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#### ABSTRACT

The paper presents the results of an investigation into CO<sub>2</sub> adsorption by a fluidized bed of pellets of 13X zeolite. The experiments compare the performance of a confined and that of a conventional fluidized bed using the same apparatus at ambient temperature and pressure. The effect of CO<sub>2</sub> concentration in the inlet air stream, superficial gas velocity and particle size of the fluidized sorbent is analysed with reference to gas streams in which the fraction of carbon anhydride is that typical of a flue gas. and the effectiveness of CO<sub>2</sub> adsorption is assessed in terms of moles of CO<sub>2</sub> adsorbed per unit mass of sorbent, breakthrough time and fraction of bed utilized at the breakpoint.

The results obtained demonstrate that confined fluidization improves the efficiency of the adsorption process thus constituting a valid alternative to the conventional technique.

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ADSORPTION OF CO<sub>2</sub> ON A CONFINED FLUIDIZED BED OF PELLETIZED 13X ZEOLITE

that we intend to submit for publication on the Powder Technology.

The paper is original and has not yet been published or submitted to any other journal. In preparing the manuscript according to the recommendations of the Guide for Authors and in compliance with Ethics in Publishing Policy.

Sincerely yours,

Rossella Girimonte

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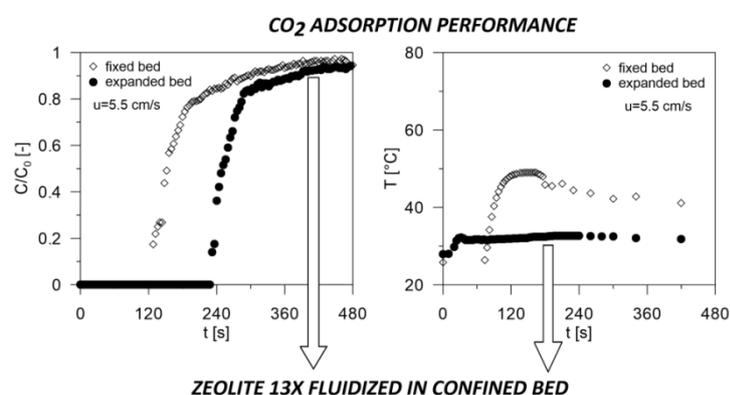
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## Graphical abstract



## Highlights

CO<sub>2</sub> adsorption on a fluidized bed of pellets of 13X zeolite is investigated.

A comparison of performances is made between confined and conventional fluidized bed.

The efficiency of the adsorption process is enhanced by confined fluidization.

Regulating of the confined fluidization velocity can optimize the adsorption process.

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## KEYWORDS

CO<sub>2</sub> capture; adsorption; zeolite 13X; confined-fluidized beds; packed-fluidized beds.

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## 1. Introduction

Today the primary energy supply is represented for more than 80% by combustion of fossil fuels and this significantly contributes to the emissions of CO<sub>2</sub> into the atmosphere with evident changes in the climate [1]. Several strategies for containing CO<sub>2</sub> emissions have been proposed such as reducing energy consumption, increasing the efficiency of energy conversion, switching to the use of renewable energy sources. While waiting for these structural objectives to be globally accepted, the techniques of carbon capture and storage (CCS) offer a valid tool in the short to medium term. The major approaches followed to achieve CCS are essentially three: post-combustion capture, pre-combustion capture and oxyfuel combustion [2-4]. Among these, post-combustion capture offers a solution to increase sustainability of fossil fuel combustion processes in existing facilities. The main challenge in the field of CCS is the development of an innovative, efficient and cost-effective CO<sub>2</sub> capture technique. Several separation technologies such as physical or chemical absorption, adsorption, cryogenic and membrane separations can be employed for the separation of CO<sub>2</sub> contained in the flue gas, but chemical absorption by an aqueous solution of alkanolamines (MEA) is surely the most commercially mature. Anyway high costs are associated to this operation because of corrosion, sorbent degradation and expensive solvent regeneration. Moreover, release of amine and water into air causes production of toxic compounds in the atmosphere [5,6]. For these reasons adsorption on solid sorbents could be a promising alternative technology whose success may depend not only on the development of highly specific materials tailored at the molecular scale [7-11] but also on the improvement of the gas-solid contact efficiency [12-19]. Highly specific sorbents should exhibit high CO<sub>2</sub> adsorption capacity and selectivity, fast adsorption/desorption kinetics, mild conditions for regeneration, good stability during repeated adsorption–desorption cycles as well as tolerance of the presence of moisture and other impurities in the feed and adequate mechanical particle strength [8]. Various materials, such as zeolites, metal organic frameworks (MOFs), activated carbon and amine-modified silica show high capacity of adsorption of CO<sub>2</sub>. In particular, great interest is aroused by ultra-fine materials as their surface can easily be tailored and/or functionalized with different ligands, thus inducing significant changes in their physical and chemical properties [2].

However, the overall capacity of capturing CO<sub>2</sub> of these fine materials (i.e. powders belonging to group C of Geldart's classification [3, 20] strongly depends on the technology adopted for the adsorption process.

Common adsorption operations are generally carried out in packed bed units, a choice dictated by the necessity of avoiding the by-pass effect in gas-solid contact typical of the bubbling regime of fluidized beds. As, however, fine particles would cause high pressure drop and excessive pumping costs, packed beds make often use of high-porosity pelletized solids and work on a semi-continuous basis. Exploiting advantages of fluidization technology such as high mass transfer rates and low pressure drop without suffering too low adsorption efficiencies requires the adsorption process to be run in the regime of particulate fluidization, i.e. in the absence of bubbly flow. It has already been shown that one of the ways of achieving this objective is provided by "sound-assisted fluidization", whose essential feature is that of superimposing an acoustic field to a fluidized bed of fine powders thus impeding the formation of channels as well as that of particle aggregates hardly permeable to the gas phase. As reported in recent works [21-23], by improving the quality of fluidization and the effectiveness of gas-solid contact such a technique makes it possible to enhance CO<sub>2</sub> adsorption on beds of fine particles.

As an alternative, adsorption can be carried out in systems often referred to as "packed-fluidized beds" or "confined fluidized beds" [17-19], i.e. beds of particles fluidized in the voids of a packing of coarser solids, usually spherical. This technique has been raising an increasing interest as its fluid-solid contact mode is particularly suitable for operations in which maximization of the conversion of a gaseous reactant is crucial. Such a goal can be reached thanks to the ability of these fluidized systems to prevent the formation of bubbles, a route through which part of the gas flow rate bypasses the contact with the solid phase, whether it is another reactant or a catalyst. Some pelletized zeolites commercially available as spheres of relative large size with respect to the ordinary powder are sorbents suitable for being used in a confined system like that used in this investigation.

The interstices network provided by the packed solid constitutes the confining environment in which the sorbent, much finer than it, can first achieve the suspended state and then

homogeneously expand without the formation of bubbles. This fluidization technique is likely to provide a very efficient fluid-solid contact, suitable for high conversion of gaseous reactants, nearly complete adsorption of specific components of the fluidizing stream, filtration of dust-laden gases and heat recovery from them [17-19, 24-35].

Consistently with that, this paper aims to illustrate how the adsorption performance of a commercial Zeolite 13X improves when the operation is conducted in a confined fluidized bed. Effectiveness of CO<sub>2</sub> adsorption has been assessed in terms of moles of CO<sub>2</sub> adsorbed per unit mass of adsorbent solid, breakthrough time and fraction of bed utilized at the breakpoint and a comparison is made with the results obtainable in a packed-bed and in a conventional fluidized-bed unit.

## **2. Materials and methods**

### **2.1 Experimental Apparatus**

Tests of CO<sub>2</sub> adsorption were carried out in a laboratory-scale fluidized bed apparatus, here schematized in Fig. 1, made of a Plexiglas column with an internal diameter of 50 mm and 700 mm high, equipped with a porous gas distributor at its bottom. The fine particle bed was fluidized by air, whose flow rates were regulated by a set of two mass flow controllers covering the range 0-6000 NI/h. The CO<sub>2</sub> concentration in the gas feed stream was adjusted by adding CO<sub>2</sub> from a cylinder to the air supplied by a compressor. A system for humidity abatement, made of a column filled with zeolites and activated carbon, was located before the CO<sub>2</sub> mixing point. The total pressure drop across the solid bed was measured by a U-tube water manometer.

The contact modes investigated ranged from the fixed to the bubbling regime in conventional fluidization and to the regime of homogeneous expansion in confined fluidization. During the CO<sub>2</sub> adsorption process the increase of bed temperature was monitored by a thermocouple vertically immersed in it. As concerns this effect, the amount of energy involved in physical adsorption of

CO<sub>2</sub> is about 10 kcal/mol. The CO<sub>2</sub> concentration in the gas stream entering or leaving the adsorption unit was measured by a gas analyzer (Madur GA-21 plus) and acquired on a PC.

## 2.2 Adsorbent

The use of zeolites as physical adsorbents for CO<sub>2</sub> capture have already been reported [11]. The adsorption efficiency of zeolites is heavily affected by their size, charge density, chemical composition and by the nature of cations in their porous structures [5]. Highly crystalline zeolites with large surface area and three-dimensional pore structure are obtained by altering their Si/Al ratio. The exchange with alkali and alkaline-earth cations in the structure of zeolites enhances CO<sub>2</sub> adsorption. On the other hand, the CO<sub>2</sub> adsorption capacity of zeolites greatly declines in the presence of moisture in the gas because of their highly hydrophilic character, so that a high regeneration temperature (often above 300°C) is needed. A commercial zeolite, 13X-APG MOLSIV™ provided by UOP LLC, has been used as adsorbent material. Si/Al is 1,7 and Na/Al is one, as obtained by EDAX analysis. Two samples, 400-500 and 710-800 μm, were prepared by sieving and their particles size distributions were characterized by a laser diffractometer (Mastersizer 2000 by Malvern Instruments), as shown in Fig. 2. Characteristic diameters from these distributions are reported in Tab. 1.

