EXPERIMENTAL INVESTIGATION OF CROSS FLOW MIXING IN AN UNSTRUCTURED PACKED BED
Ali Alkhalaf, Hermann Woche, Eckehard Specht

Institute of Fluid Dynamics and Thermodynamics
Otto von Guericke University
Universitätsplatz 2 D-39106, Magdeburg, Germany
E-mail: ali-mohammed.ridha@ovgu.de

ABSTRACT

Packed bed has become a widely used in the industrial application, such as shaft kiln, the understanding of radial gas mixing plays a very important role in design of shaft kilns. Because of geometric complexity and the movement of the lumpy processed material, which make the measuring of main parameters, such as temperature, species, and velocity impossible, therefore it is important to understand the details of flow information in the packed bed. However, less experimental work has been carried out for the mixing of an axial flow with a cross flow. The present study deals with an experimental investigation of an axial flow with cross flow in an unstructured bed under the different operating conditions, including Measurement height, injection velocity, volume flow rate ratio, flow conditions and location of injection. The dimensions of the tested box are 0.624 m long (L), 0.364 m width (B) and 0.6 m height (H). Small glass spheres at 4 mm diameter was used as an unstructured bed which leads to porosity 0.4, different values of volume flow rate ratios were examined. The mixing efficiency over the test rig at height Z=0.473 m was defined as the parameter to evaluate the mixing quality. The results revealed that the form of the jet is independent from the lance location and the bed height. The lower volume flow rate ratio is, the higher the mixing is.

Keywords: cross flow, radial gas mixing, packed bed, shaft kiln, porous medium.

INTRODUCTION

Packed beds are used in numerous and diverse areas of industry, such as shaft kilns, heat storage systems, cooling/heating of granular materials, chemical process industries and distillation processes. Shaft kiln, basically, is a packed bed reactor, works on a simple principle. The raw material is fed in at the top of the kiln and the product is withdrawn from the bottom. A major problem of the lime production is the erratic distribution of fuel inside the kilns, which is responsible for the emergence of high-temperature zones. The high temperatures and the movement of the packed bed, makes the measurement of concentration profiles in shaft kilns is not possible. Therefore, for simplification a simple cubic unstructured bed was used and the Experiments were conducted for 4 mm glass spheres as a bed which lead to porosity 0.4. The measurement results are required to analyze the oxygen concentration (mixing efficiency) in the inside as well as for the examination of the influences of both the inputs: air and test gas. Finally The Computational Fluid Dynamics (CFD) porous approach has been used to create the geometry of packed bed correspond to the experimental setup. Therefore, the same dimensions as
well as operating conditions apply to it. The location of injection simulation results is validated with experimental data. The mixing problems in the calcining zone, causes the regions of deficient heating or overheating, this results in decreased quality of products, reduced productivity, and low thermal efficiency [1]. There are two principal categories of packing; unstructured packed bed (randomly) and structured packed bed. The randomly packed beds predominate the industry because of their ease of use and low price compared to other packing methods, which is well represented in literature [2 - 4]. Salewski et al. [5] studied numerically and experimentally the coherent structures and mixing in the flow field of a jet in cross flow. The results revealed that the distribution of a passive scalar in a cross-sectional plane can be single- or double-peaked, depending on the nozzle shape and orientation. Huang et al. an experimentally investigated one-dimensional uniform flow in homogeneous porous media have been performed [6]. A group of experiments was conducted in four test tubes with cubic arrays of spheres in diameter 3, 5, 8 and 10 mm. Wen experimentally measured the axial and radial direction, temperature distribution through a packed bed under the constant wall temp [7]. The results reveal a large temperature drop at the wall region and the temperature drop depends on the distance from the entrance of the column. Papageorgiou spotted that the fluid flow is channeled in the area near the wall due to the high void fraction in unstructured beds causing non homogeneous overall radial flow profiles [8]. The mixing in a rectangular cross section for non-reacting jet injection was investigated in [9], the study revealed the mixing improves continuously with increasing momentum flux ratio, the mixing is more dependent on injector geometry than a mass flow ratio. Nirmolo use a cylindrical chamber with multiple jets injected radially to study the temperature homogenization of reactive and non-reactive cross flow numerically, they defined the maximum temperature difference over the chambers cross sectional area as the parameter to evaluate the mixing quality [10]. Xu investigated numerically the flow of structured packed bed reactors with jet injections using (CFD) [11]. The results showed that the jet behavior was independent of the bed height. Also, he was creating a 3D geometric model with 30° segment and bed height of about 0.8 m. In addition, he illustrated that, an increase of the lance location may be helpful to protect the refractory wall to being overheated but it has only a slight effect on the overall radial temperature distribution, the mixing between combustion gas and the cooling air can be improved by reducing the burner diameter or by preheating the combustion air. He developed a 3D geometries using the porous media model for three different porosity 0.4, 0.6 and 0.8 respectively. The results compared with discrete particle geometry. He found that, by application of the porous media model, the penetration of the combustion gas is under-predicted for porosity 0.4, to achieve a deeper penetration, porosity must be bigger. Dixon in [12] validated the CFD simulations of heat transfer in fixed beds of spheres by comparing the results with experimental measurements in a pilot-scale rig, the agreement between CFD simulations and experimental data was very satisfactory. A successive simulation steps (packing generation, fluid flow and species calculation) and their validation with experimental data was described in [13]. In addition, Bu et.al, in [14 - 16] made a series of experimental studies by using the electrochemical techniques. They investigated the transition flow in the packed beds of spheres with different particle sizes experimentally. Wu and Ferng in [17], and Nijemeisld and Dixon in [18], used two main methods in CFD approach to create the geometry for a closely packed bed: the porous medium approach and the realistic discrete particle approach. In a porous approach, the geometry of packed bed is represented as an effective porous medium. This approach is used for a wide variety of single phase and multiphase problems, including flow through packed beds, filter papers, perforated plates, flow distributors, and tube banks [19 - 21]. All these studies showed that there is much knowledge of flow transition, mass transfer and pressure drop in random and structured packed beds. In a shaft kiln for the heat treatment of granular material the fuel and a part of the combustion air is injected radially. The cooling air flows from the bottom. The mixing behavior of these two flows is important for the temperature distribution in the cross section and thereby the quality of the product. These kilns have a diameter of up to 4 meters. The industrial
processing shows that the penetration depth of the radial flow is relatively low. Therefore, a part of the cross flow is injected through lances which are inserted into the bed. So that, the present experimental work describes a method to report the mixing in the shaft kiln.

