

Moisture-Dependent Fluidization Behavior of Zeolite 4A in Fluidized Bed Dryer

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Abstract

The hydrodynamic behaviour of gas–solid fluidized bed drying systems is governed by particle properties, superficial gas velocity, reactor geometry, and moisture content. Materials classified as Geldart Group D frequently exhibit non-ideal fluidization behaviour, such as spouting, slugging, and pronounced pressure-drop fluctuations, which can adversely affect drying efficiency and operational stability. In this study, the fluidization behaviour of nearly spherical LTA 4A zeolite particles with diameters of 1.6–2.5 mm was investigated at different moisture contents, with a specific focus on fluidized bed drying applications. Fluidization curves were determined by measuring the pressure drop across the particle bed as a function of superficial air velocity. Particle motion and flow regimes were visually documented throughout the experiments. The results clearly demonstrate that increasing moisture content significantly influences both the minimum and maximum fluidization velocities and leads to higher and more unstable pressure drops, indicating increasing deviation from ideal fluidization conditions.

To quantify these deviations, the Fluidization Index (FI), defined as the ratio of measured to theoretically predicted pressure drop, was applied. While classical correlations based on the Ergun equation provide satisfactory predictions for more ideal fluidization regimes, considerable discrepancies were observed for the investigated moist, Group D material. To address this limitation, an empirical correlation was developed that expresses the FI as a function of the ratio between the particle Archimedes number and a reference value corresponding to the lower boundary of Geldart Group D. This formulation reflects the increasing distance from the ideal fluidization regime as moisture content and effective interparticle cohesion increase. The proposed correlation showed good agreement with experimental data over the investigated moisture range. The results contribute to a more accurate hydrodynamic description of moist, nearly spherical granular materials and provide practical guidance for the design and optimization of energy-efficient fluidized bed dryers used for zeolite-based drying processes.

Keywords: fluidized bed drying; zeolite LTA 4A; pressure drop; moisture effects; Geldart Group D.

Introduction

Fluidization remains one of the most versatile and widely applied contacting techniques in particulate process engineering, owing to its favourable heat and mass transfer characteristics and its ability to handle granular solids under well-controlled hydrodynamic conditions. Despite their extensive use, fluidized beds often exhibit complex and non-ideal behaviour that is strongly dependent on particle properties and operating conditions.

A widely accepted framework for classifying fluidization behaviour is the Geldart classification (Cocco & Chew, 2023), which groups particles into four categories based primarily on particle size and density contrast between the solid and the fluidizing medium. Group A and Group B particles typically exhibit relatively stable and homogeneous fluidization, while Group C particles are dominated by cohesive effects that hinder fluidization. Group D particles, which are characterised by large particle diameters and high particle densities, represent a particularly challenging regime. These materials tend to fluidize non-ideally and are prone to phenomena such as channelling, slugging, and partial bed mobilization. As a result, only a fraction of the bed may actively participate in the fluidization process, while the

remainder remains in a quasi-static state. This present study focuses explicitly on Group D particles, for which experimental data and predictive models are considerably more limited compared to finer particle classes.

The behaviour of a fluidized bed is commonly described by the fluidization curve (Fig. 1), which relates the pressure drop across the bed to the superficial fluid velocity. At low gas velocities, the bed behaves as a fixed porous medium, and the pressure drop increases linearly (A-B), then quadratically (B-C) with velocity. Upon reaching the minimum fluidization point (D), the drag force exerted by the fluid balances the apparent weight of the particles, and further increases in velocity no longer lead to a significant rise in pressure drop. Instead, bed expansion and structural rearrangement occur, reflecting changes in porosity and particle mobility (D-E). For Group D systems, deviations from the idealised fluidization curve are frequently observed, including reduced pressure drop levels and extended transition regions. The pressure drop remains constant until the maximum gas velocity is reached (F), where the pneumatic transport carries the particles out of the system (F-G).