Samples morphology was characterized by SEM analysis using a FEI Inspect F50 instrument.

Particles of 13X zeolite (Fig. 3a), as obtained by granulation of its powder with a binder, have quasi-spherical morphology with size ranging between 400 to 2000 μm. SEM micrographs 3b, 3c and 3d show the powder crystals with their cubic habit and size between 1 and 3 μm. Particle density is 1440 kg/m<sup>3</sup>.

Specific area was determined according to the BET method, using N<sub>2</sub> adsorption at 77 K performed with a Micromeritics ASAP 2020 analyzer. Pore size distribution and volume were evaluated using a DFT equilibrium model. Samples were degassed at 350°C until 30 μm Hg was reached. Both samples, with different particle size, have a BET surface area of 650 m<sup>2</sup>/g, pore volume of 0.24 cm<sup>3</sup>/g and pore size of 4.7 Å. These values are in agreement with those reported in

the literature and not influenced by the sample size [36]. The nature and the amount of the species adsorbed were determined by TG analysis carried out on a Netzsch STA 409 instrument. As shown in Tab. 2, all samples have weight loss centered at about 200 °C, due to water desorption. Analogously, desorption of CO<sub>2</sub> from 13X zeolite samples previously used for adsorption occurs at 70 °C and is signalled by a similar weight loss.

### 2.3 Fluid-dynamic characterization

The two zeolite samples were subjected to characterization of their regime of fluidization according to both the conventional and the confined bed technique. These tests were performed at ambient temperature and pressure using dehumidified air as fluidizing gas. Two values of the bed aspect ratio H/D were adopted, 1.7 and 3.5, to obtain the minimum fluidization velocity of the conventional bed and of the confined fluidized bed. The pressure drop and bed expansion curves were obtained by measuring pressure and bed height in experiments performed both at increasing and decreasing superficial gas velocity that gave the same results [17-19]. The minimum fluidization parameters, as determined from figures 5 and 6, are collected in Tab. 3.

In comparison with the conventional system, the confined bed undergoes suspension at a lower superficial gas velocity but the corresponding value of the interstitial velocity is higher because bed voidage is much lower, nearly half the value measured in the conventional fluidized bed (e.g. 0.19 instead of 0.41 for the sample 400-500 μm). Moreover, when the solid is fluidized according to the conventional technique, beyond the incipient fluidization threshold it immediately enters the bubbling regime. As regards the confined fluidized bed, instead, suspension coincides with the beginning of its homogeneous expansion, a regime that has been modeled by means a modified form of the Richardson-Zaki's equation [17-19]. This confirms the ability of the novel gas-solid contact mode to enhance the fluidization quality. It has been shown, to this regard, that the amplitude of the interval of the regime of homogeneous expansion can be controlled by regulating the ratio between height of the particle bed subjected to fluidization and height of the packed bed in

which it is confined, a circumstance that qualifies confined fluidization as a noticeably attractive processing technique.

#### 2.4 Adsorption tests

The conditions for all adsorption experiments were ambient temperature and pressure. Prior of each test, the sorbent solid has been heated up to 300 °C to remove any trace of moisture and of CO<sub>2</sub> adsorbed. In a typical experiment based on conventional fluidization, the sorbent is loaded onto the column, then it is fluidized and defluidized in order to obtain repeatably the bed height of 8.0 cm. The adsorption process is preceded by a conditioning period of about 10 min, during which air is let flow through the particle bed in order to stabilize the regime for the gas-solid exchange at one of the values of superficial gas velocity indicated in Tab. 4.

Such velocity values were selected to allow a comparison of adsorption data relevant to pair of experiments performed on either fluidized-bed system (conventional or confined) crossed by a gas stream having the same flow rate and CO<sub>2</sub> concentration and with beds of the same mass and particle size. For either sample of zeolite at the lower velocity the conventional bed finds itself in the fixed state, whereas at the higher  $u$  it is crossed by bubbles; the packed-fluidized bed, instead, is always in the regime of fluidization and homogeneous expansion in the voids of the packing of coarse spheres.

In a typical experiment of confined fluidization, the coarse spheres are first poured onto the column to form a packing with a height of 38 cm; subsequently, 100 g of the finer solid are loaded and after a complete fluidization–defluidization cycle their height is recorded. Then, air is fed to the column for about 10 min, to stabilize the regime at one of the the selected values of superficial gas velocity reported in Tab. 4. In any adsorption test a gas mixture of air and carbon anhydride with a fixed volume percentage of CO<sub>2</sub> is fed to the column. CO<sub>2</sub> concentration in the effluent gas is continuously monitored at the exit of the column until the gas composition reaches 95% of the inlet value, i.e. until sorbent saturation is reached. CO<sub>2</sub> concentration data are plotted in function of time (breakthrough curve) since the instant at which the gas mixture begins to flow from the fluidized

bed to the analyzer. For each solid sample used in adsorption experiments both in the conventional and in the confined fluidization apparatus, the effect of fluidization velocity and CO<sub>2</sub> partial pressure on adsorption efficiency was investigated.

The breakthrough curves (figure 7-10) have been worked out to evaluate:

- (i) the breakthrough time  $t_b$  [s], or breakpoint. It is the time it takes for CO<sub>2</sub> to reach 5% of the inlet concentration at the outlet of the adsorption column. In a continuous process it also represents the time at which the the gas feed must be switched to the stand-by column in order to regenerate the saturated sorbent of the first one.
- (ii) the fraction of bed  $W$  utilized at the breakpoint, namely the ratio between the amount of CO<sub>2</sub> adsorbed up to the the breakpoint and that adsorbed at saturation. This parameter is strictly related to the performance of the adsorber: given the contact time, a higher  $W$  means that a lower amount of sorbent is required. On the other hand, given the mass of solid in the column, a higher  $W$  means that sorbent saturation occurs after a longer time.
- (iii) the mass of CO<sub>2</sub> adsorbed per unit mass of adsorbent,  $m_{ads}$  (reported in this paper in gCO<sub>2</sub>/kg13X), calculated by integration of the breakthrough curves;
- (iv) the maximum temperature,  $T_{max}$ , reached during the adsorption test (as measured by the thermocouple immersed in the bed).

Table 5 reports all these parameters at the various operating conditions selected for the adsorption experiments of this work.

The solid-gas fluidization regime adopted for the process influences the contact time  $t_c$  but not the quantity of CO<sub>2</sub> adsorbed until the sorbent is saturated; this depends on the inlet concentration of CO<sub>2</sub> in the gas. In the case of confined fluidization, homogeneous expansion of the solid occurs so that with the increase of the bed voidage also the contact time between gas and sorbent increases. As CO<sub>2</sub> adsorption is an exothermic process, any increase of temperature is unfavorable for the adsorption capacity of the solid bed. That is the reason for monitoring the bed temperature during the adsorption process, so as to become aware of the variation of the adsorption capacity.

### 3. Results

Figures 6a and 7a compare typical breakthrough curves, i.e. the trend of  $C/C_0$  vs time, obtained by experiments of conventional and confined fluidization. Each pair of experiments employed the same sorbent (zeolite 13X, 400-500  $\mu\text{m}$ ) and was run at the same superficial gas velocity ( $u=5.5$  cm/s) and inlet concentration of  $\text{CO}_2$  (5% or 10%, respectively). At the velocity value chosen for the experiments the conventional bed is still in its fixed state, while the confined bed finds itself over its incipient fluidization threshold, so that its state is that of a homogeneously expanded particle system. The related trends of the bed temperature are also reported in Figs 6b and 7b.

The analysis of the two pairs of curves suggests that the confined fluidization of the sorbent greatly enhances the breakthrough time, in a way that in confined bed tests  $t_b$  is almost two times the value measured in the conventional process; for either system, however, higher inlet  $\text{CO}_2$  concentration reduces the characteristic time parameters (breakthrough and saturation time) to a lower value. It is also observed that adoption of the confined fluidization technique causes an increase of bed temperature more moderate than in the conventional fixed bed.

Breakthrough curves reported in Figs 8a and 9a as well as the corresponding bed temperature trends of Figs 8b and 9b are relevant to adsorption tests carried out with the coarser cut of sorbent (zeolite 13X, 710-800  $\mu\text{m}$ ) at  $u=28.5$  cm/s and with an inlet concentration of  $\text{CO}_2$  equal to 5% and 10%, respectively. With this solid material the new value of gas velocity determines two different fluidization regimes: free bubbling in the conventional fluidized system and homogeneous expansion in the confined fluidized bed.

Also when the comparison is made with a freely bubbling fluidized bed, the result is the same: with respect to what observed on employing the conventional fluidization technique, adsorption on the confined fluidized bed of sorbent is characterized by an increased breakthrough time and a limited increase of the bed temperature. The fact that the same findings are obtained with both samples of zeolitic sorbent evidences that the confined-fluidized mode improves the efficiency of gas-solid contact with respect to both the fixed-bed adsorption and the ordinary fluidized-bed technique.

Table 5 reports the experimental results of all the adsorption tests performed in the present investigation. In particular, the analysis of the effects of each experimental variable on the characteristic parameters of the process carried out in a confined fluidized bed is likely to provide useful suggestions for improving the overall adsorption effectiveness.

