) 967–972. https://doi.org/10.1021/ie00065a020.

[50] L. Mbua Egbe, Ph.D. Thesis, Middlesex University UK, 2001. https://eprints.mdx.ac.uk/id/eprint/8005 (accessed 16. November 2021).

BENSABER BENSEBIA[1]
FATMA-ZOHRA CHAOUCHE[1]
OUAHIDA BENSEBIA[2]
SOUMIA KOUADRI MOUSTEFAÏ[3]

[1]Laboratory of Plant Chemistry-Water-Energy, Department of Process Engineering, Faculty of Technology, Hassiba Benbouali University, Chlef, Algeria

[2]Industrial Process Engineering Sciences Laboratory, Houari Boumediene University of Sciences and Technology, Bab Ezzouar, Algeria

[3]Department of Process Engineering, Faculty of Technology, Hassiba Benbouali University, Chlef, Algeria

NAUČNI RAD

EKSPANZIJA SLOJA U TURBULENTNOM KONTAKTORU: EKSPERIMENTI I PREDVIĐANJE

U ovom radu, hidrodinamika turbulentnog kontaktoru (TBC) je proučavana u smislu ekspanzije sloja (H_d/H_{st}) koristeći poseban pristup za predviđanje ovog važng svojstva za projektovanje takve opreme. Studija je zasnovana na 1604 eksperimentalnih podataka o ekspanziji sloja, dobijenih variranjem operativnih varijabli (brzina gasa, raspršivanje tečnosti, karakteristike pakovanja, statička visina sloja i slobodna površina noseće mreže. Predviđanje širenja sloja zahteva procenu zadržavanja gasa i tečnosti. Da bi se to postiglo, korišene su različite korelacije iz literature, i to šest jednačina za zadržavanje gasa i dvadeset jednačina za zadržavanje tečnosti. Od ukupno 120 slučajeva, procenjeno je širenje sloja, a tačnost modela je procenjena izračunavanjem srednje apsolutne greške u procentima (MAPE), srednje kvadratne greške (RMSE), koeficijenta korelacije (rKSI) i objašnjene varijanse (VECV). Ovom studijom su identifikovane odgovarajuće korelacije za gas i tečnost. Štaviše, statistička analiza je korišćena u sledećoj fazi studije da bi se utvrdile najprikladnije korelacije za predviđanje ekspanzije sloja među onima koje su predložili različiti autori.

Ključne reči: trofazna fluidizacija, turbulentni kontaktor sa fludizovanim slojem, ekspanzija sloja, zadržavanje gasa, zadržavanje tečnosti.