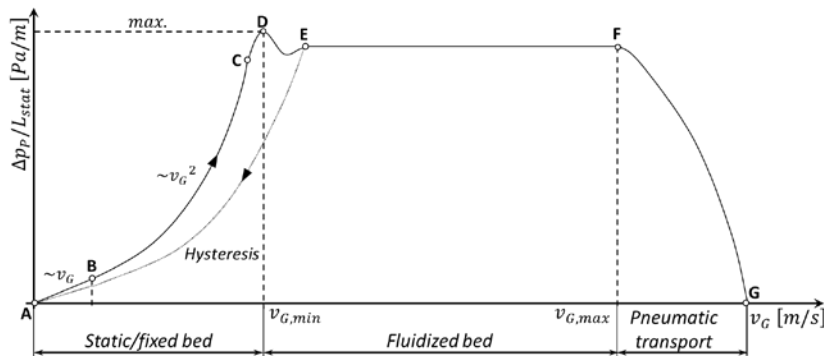


Fig. 1. Pressure drop of the fluidized bed as a function of superficial gas velocity

The pressure drop of static bed phase of Group A and B particles can be calculated using the Ergun-equation (Ergun, 1952), which general form is the following:

$$\frac{\Delta p_p}{L_{stat}} = 150 \frac{(1 - \varepsilon)^2}{\varepsilon^3} \frac{\mu_g v_g}{d_p^2} + 1.75 \left(\frac{1 - \varepsilon}{\varepsilon^3} \right) \left(\frac{\rho_g v_g^2}{d_p} \right). \quad (1)$$

The pressure drop across the fully fluidized bed has to equal the apparent weight of the particles, since they are suspended only by the gas flow. The general form of this equation is (J. M. Coulson et al., 2002):

$$\frac{\Delta p}{L_{stat}} = (1 - \varepsilon)(\rho_p - \rho_g)g. \quad (2)$$

Although the pressure drop is constant across this phase, the height of the bed continuously increases, which can be interpreted as an increase in porosity.

The onset of pneumatic transport occurs when the gas velocity reaches the single-particle terminal velocity, however in some cases the terminal velocity calculated for the whole porous mass provides a better approximation (Jones & Williams, 2008). The equation for the single-particle terminal velocity is:

$$v_{g,max} = \sqrt{\frac{4gd_p}{3C_d} \left(\frac{\rho_p - \rho_g}{\rho_g} \right)}. \quad (3)$$

The change in porosity can be approximated, knowing the minimum fluidization velocity ($v_{g,min}$) and the terminal velocity ($v_{g,max}$), using the Richardson-Zaki equation (Richardson & Zaki, 1954), which can be written in the following form:

$$L^* = L_{stat} \frac{1 - \varepsilon_0}{1 - \left(\frac{v_B}{v_{g,max} - v_{g,min}} \right)^{\frac{1}{n}}}, \quad (4)$$

where $v_B = v_g - v_{g,min}$. The bubble velocity (v_B) is the excess volumetric flow, that is not actively used to suspend the bed, over the empty cross section of the fluidization chamber.

Fluidization curves and porosity-change curves of zeolite particles were determined at different moisture contents based on data measured in laboratorial circumstances.

Material and methods

Material

During the experiments, zeolite particles were examined. Zeolite is mainly used as a desiccant or a catalyst in process engineering. Zeolite can have different forms; it is an alkali or alkaline-earth metal that contains microcapillaries and has a crystal structure. Different types of zeolites are hydrated aluminosilicate minerals. This means that the grid of zeolite has a negative charge, but it can be neutralized by cations (Petrov & Michalev, 2012). The general structural formula of zeolite is the following:

$$M_{x/n}[(AlO_2)_x(SiO_2)_y]wH_2O, \quad (5)$$

where M is the alkali or alkaline-earth cation, n is the valence of the M cation, w is the number of water molecules per cell, x and y are the number of tetraethers per cell (Petrov & Michalev, 2012). In this specific case zeolite LTA 4A was used, its structural formula is the following (László, 2023):

$$Na_{12}[Al_{12}Si_{12}O_{48}]27H_2O. \quad (6)$$

In LTA zeolite types $Al/Si = 1$, and is considered to be in the low Si -content group. When this material is synthesized with Na , and the number of Na , Al and Si atoms in the tetraether are equal, it can be called 4A zeolite.