Altogether, data of Tab. 5 show how in a confined fluidized bed the contact time  $t_c$  nearly increases on average by 50% with respect to that measured in the conventional system, either when gas velocity is such that adsorption is carried out on a fixed bed and when the gas-solid contact regime is that of a fluidized system crossed by bubbles; at the same time the increment of the breakthrough time  $t_b$  is roughly equal to 70%. The fraction of bed  $W$  utilized at the breakpoint in the confined fluidized, i.e. the ratio between the amount of  $\text{CO}_2$  adsorbed up to the breakpoint and that adsorbed at saturation, is always higher by nearly 30% than that measured in the conventional bed. The mass of  $\text{CO}_2$  adsorbed per unit mass of adsorbent,  $m_{\text{ads}}$ , calculated by integration of the breakthrough curves, depends on the inlet  $\text{CO}_2$  concentration and varies with the average size of the sorbent: irrespective of the contact regime, with the zeolite 400-500  $\mu\text{m}$  an average value of  $m_{\text{ads}}=73 \text{ gCO}_2/\text{kg13X}$  is found when the inlet concentration of  $\text{CO}_2$  is 5%, whereas a value of 88  $\text{gCO}_2/\text{kg13X}$  is calculated when  $\text{CO}_2$  concentration is 10%. With the sorbent 710-800  $\mu\text{m}$ , the corresponding values of  $m_{\text{ads}}$  are equal to 84 and 107  $\text{gCO}_2/\text{kg13X}$ , respectively. Thus,  $W$  is found to be more sensitive to the variation of  $\text{CO}_2$  inlet concentration of the gas stream than to the variation of the particle size of the sorbent. In terms of  $m_{\text{ads}}$ , the cut 710-800  $\mu\text{m}$  exhibits the best performance.

In order to identify the effects of the operating conditions on the performance of the confined fluidized bed, Fig.10 compares the breakthrough curves (Fig.10a) and the temperature trends (Fig.10b) relevant to the adsorption tests conducted on the confined fluidized system at the two values of  $\text{CO}_2$  inlet concentration and a superficial gas velocity of 7.9 cm/s. Of the two curves, that relevant to a  $\text{CO}_2$  concentration of 10% exhibits a steeper increase of the ratio  $C/C_0$ , followed by a slower approach to sorbent saturation. That makes the area under the curve wider, so that  $m_{\text{ads}}$  results larger while a lower value of  $W$  is obtained. Similarly, in Fig. 10b the trend of temperature

relevant to 10% CO<sub>2</sub> inlet concentration has a faster increase, with a maximum value of 37°C followed by a decrease to about 30°C.

A comparison of adsorption tests conducted at the same value of CO<sub>2</sub> inlet concentration (10%) and type of fluidization regime (homogeneously expanded bed) but with the two different cuts of the sorbent (400-500 and 710-800 μm) is shown in Fig. 11: on average, the ratio CO<sub>2</sub> adsorbed mass/sorbent mass, namely  $m_{ads}$ , is higher for the bigger cut of zeolitic particles than for the smaller (Fig.11a). As regards the temperature trends (Fig.11b), the maximum values of T reached with either sorbent are altogether comparable.

#### 4. Discussion

In the confining environment provided by the interstitial voids of a packed bed of coarse spheres homogeneous fluidization and expansion of the bed of zeolite 13X determines an improvement of the contact time in comparison with the case of the conventional fluidization regime (i.e. that of a freely bubbling bed). To this regard, a variation of the time of breakthrough is observed which determines a larger fraction of the bed to be utilized at the breakpoint. On the other hand, the contact time decreases with the degree of bed expansion. The analysis of temperature trends indicates that the increase of gas velocity allows a better temperature control during the adsorption process: the decrease of  $T_{max}$  at higher gas velocity is likely to be due to a more effective mechanism of thermal exchange between the solid phase, whose temperature tends to be raised by the heat released by the process of adsorption, and the effluent gas. As these thermal effects are detrimental to adsorption efficiency, gas velocity can be regulated in order to achieve a condition of good thermal control of the confined fluidized bed.

In the experiments of the present study the two cuts of solid sorbent were confined in a packing of spheres of different diameter, a circumstance that causes bed expansion to occur in a network of interstitial channels characterized by a different hydraulic diameter, namely 5.76 mm for the packing of spheres with a diameter of 11 mm (used with the 710-800 μm sorbent) and 3.71 mm for the spheres of 8 mm (used with 400-500 μm particles). Notwithstanding this difference, a similar

conditions of expansion of the two beds is observed, since the percolation ratio  $d_{VF}/d_h$  is of the same order of magnitude. The slight difference found in the values of  $m_{ads}$  measured with the 710-800  $\mu\text{m}$  sorbent can perhaps be explained with the better quality of expansion shown by bigger particles, associated to the higher value of the percolation ratio in the confined environment.

## 5. Conclusions

In the present work the efficiency of the capture of  $\text{CO}_2$  by a confined fluidized bed of pellets of zeolite 13X has been investigated. Adsorption tests have been performed both in a conventional and a confined fluidized apparatus and the effect of the size of sorbent particles, of the  $\text{CO}_2$  inlet concentration and of the superficial gas velocity has been analysed.

The experimental results show that confined fluidization positively affects the efficiency of the adsorption process as it determines a remarkable increase of the breakthrough time as well as of the fraction of bed utilized up to the breakpoint and of the adsorbed mass of  $\text{CO}_2$ .

As regards the influence of the  $\text{CO}_2$  inlet concentration, the  $\text{CO}_2$  capture capacity of the 13X zeolite increases with it coherently with the fact that the partial pressure of the species subjected to adsorption is the driving force of the process.

The tests performed in the confined fluidized bed at a fixed  $\text{CO}_2$  inlet concentration and at varying fluidization velocity show the dependence of the breakthrough time on the gas-solid contact time, which is inversely proportional to the fluidization velocity. In the confined fluidized bed the increase of temperature associated to the exothermic nature of the process is small and can be controlled by regulating the superficial gas velocity, a favorable circumstance for the optimization of the performance of an apparatus based on this novel contact mode.

## NOMENCLATURE

$C$	CO <sub>2</sub> concentration in the effluent gas, % vol
$C_0$	CO <sub>2</sub> concentration in the inlet gas, % vol
$d_h$	hydraulic diameter of the voids , mm
$d_p$	diameter of the packed solid, mm
$d_{SF}$	Sauter mean diameter of sorbent, $\mu\text{m}$
$d_{VF}$	volume mean diameter of sorbent, $\mu\text{m}$
$m_{ads}$	mass of CO <sub>2</sub> adsorbed per unit mass of sorbent, gCO <sub>2</sub> /kg13X,
$u$	superficial gas velocity, cm/s
$u_{mf}$	minimum fluidization velocity of the conventional bed, cm/s
$u_{mfc}$	minimum fluidization velocity of the confined bed, cm/s
$W$	fraction of bed utilized at breakpoint, %
$t$	time, s
$t_b$	breakthrough time, s
$t_c$	contact time, s
$T$	temperature in the middle of the confined fluidized bed, °C
$T_{max}$	maximum temperature in the middle of the confined fluidized bed, °C

## Greek symbols

$\Delta P$	pressure drop in the conventional system, Pa
$\Delta P_{conf}$	pressure drop in the confined system, Pa
$\varepsilon$	voidage in the packed-fluidized bed, -
$\varepsilon_{mf}$	voidage at incipient fluidization in the conventional bed, -
$\varepsilon_p$	voidage of the packed bed, -

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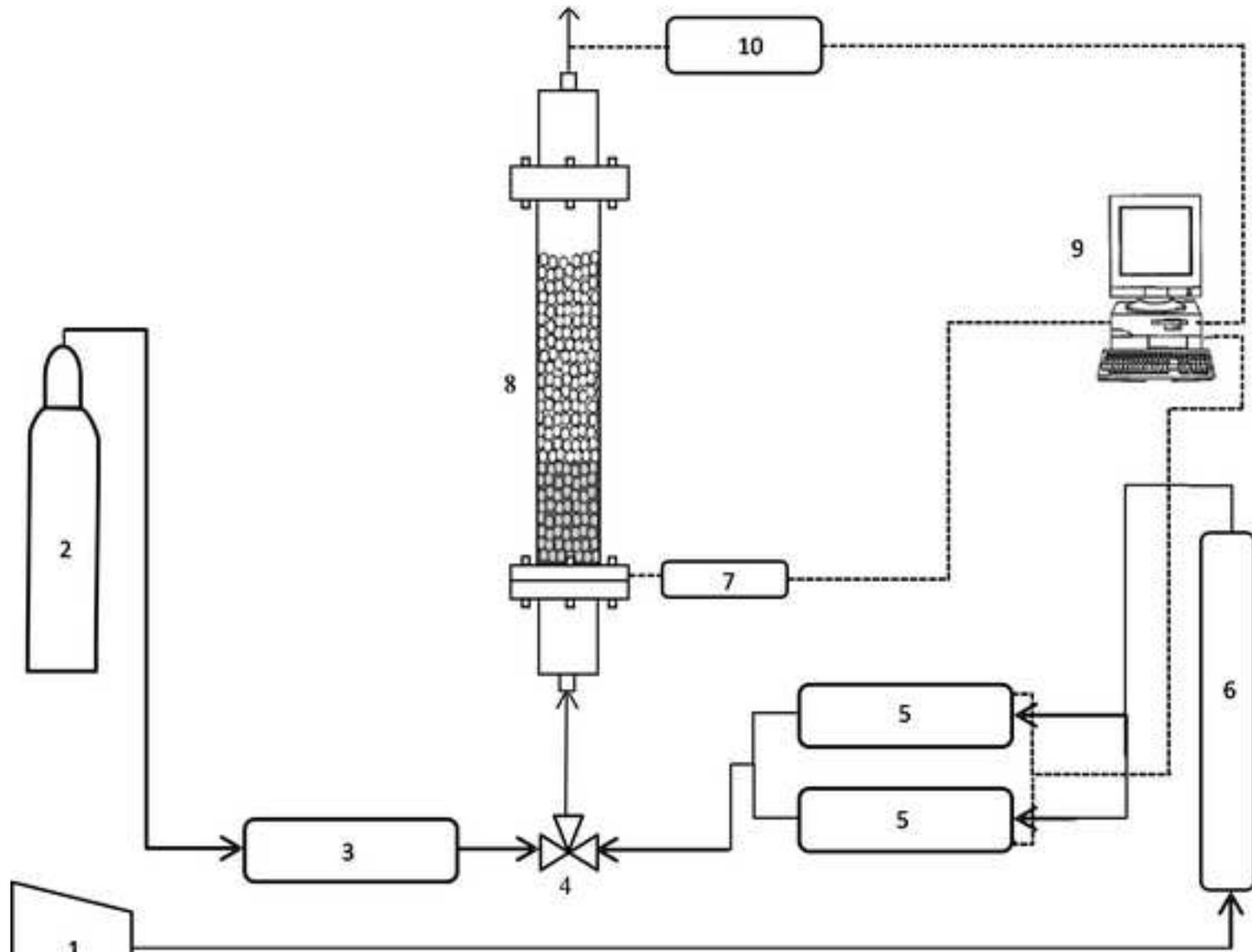
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Figure1