EXPERIMENTAL

Fig. 1a shows the experimental setup of the cross flow mixing in the packed bed. The setup consists of cubic boxes as a packed bed, a free space for distributing air from the bottom surface of the packed bed, a centrifugal blower, nitrogen bundle from which nitrogen is injected with a lance, volume flow measuring device, gas analyzer, data evaluation system and control devices for the monitoring and readjustment of the operating parameters. The operating conditions record is presented in Table 1. The dimensions of the tested box are 0.624 m long (L), 0.364 m width (B) and 0.6 m height (H). Ambient air was blown through the packed bed from the bottom of the test section box (axial flow). The bottom of the box consists of a perforated plate with 66 holes in 20 mm diameter for each hole which has a high flow resistance. The volume of the lower box distributes the incoming air from the blower homogeneously to the perforated plate. Thereby it was insured that the flow is well distributed in the cross section. The volume flow was measured using a Rotameter. Different series of flow rates (40, 83, 150 and 250 m³ h⁻¹) were examined. Fig. 1b shows the top view with the 11 locations for the measurements in x axis.

A lance is attached to the box from which nitrogen is injected perpendicular to the air flow as shown in Fig. 1a. The nitrogen flow coming from a bundle was measured using a rotameter. Three flow rate values (5, 15 and 25 m³ h⁻¹) were tested. Three different lances were used with inner diameters of 6, 12 and 20 mm. The experiments were done in lance injection locations of 0, 0.156 m and 0.312 m. The unstructured packing forms include a glass spheres particles at 4 mm diameter which leads to a porosity 0.4, (see Table 2). The oxygen molar concentration was measured using a gas analyzer at 11 positions in the bed, therefore a lance filter was placed in the bed and a small part of the gas mixture was sucked off Fig. 1c. The measurements were taken at two different heights in z-direction (0.223 m and 0.473 m) for bed.

Fig. 1. a) Schematic description of the experimental setup, b) Top view (with the 11 measurement points, 52 mm to 572 mm), c) Real photo for the use packed beds.
RESULTS AND DISCUSSION

Several studies [22 - 25] had investigated parameters to evaluate mixing such as mixture fraction, equilibrium mixture fraction, and the normalized maximum temperature difference depending on the temperature difference inside the chambers for reactive and non-reactive flows. For this study it is important to obtain the local mixing efficiency instead of oxygen concentration because the \( \text{O}_2 \) concentration is confusing as the “volume ratio” is changing.

The knowledge of flow behavior inside a packed bed of the radial cross flow will improve the temperature distribution in the cross section of the shaft kilns, which leads to better product quality, high thermal efficiency and energy saving. The experimental measurements were done under ambient temperature for both flow inlets (cold flow).

### Table 1. Operating conditions.

<table>
<thead>
<tr>
<th>Air flow</th>
<th>Nitrogen flow</th>
<th>Volume flow ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{m}^3 \text{ h}^{-1} )</td>
<td>( \text{Superficial Velocity (m s}^{-1}) )</td>
<td>( \text{Real velocity (m s}^{-1}) )</td>
</tr>
<tr>
<td>40</td>
<td>0.050</td>
<td>0.125</td>
</tr>
<tr>
<td>83</td>
<td>0.101</td>
<td>0.253</td>
</tr>
<tr>
<td>150</td>
<td>0.183</td>
<td>0.457</td>
</tr>
<tr>
<td>250</td>
<td>0.306</td>
<td>0.765</td>
</tr>
</tbody>
</table>