The material properties of this specific type of zeolite were determined during other researches carried out by my research group. Zeolite particles were sorted, with a vibrating screen, into different groups based on their diameter. Two groups had sufficient amount of material to carry out measurements, the diameter ranges of these groups were: $d_{p1} = 1.6 - 2 \text{ mm}$ and $d_{p2} = 2 - 2.5 \text{ mm}$. The particles were cleaned using a Petkus K293A type air separator. This allowed particles with different aerodynamic properties, such as drag coefficients, to be removed, as well as the particles to be cleaned.

Moisture content of the samples was created by drying the material to achieve the smallest water content possible, then adding distillate water to the samples, and leaving them for 24 hours to achieve equilibrium. During this time, the agitation of the samples was done multiple times, to achieve the desired consistency.

Measuring equipment

The measurements were carried out in the Stokes Laboratory of the Department of Building Services and Process Engineering in Budapest University of Technology and Economics. The laboratory is equipped with a fluidized bed dryer shown on Fig. 2. It is a closed-loop system to ensure that during non-drying applications, the only moisture loss is due to the sample achieving equilibrium with the air that is inside the system. During measurements no heating device was used to increase the temperature of the air. This equipment has a rotary drum dryer section as well but was closed off with valves during the experiments.

The air current is created by a side channel blower (C-101), that can be controlled by a frequency changer located above it. For more precise control of volumetric flow, a butterfly valve (hv-101-03) is installed right before the fluidization chamber (D-101). The volumetric flow can be measured using an orifice located on the lower segment pipe. Next to the orifice is a T-type thermocouple that measures the air temperature that is equivalent to the ambient temperature of the laboratory. Upon pneumatic transport the air and zeolite particles are separated in a cyclone (DC-101). Zeolite particles are transported to the tank (TK-102) by a rotary valve, while air circulates back to the blower. Any remaining dust or zeolite particles are filtered (CF-101) before entering the blower.

The wet material can be loaded in at the top of the fluidization chamber by removing the lid that is held in place by a tri-clamp collar. The chamber has a diameter of 100 mm . For measuring the pressure drop of the fluidized bed, the difference of pressure is measured using two pressure sensors on the bottom and at the top of the chamber. All of these sensors are connected to an Ahlborn ALMEMO 2590-9 type data collector and using IMPERIUM Laboratory Information System Apollo (Interconnect Magyarország Kft., 2023) module, the data sets are recorded to a central server, with a sampling rate of 5 s .

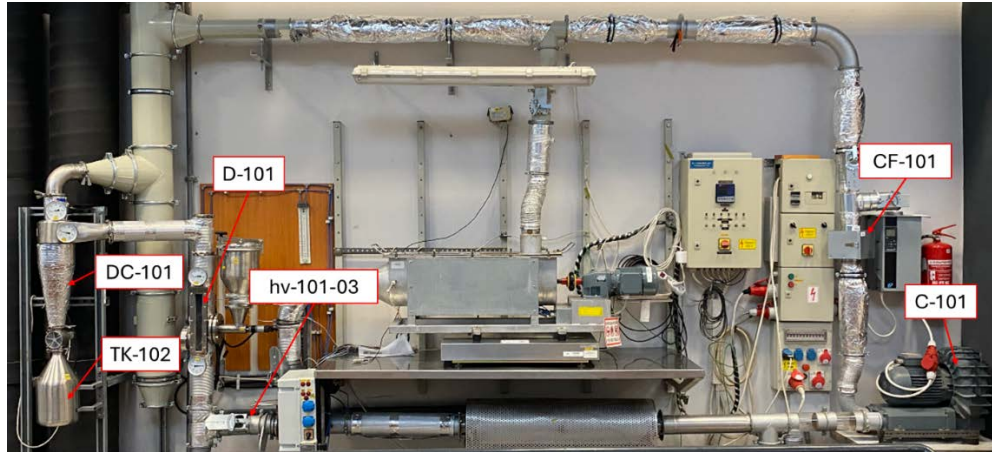


Fig. 2. The fluidized bed dryer (C-101: Blower; D-101: Fluidization chamber; DC-101: Cyclone separator; CF-101: Air filter; TK-102: Tank for the outlet particles; hv-101-03: Butterfly valve for airflow)