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1	Compressor	6	Humidity abatment system
2	CO <sub>2</sub> cylinder	7	Pressure trasducer
3	CO <sub>2</sub> mass flow controller	8	Fluidization column
4	Three-ways valve	9	Personal Computer
5	Air mass flow controllers	10	Gas analyser

Figure2

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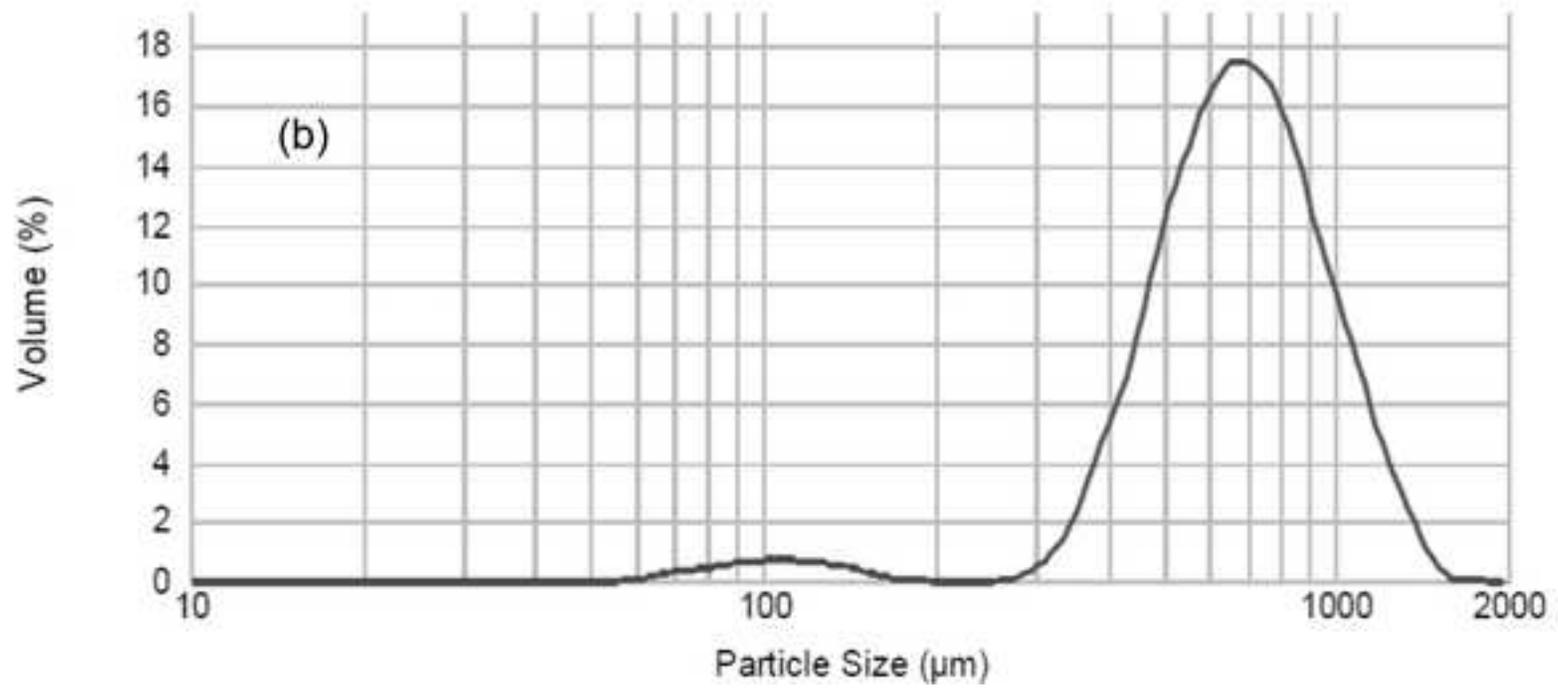
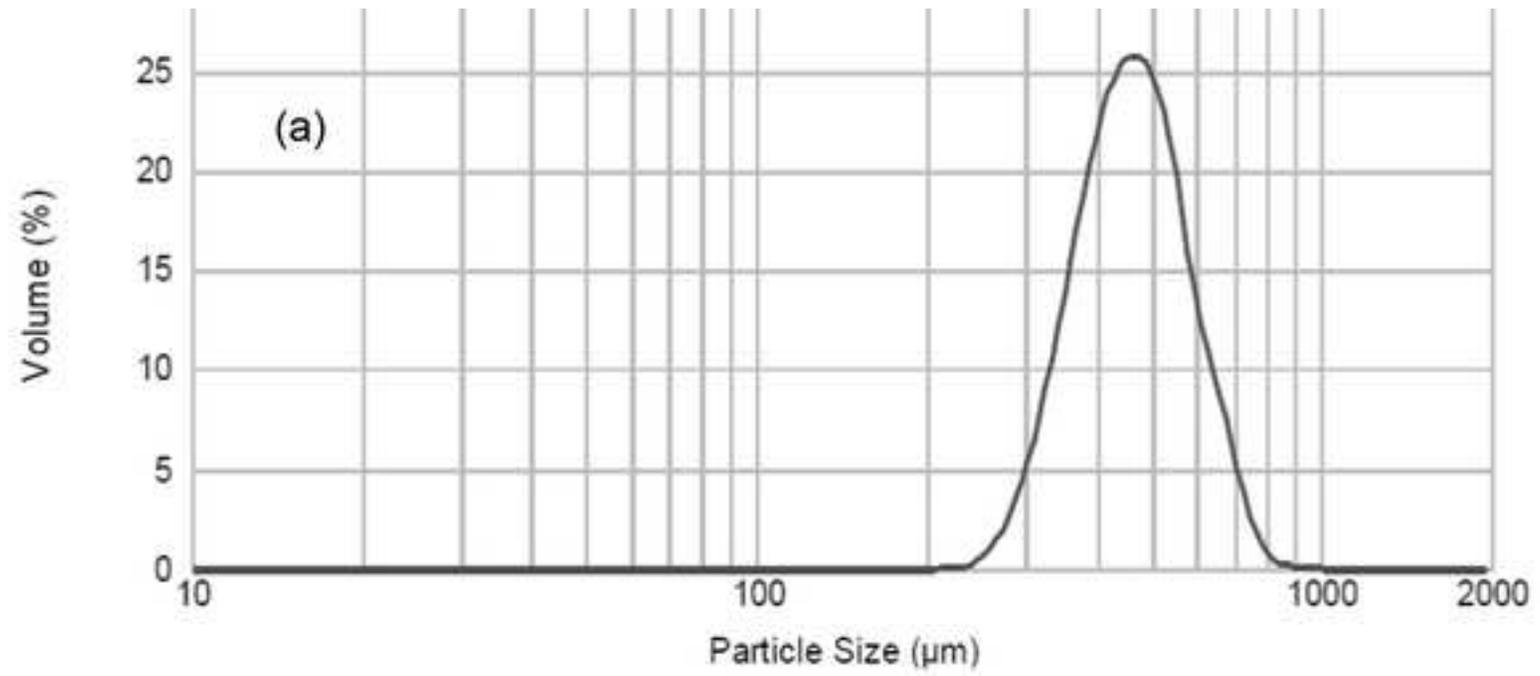


Figure3

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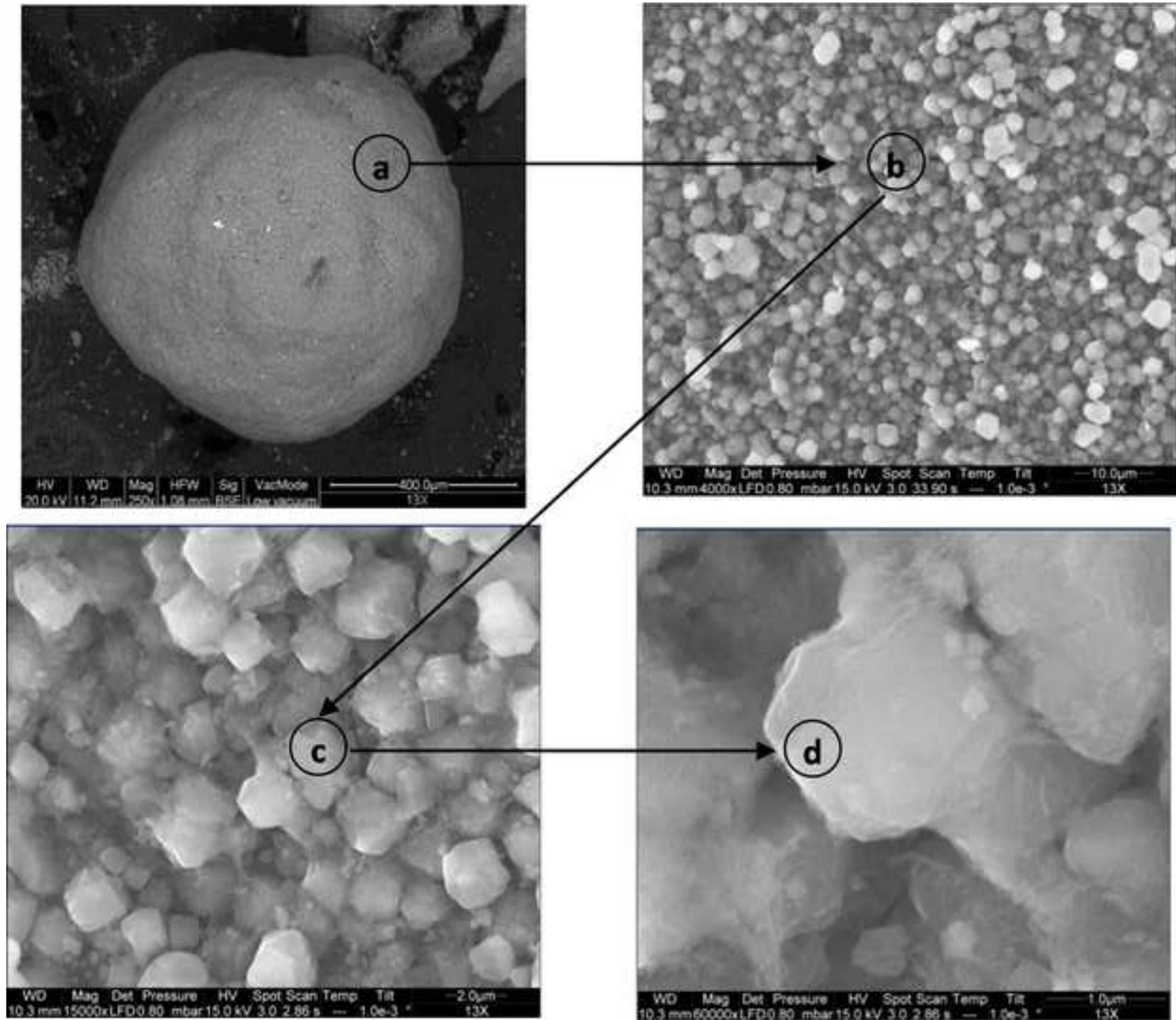


Figure 4

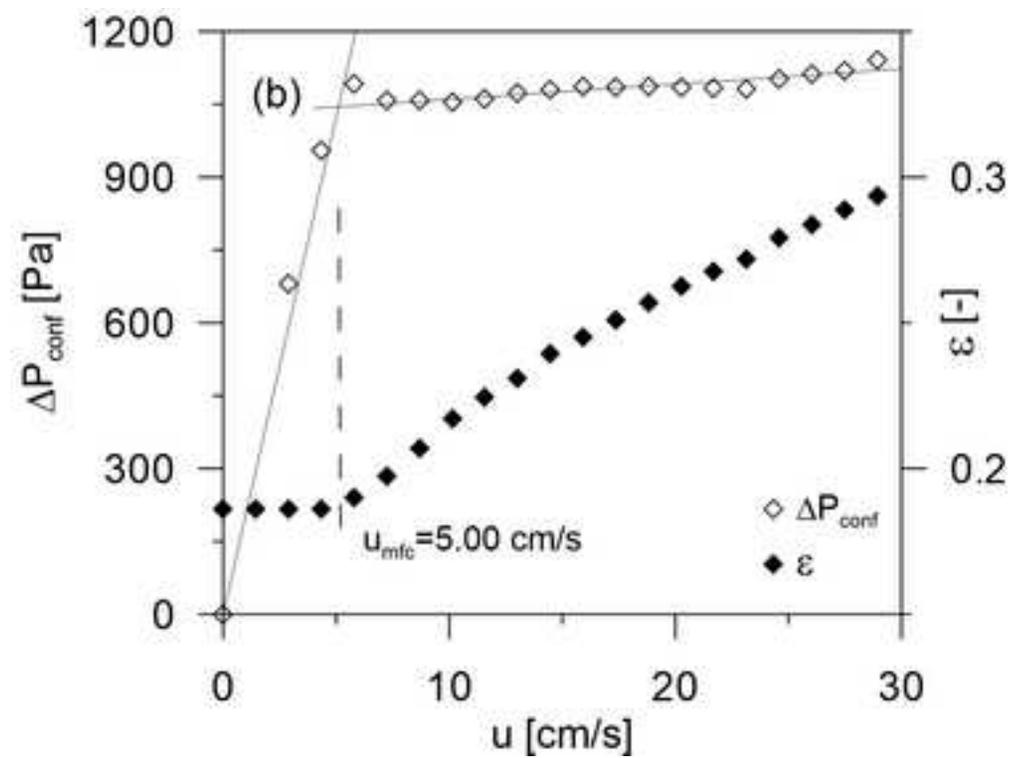
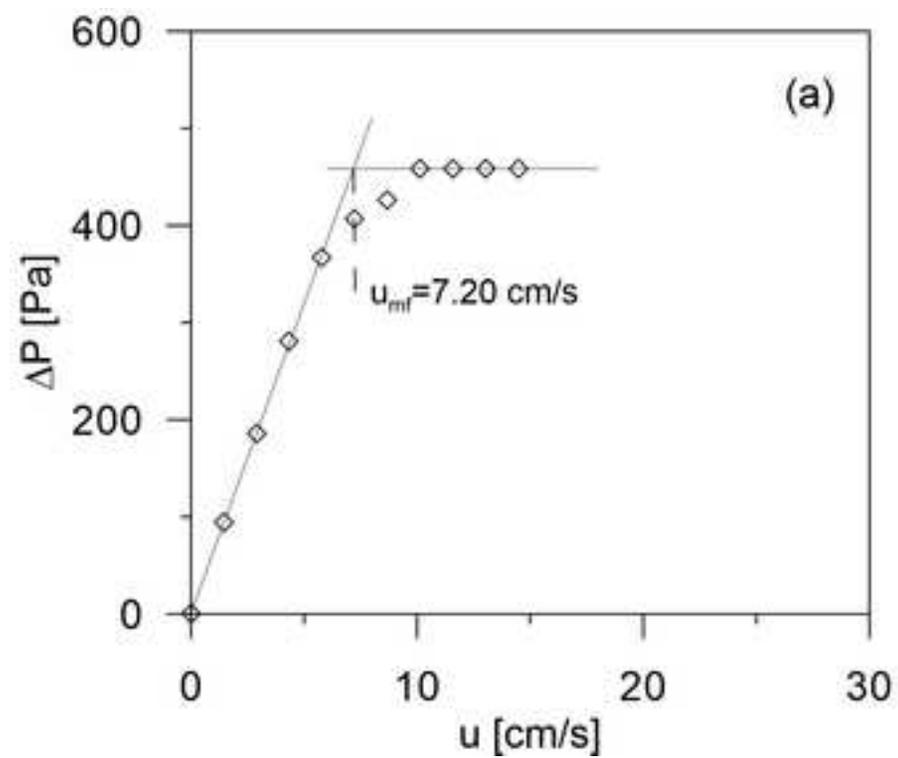
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Figure5  
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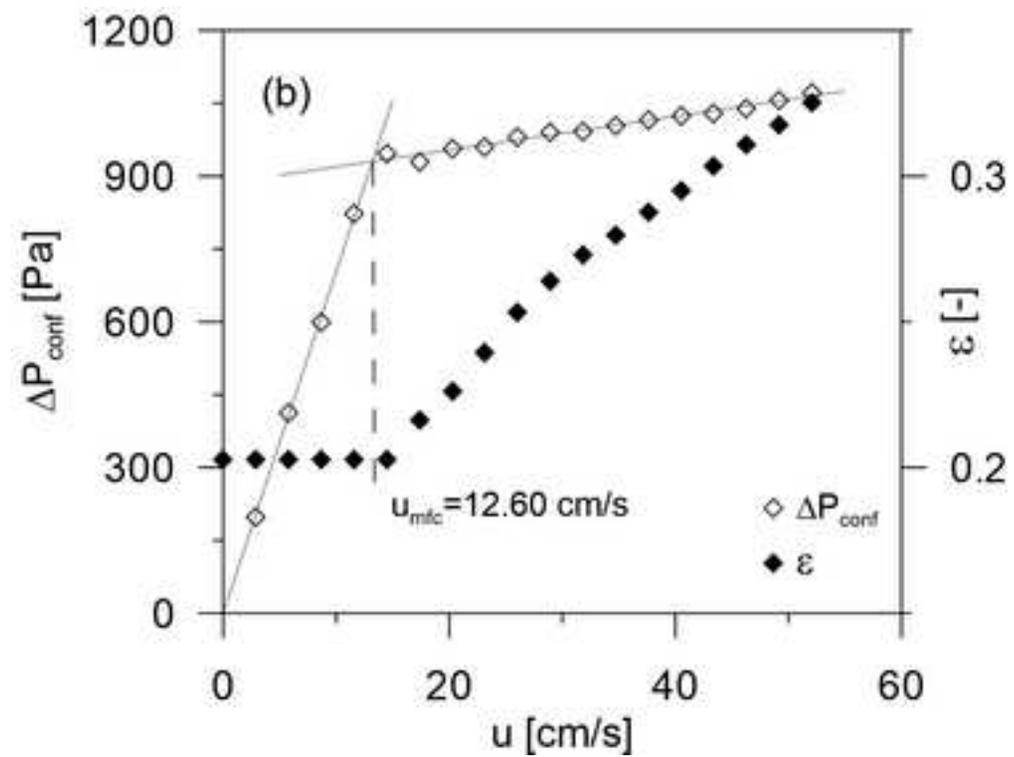
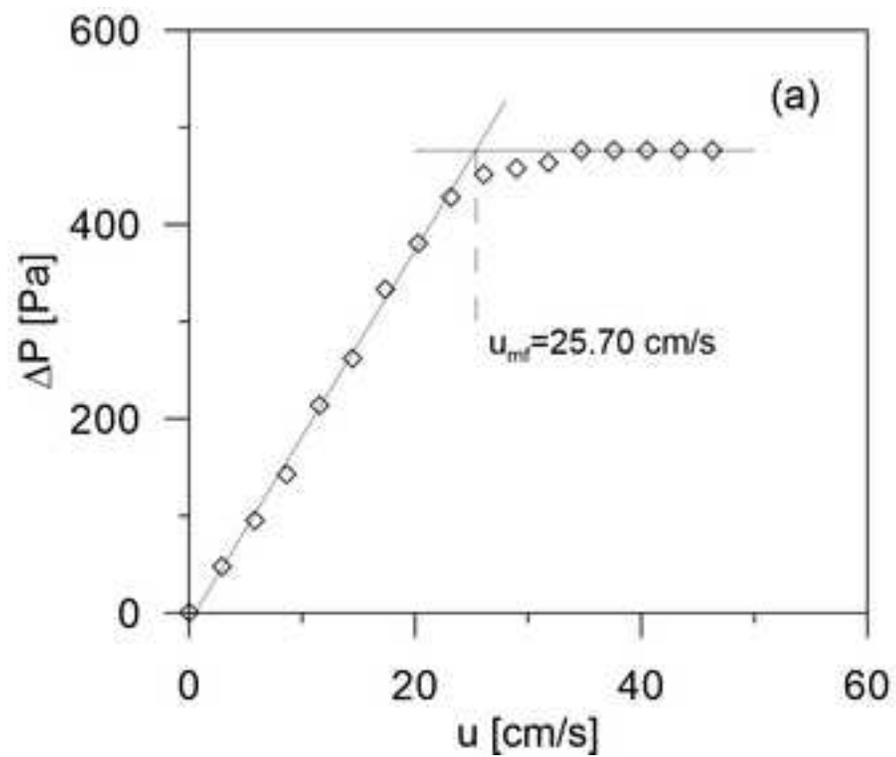