Methods

For determining the fluidization curves at different moisture levels, the measured pressure difference has to be divided. It can be divided to the pressure difference caused by the zeolite, and losses. The losses come from the friction of the wall, the inherent pressure drop of the plate that holds the zeolite in place, and any measurement devices that penetrate into the fluidization chamber. These losses were determined together as a function of the superficial gas velocity. Expressing the losses as function of the superficial gas velocity allowed us to calculate the pressure drop caused by the zeolite particles easier:

$$\Delta p = \Delta p_{tot} - \Delta p_{losses} . \quad (7)$$

For determining the porosity change that occurs in the bed, short videos and photos were taken with timestamps. These timestamps allowed for finding the corresponding gas velocity to the point in time that the photos and videos were taken. After determining the bed height, and the corresponding gas velocity, knowing the chamber geometry, the porosity could be calculated:

$$\varepsilon^* = \frac{V_v^*}{V_{tot}^*} = \frac{V_{tot}^* - V_p}{V_{tot}^*} = \frac{(A_{bed}L^*) - (A_{bed}L_{stat}(1 - \varepsilon_0))}{A_{bed}L^*} = \frac{L^* - L_{stat}(1 - \varepsilon_0)}{L^*} . \quad (8)$$

When talking about porosity change in group D materials, it is important to mention that the poor quality of fluidization also influences the homogeneity of the bed. Spouting is the most common fluidization behaviour for group D, where a small cross section starts fluidization much earlier than it is expected, therefore creating a pathway for the fluidizing medium to escape, making one part of the bed fluidized, the other static. Using Eq. (7), only the approximate, theoretically homogenous porosity can be calculated. Fig. 3. shows zeolite particles during fluidization, the porosity is visibly not homogenous across the bed.

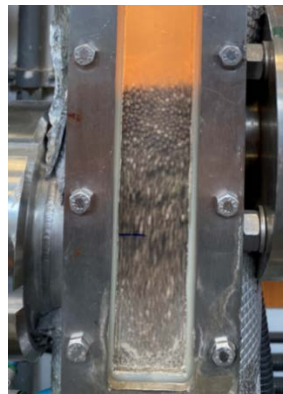


Fig. 3. Wet zeolite particles during fluidization

$$d_p = 2.25 \text{ mm}; L^* \approx 0,2 \text{ m}; v_G \approx 1.4 \frac{\text{m}}{\text{s}}; X = 0.21 \frac{\text{kg}_{H_2O}}{\text{kg}_{dP}}$$

Results and Discussions

In this section the results are presented.

Fluidization results

The determination of fluidization curves was successful for different moisture contents. The moisture content ranged from $X = 0.06 - 0.21 \frac{kg_{H_2O}}{kg_{dP}}$, and the measurements were carried out with two different diameter ranges, as mentioned earlier. The fluidization curve results show a great difference between the theoretically calculated and the measured curves.

The main differences are due to the non-ideal fluidization. As mentioned before, the bed becomes partially fluidized, therefore a smaller pressure drop is measured during the fully fluidized bed section. The pneumatic transport occurs much earlier as well, that is due to the fact that a smaller fluidized cross section creates an aerodynamically less resistant pathway for air to flow through. This smaller cross section results in local superficial gas velocity to increase that can reach the terminal velocity.