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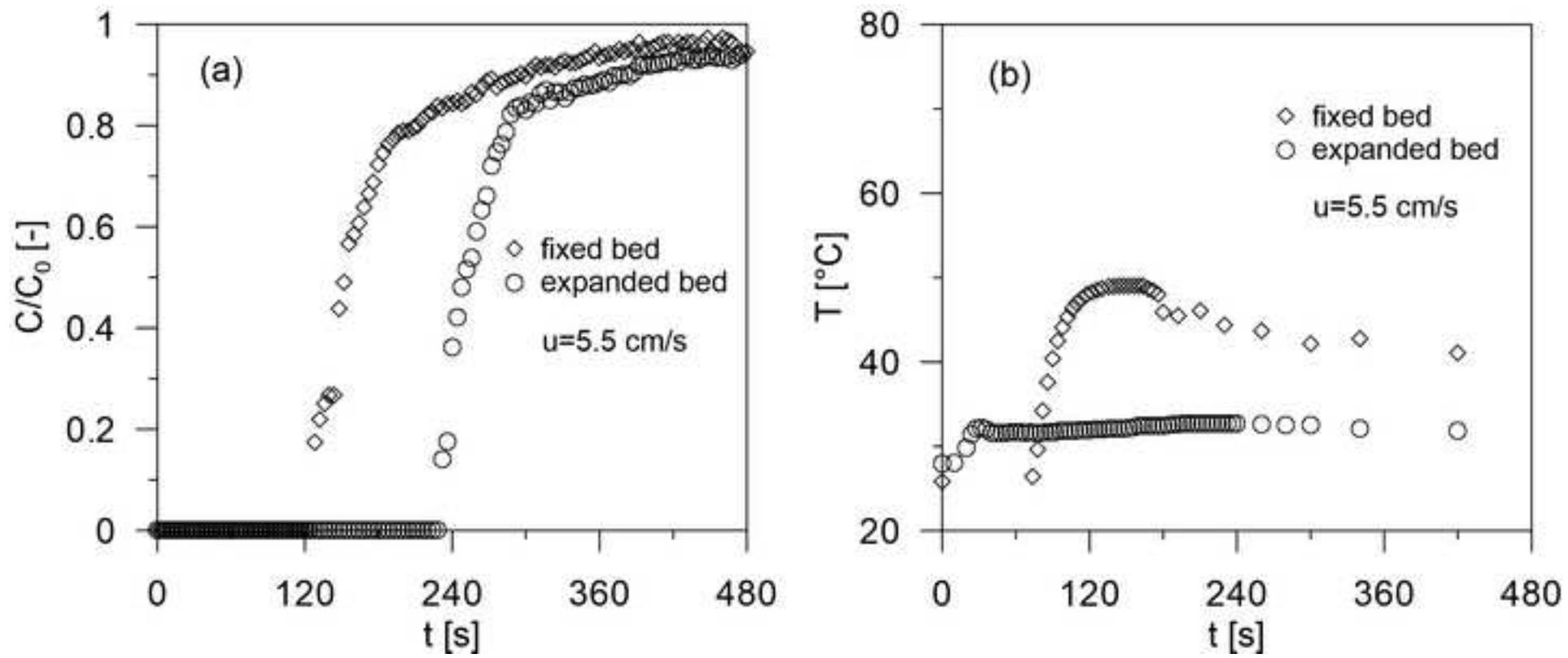


Figure 7

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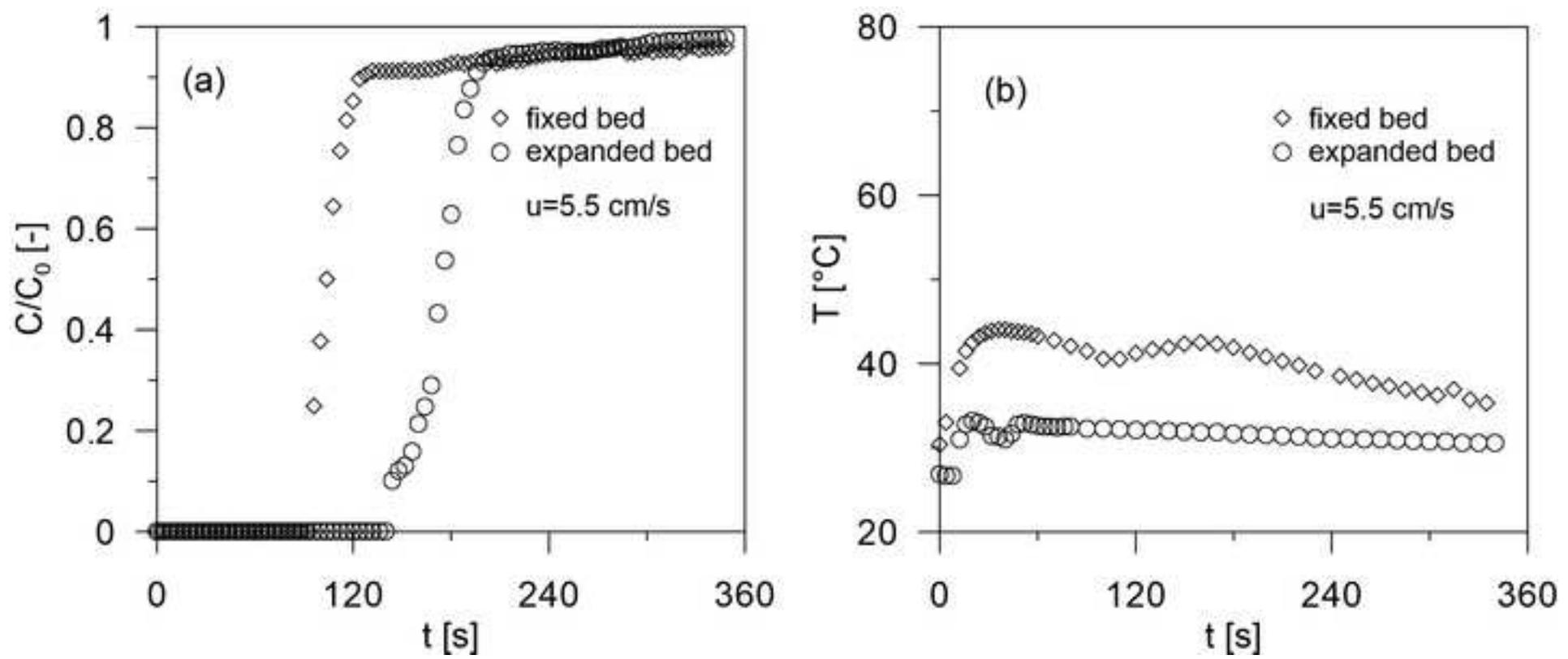