For describing this unideal fluidization, the fluidization index (FI) is used. The fluidization index shows the ratio of the real pressure drop and the theoretical pressure drop on the fully fluidized bed section. The main goal was to be able to predict the measured curve, and without being able to predict the fluidization index in advance, it is not possible for these non-ideal cases. According to R. Cocco and J. W. Chew, the boundaries of Geldart groups can be approximated using constant Ar numbers (Cocco & Chew, 2023). After calculating the Ar number for the system, the ratio of the system specific Ar number and the Ar number for the lower boundary of group D, and using a correctional term (k), the fluidization index can be successfully approximated:

$$FI = \frac{\Delta p}{\Delta p_{theoretical}} = k \frac{Ar}{Ar_{D,lower}} \quad (9)$$

This empirical equation works on the assumption, that at the boundary of group B and D is corresponding to the last Ar number where fluidization is considered to be ideal. The correctional term was fitted for every moisture content, but separately for the different diameters. Both cases showed that by knowing this k constant, the pressure drop for different moisture contents could be approximated with adequate accuracy. The values of k are: $k_{dp1} = 0.2372 [1]$; $k_{dp2} = 0.1213 [1]$. As of this paper is published, a correlation that connects k to physical parameters of the material or the fluidized system has not been found.

The corrected force-balance equation is the rearrangement of Eq. (9) as the following:

$$\frac{\Delta p_{approx}}{L_{stat}} = \frac{\Delta p_{theoretical}}{L_{stat}} FI = \frac{\Delta p_{theoretical}}{L_{stat}} k \frac{Ar}{Ar_{D,lower}} \quad (10)$$

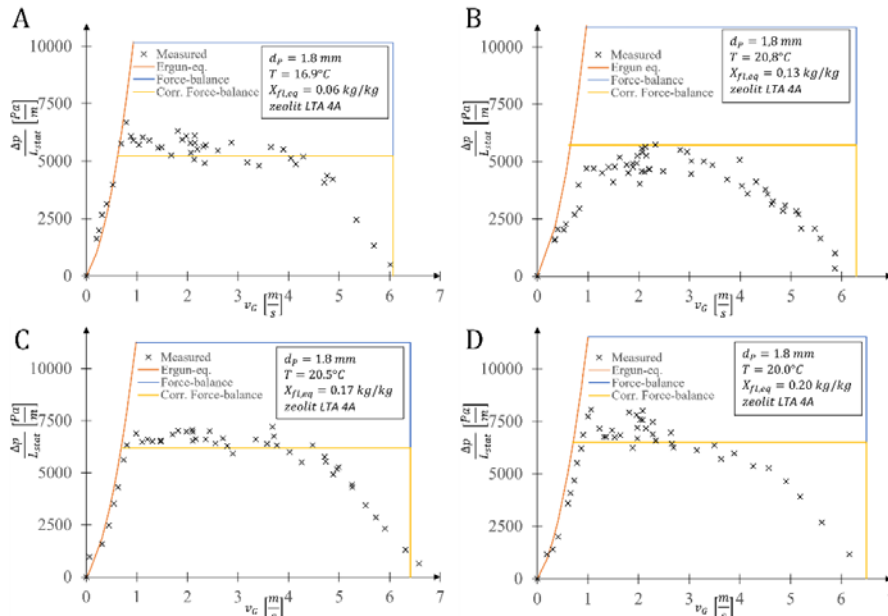


Fig. 5. The fluidization curves of zeolite ($d_{p1} = 1.8 \text{ mm}$) at different moisture contents ($\Delta p/L_{stat}$ plotted against v_g)

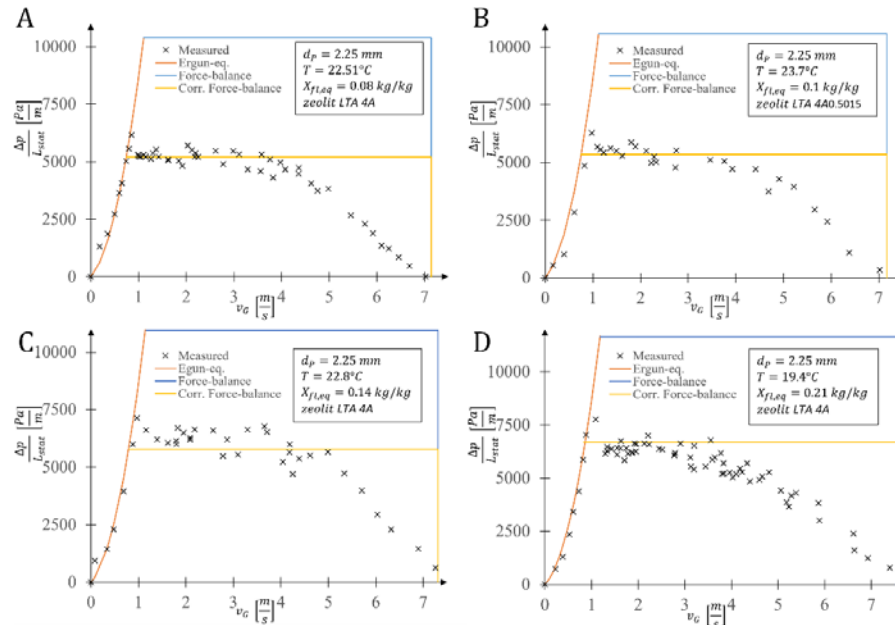


Fig. 6. The fluidization curves of zeolite ($d_{p2} = 2.25$ mm) at different moisture contents ($\Delta p/L_{stat}$ plotted against v_g)

The results of the approximated pressure drop calculation can be seen on Fig. 5. for $d_{p1} = 1.8$ mm and Fig. 6 for $d_{p1} = 2.25$ mm. The calculated fluidization indexes are in Table 1.

Table 1. Approximated FI values for $d_p = 1.8$ mm (left) and $d_p = 2.25$ (right) using Eq. (10).

$X \left[\frac{kg_{H_2O}}{kg_{dP}} \right]$	0.06	0.13	0.17	0.20	0.08	0.1	0.14	0.21
$FI = k \frac{Ar}{Ar_{D,lower}}$	0.5138	0.5268	0.5515	0.5632	0.5015	0.5054	0.5279	0.5755

Porosity-change results

The determination of porosity-change curves was successful for different moisture contents. There is a great agreeance between the measured and the theoretical values. Moisture content effects the minimum and maximum values of the superficial gas velocity, because the moisture increases the density of the examined material, furthermore any moisture on the surface increases interparticular forces, and agglomeration in the bed. As mentioned, the determination of porosity change is based on photographs and short video recordings, and that means that the bed can only be seen from one specific angle, where the plexiglass is located. A series of photos is presented in Fig. 7. with approximate superficial gas velocities.

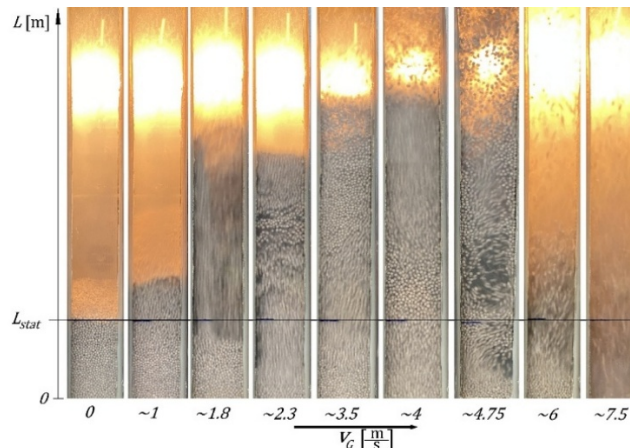


Fig. 7. The change of bed height (L) in relation to the superficial gas velocity ($d_{p1} = 1.8$ mm; $X = 0.09$ kg_{H_2O}/kg_{dP})

The porosity-change curves were created using specific values for porosity plotted against v_B . The diagrams on Fig 8. and Fig. 9. show that the maximum relative porosity is reached at lower bubble velocities with increasing moisture

content. This phenomenon occurs due to the increase in interparticle forces that enables particles to stick together, creating a significantly bigger and non-uniform frontal area, which increases the drag

coefficient.