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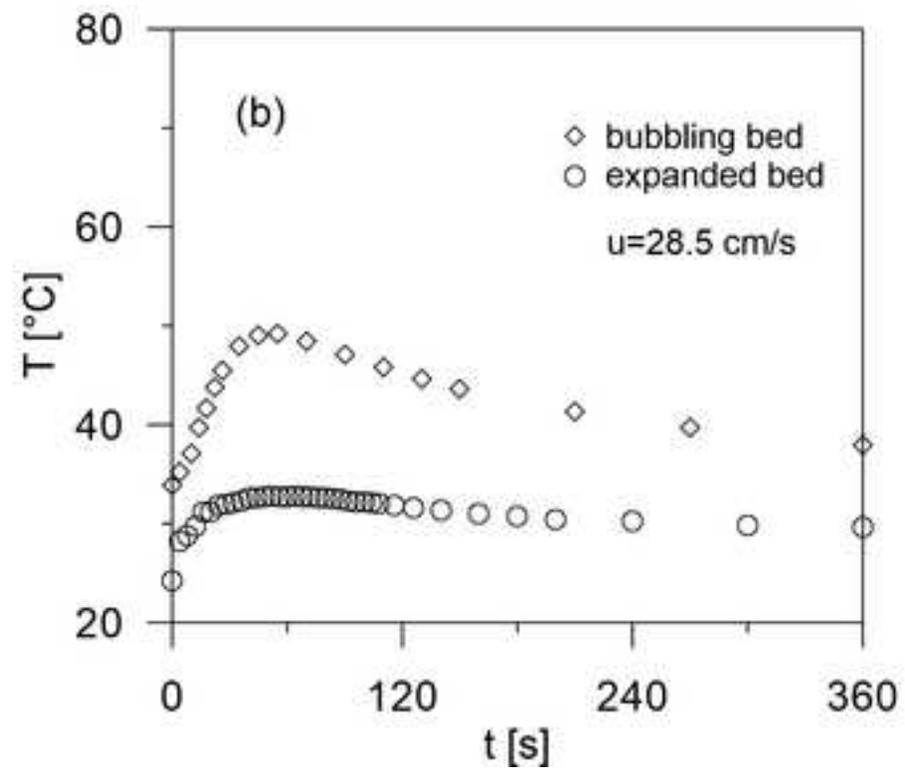
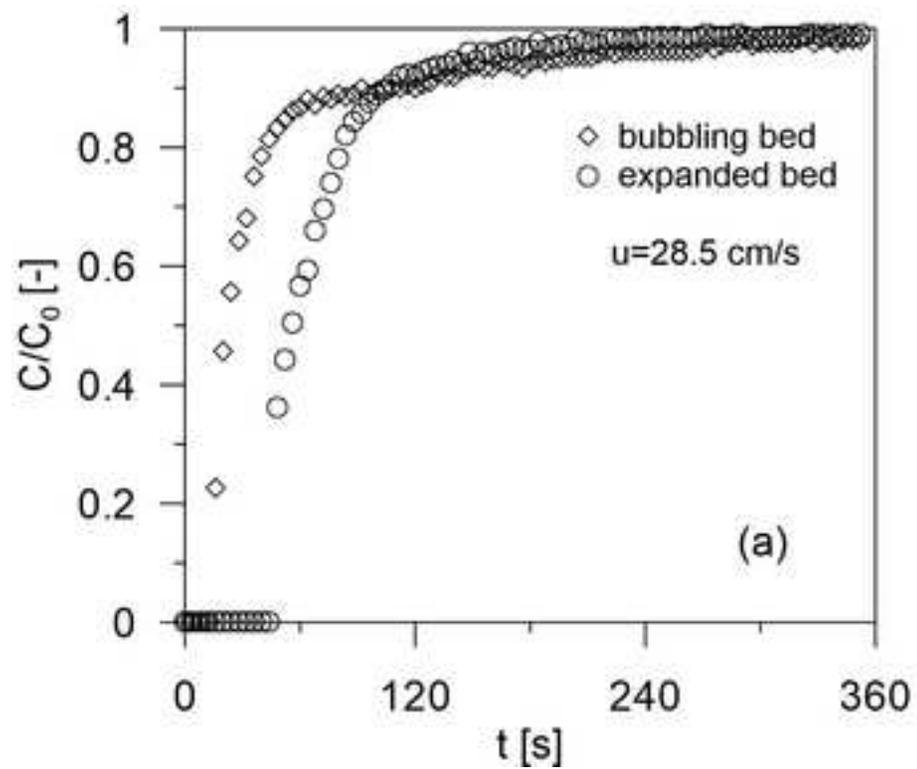


Figure9

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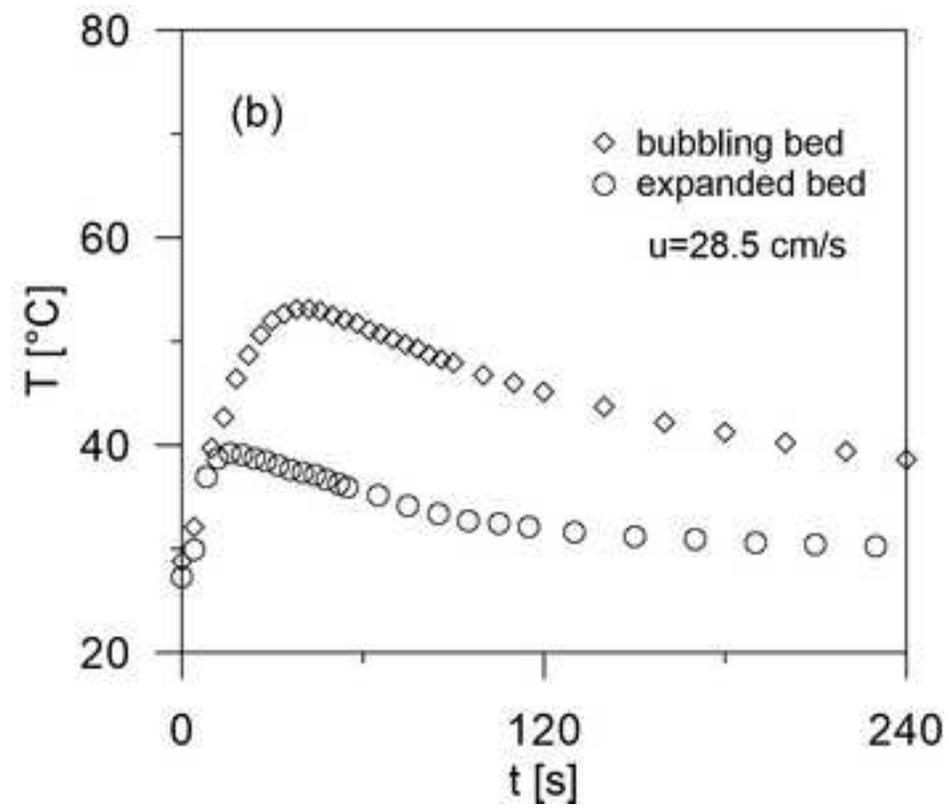
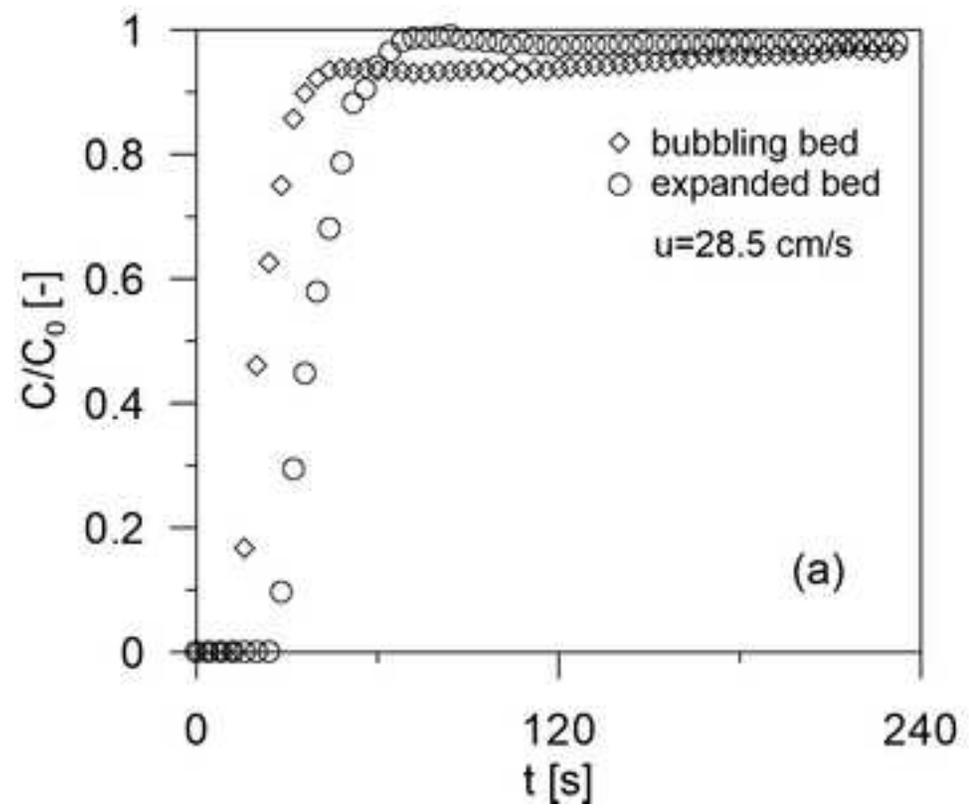