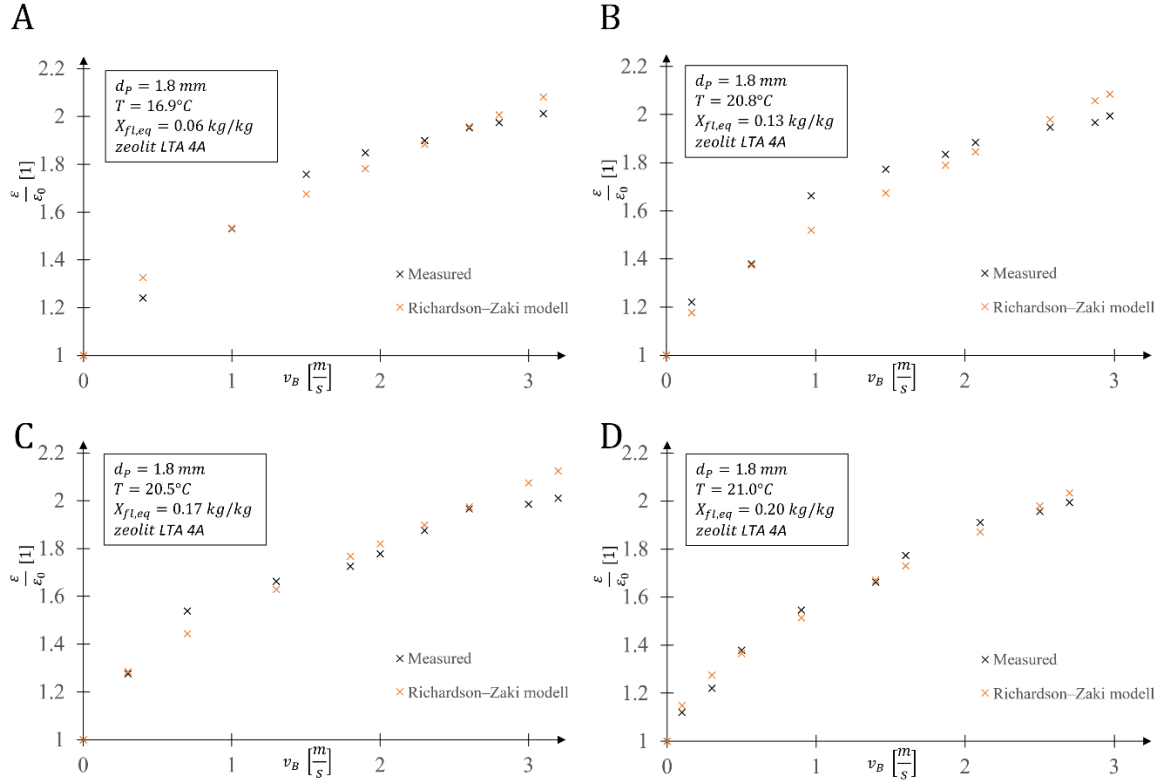


Fig. 8. The porosity-change curves of zeolite ($d_{p1} = 1.8 \text{ mm}$) at increasing moisture contents ($\varepsilon/\varepsilon_0$ plotted against v_B)