Figure10  
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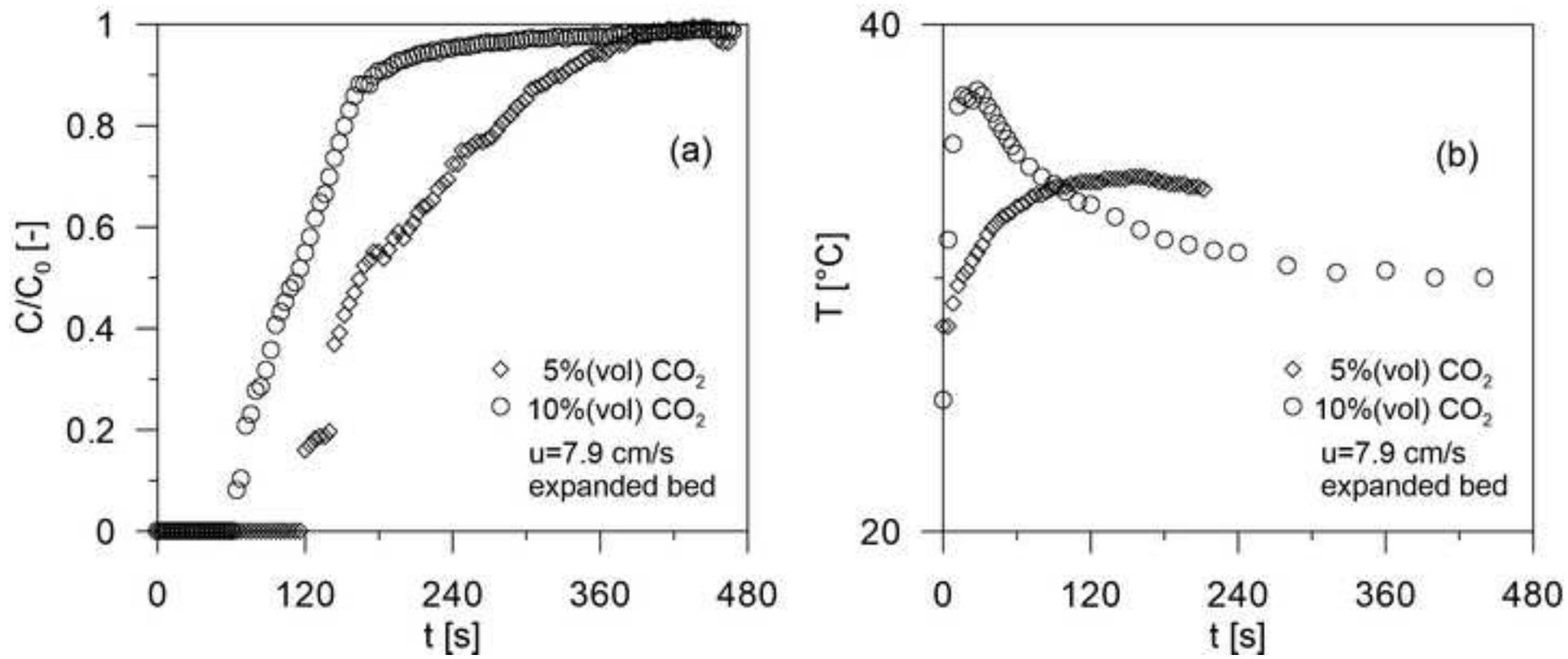
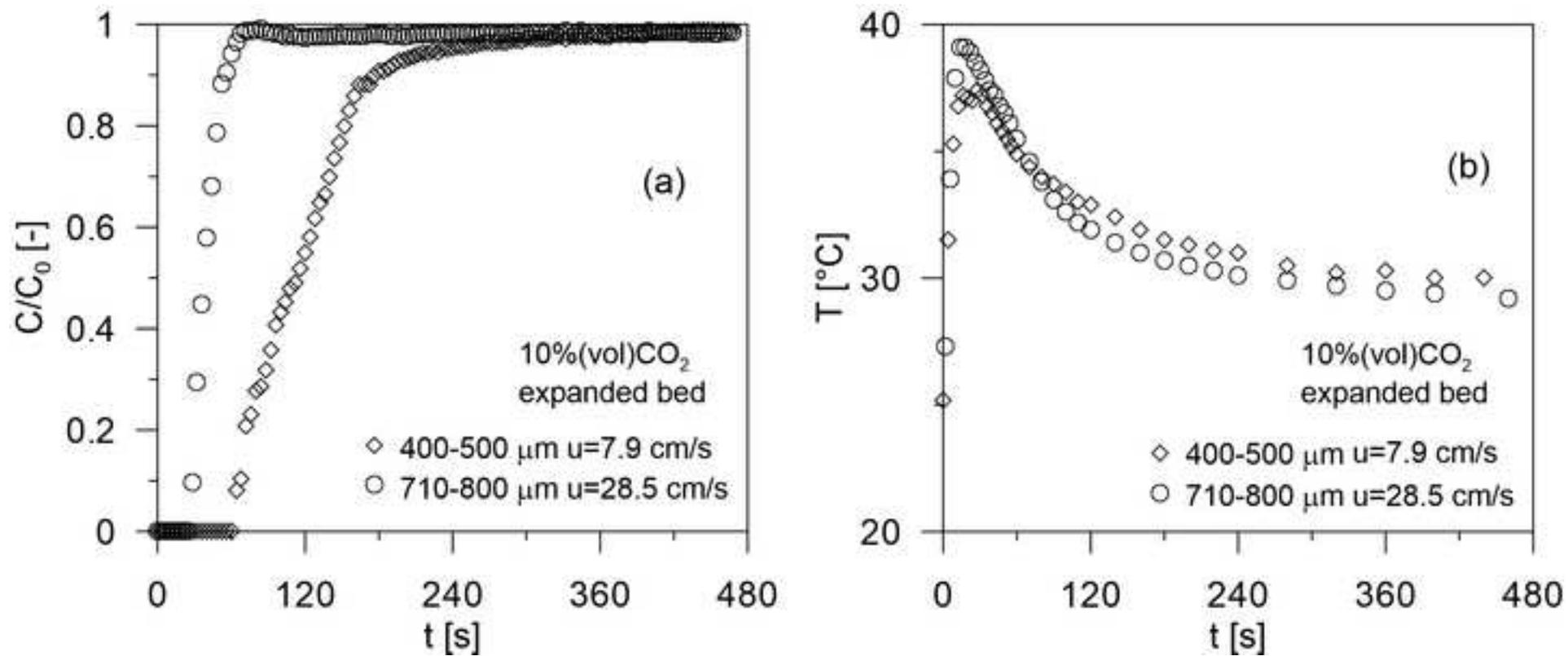


Figure 11  
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Tab.1 - Size distribution data.

Sieve size [ $\mu\text{m}$ ]	Volume diameter, $d_{VF}$ [ $\mu\text{m}$ ]	Sauter diameter, $d_{SF}$ [ $\mu\text{m}$ ]	$d(10)$ [ $\mu\text{m}$ ]	$d(50)$ [ $\mu\text{m}$ ]	$d(90)$ [ $\mu\text{m}$ ]
400-500	471	448	343	460	616
710-800	701	558	426	675	1036

Tab.2 - Thermogravimetric data.

<b>Sample</b>	<b>Weight loss %</b>
As made	21,5 (at 200°C)
Treated at 300°C/8 hour	4 (at 200°C)
After CO <sub>2</sub> adsorption	3 (at 70°C); 4 (at 200°C)

Tab.3 - Fluid-dynamic data.

Sieve size [ $\mu\text{m}$ ]	conventional bed		confined bed					
	$u_{mf}$ [cm/s]	$\varepsilon_{mf}$ [-]	Packing diameter $d_p$ [mm]	Packed bed voidage $\varepsilon_p$ [-]	Hydraulic diameter, $d_h$ [mm]	Percolation ratio, $d_{VF}/d_h$ [-]	$u_{mfc}$ [cm/s]	$\varepsilon$ [-]
400-500	7.20	0.41	8	0.41	3.71	0.13	5.00	0.19
710-800	25.70	0.39	11	0.44	5.76	0.12	12.60	0.20

Tab.4 - Superficial gas velocities during the absorption tests.

Sorbent sieve size [ $\mu\text{m}$ ]	u [cm/s]	Regime in the conventional system	Regime in the confined system
400-500	5.5	Fixed bed	Expanded bed
	7.9	Bubbling bed	
710-800	13.9	Fixed bed	Expanded bed
	28.5	Bubbling bed	

Tab. 5 - Process parameters and results of the adsorption experiments.

Sorbent size	CO <sub>2</sub> fraction [%]	Gas velocity [cm/s]	Regime	t <sub>c</sub> [s]	t <sub>b</sub> [s]	W [%]	m <sub>ads</sub> [gCO <sub>2</sub> /kg13X]	T <sub>max</sub> [°C]
400-500 μm	5	5.5	Fixed bed	0.69	136	74	75	49
			Expanded bed	0.95	234	84	74	33
		7.9	Bubbling bed	0.52	86	50	71	44
			Expanded bed	0.78	129	64	71	34
	10	5.5	Fixed bed	0.65	93	79	91	44
			Expanded bed	0.95	156	89	89	33
		7.9	Bubbling bed	0.54	39	40	87	50
			Expanded bed	0.78	66	55	84	37
710-800 μm	5	13.9	Fixed bed	0.28	56	58	91	65
			Expanded bed	0.43	91	80	81	38
		28.5	Bubbling bed	0.16	15	37	83	49
			Expanded bed	0.40	46	68	79	33
	10	13.9	Fixed bed	0.27	38	86	109	54
			Expanded bed	0.44	69	90	105	41
		28.5	Bubbling bed	0.19	14	46	110	53
			Expanded bed	0.30	29	71	104	39

**Captions to the figures**

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