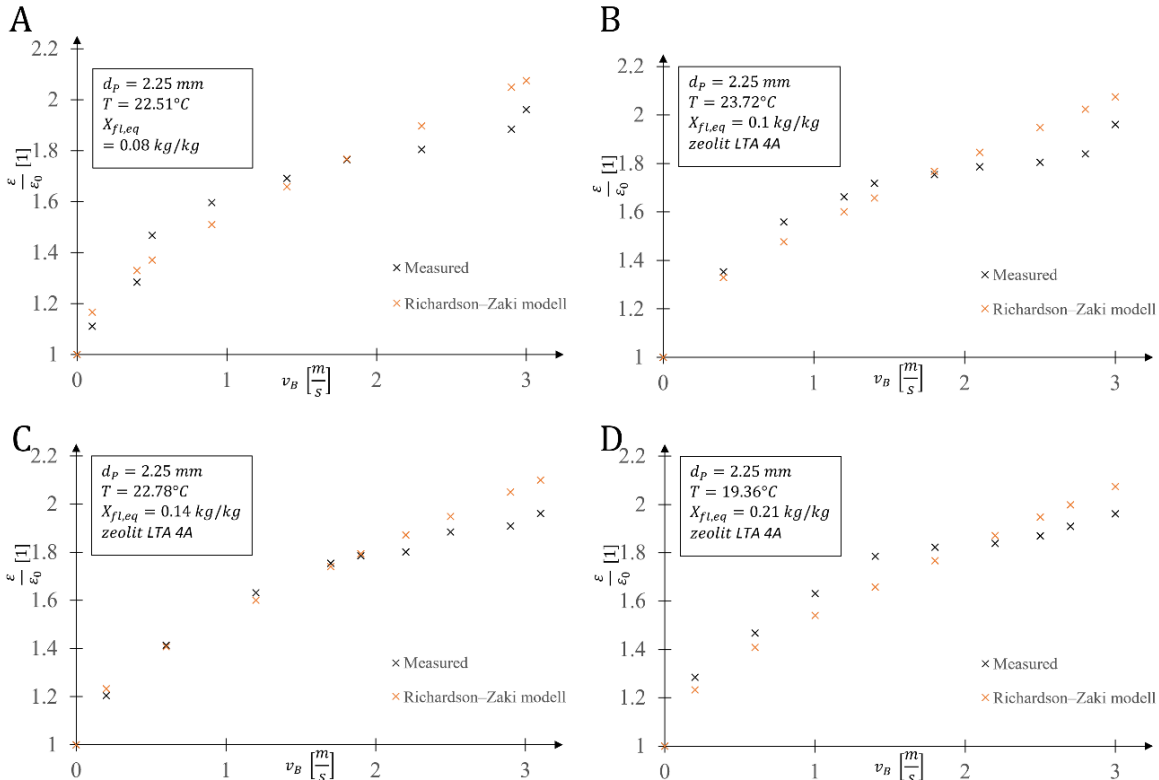


Fig. 9. The porosity-change curves of zeolite ($d_{p2} = 2.25 \text{ mm}$) at increasing moisture contents ($\varepsilon/\varepsilon_0$ plotted against v_B)

Conclusions

The usage of the fluidization index can greatly improve the accuracy of theoretically calculated pressure drop values for group D materials, however the correctional term (k) in the empirical correlation (Eq. (9)) is yet to be described as a function of one or more material property or system parameter. In case of fluidization, the great agreeance between the measured values and the Richardson-Zaki equation allows us to trust the results of the equation even for group D materials. The increase in moisture content produced results that were expected, higher moisture will result in higher minimum and maximum superficial gas velocities, as well as increase the theoretical pressure drop during the fully fluidized section. This results in the porosity-change curves to flatten with increasing moisture content due to the higher interparticular forces.

Acknowledgments: The author gratefully acknowledges the contribution of Csanád Győri, MSc student, who assisted in the experimental measurements. This work was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (BO/00059/23/6) and by the Hungarian Scientific Research Fund (NKFIH FK-142204).

Nomenclature

A	Cross-section	m^2
Ar	Archimedes-number	1
C	Coefficient	1
d	Diameter	m
FI	Fluidization index	1
k	Correctional term	1
L	Height	m
n	Richardson-Zaki hindered settling index	1
p	Pressure drop	Pa
T	Temperature	$^{\circ}C$
v	Velocity	m/s
V	Volume	m^3
X	Wet basis moisture content of particles	kg_{H_2O}/kg_{dP}
ε	Porosity, Void fraction	m^3/m^3_{tot}
μ	Dynamic viscosity	$Pa \cdot s$
ρ	Density	kg/m^3
Subscripts, superscripts		
<i>approx</i>	Approximate value	
<i>B</i>	Bubble	
<i>bed</i>	The fluidized bed	
<i>d</i>	drag	
<i>D, lower</i>	Lower boundary of group D	
<i>P</i>	Particles	
<i>G</i>	Gas	
<i>losses</i>	Losses	
<i>stat</i>	Static bed	
<i>theoretical</i>	Theoretical value	
<i>tot</i>	Total value	
<i>v</i>	Void	
<i>0</i>	Starting value	
<i>*</i>	Change of value	

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