### Table 2. Porosity calculations.

<table>
<thead>
<tr>
<th>Packed bed</th>
<th>Particle density ( (\text{kg} \cdot \text{m}^{-3}) )</th>
<th>Bed weight kg</th>
<th>Bed height m</th>
<th>Bed volume m(^3)</th>
<th>Total of test space m(^3)</th>
<th>Porosity ( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Spheres ( d_s=4 \text{ mm} )</td>
<td>2536.5</td>
<td>172.9</td>
<td>0.50</td>
<td>0.0682</td>
<td>0.1136</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The mixing efficiency \( X_i \) was calculated from:

\[
X_i = \frac{C_{oi}}{C_{im}} \quad \text{for} \quad (\text{C}_{oi} < \text{C}_{im})
\]

\[
X_i = \frac{100 - C_{oi}}{100 - C_{im}} \quad \text{for} \quad (\text{C}_{oi} > \text{C}_{im})
\]

where \( C_{oi} \) is the local \( \text{O}_2 \) concentration, in vol. %, and \( C_{im} \) is the \( \text{O}_2 \) concentration at ideal mixing.

\[
C_{im} = \frac{V_a C_{oa}}{(V_a + V_n)}
\]

where \( V_a \) and \( V_n \) are air and nitrogen flow rate respectively and \( C_{oa} \) is \( \text{O}_2 \) concentration in air.

Then the average mixing efficiency can calculated from the expression:

\[
X_{av} = \frac{X_1 + X_2 + \ldots + X_n}{N}
\]

where \( N \) is the number of local measurements.
From $X_n$, the influence of different parameters can be evaluated.

**Measurement height**

The effect of measurement height on the cross flow mixing was studied. The lance of the gas analyzer was inserted from the top into the bed between the particles at 11 fixed points. These points were used in measurement in two different levels, 0.223 m and 0.473 m from the bottom. The flow rate ratio $V_R$ of injection flow $N_2$ ($V_i^\circ$) to axial flow air ($V_{ax}^\circ$) was 0.625. Fig. 2 shows the measured mixing efficiency versus the injection direction, the measurement height has not effected on the mixing efficiency at both injection locations (0, 0.156 m).

**Measurement height**

The effect of measurement height on the cross flow mixing was studied. The lance of the gas analyzer was inserted from the top into the bed between the particles at 11 fixed points. These points were used in measurement in two different levels, 0.223 m and 0.473 m from the bottom. The flow rate ratio $V_R$ of injection flow $N_2$ ($V_i^\circ$) to axial flow air ($V_{ax}^\circ$) was 0.625. Fig. 2 shows the measured mixing efficiency versus the injection direction, the measurement height has not effected on the mixing efficiency at both injection locations (0, 0.156 m).

**Fig. 2.** Effect of measuring level on mixing efficiency with different penetration depth, lance diameter 20 mm, $V_R = 0.625$.

**Fig. 3.** Influence of injection velocity $U_i$ (lance diameter) on mixing efficiency, lance depth 0.156 m.

**Fig. 4.** Influence of axial flow rate ($V_{ax}^\circ$) with a fixed injection flow rates ($V_i^\circ$) on mixing efficiency, lance depth 0.312 m.
0.156 m), A condense bed with porosity 0.4 effects on the curve behavior represented by sharply increasing of O\(_2\) concentration after 0.15 m after the injection to reach to 21 % in both lance locations 0 and 0.156 m.

Injection velocity
Fig. 3 shows the influence of the injection velocity on the flow mixing depending on different lance diameter (6, 12 and 20 mm), the mixing efficiency does not effect by changing lance diameter.

Volume flow rate ratio

a. Effect of air flow rate (axial flow)
The effect of the air flow rate of the mixing efficiency is shown in Fig. 4. The lance location was 0.312 m, the air flow was the parameter while the N\(_2\) (injection flow) was fixed at 25 m\(^3\) h\(^{-1}\). All curves are at the same tendency. The width of the curves proportion with the axial flow rates, the wide curve for the minimum axial flow rate gives a better mixing.

b. Effect of nitrogen flow rate (injection flow)
The effect of the nitrogen flow rate (injection flow) on the mixing efficiency is shown in Fig. 5. The lance location was 0.312 m. The N\(_2\) (injection flow) was the parameter while the air flow was fixed at 40 m\(^3\) h\(^{-1}\). The curves are symmetrical on both sides of injection. It is clear to see the effect of the different injection flow rate on the mixing from the wide of the curves.

The two previous parameters were a strong effect on the cross flow mixing, which means the better mixing can be achieved in higher volume flow rate ratio \(V_R\).

Flow conditions
The volume flow rate ratio could be adjusted by the air and nitrogen flow rates. Therefore, the same ratio was obtained by different combinations. For example, to obtain the volume flow rate ratio \(V_R\) of 0.1 by combining a nitrogen flow rate of 25 m\(^3\) h\(^{-1}\) with an air flow rate of 250 m\(^3\) h\(^{-1}\) or by using 15 and 150 m\(^3\) h\(^{-1}\) for nitrogen and air flow rates, respectively. Fig. 6 represents the effect of the obtained volume flow rate ratio on the mixing efficiency with a location of injection of 0.312 m. It is obvious that the curves are identical to the same volume flow rate ratio \(V_R\). In other words the mixing are independent of the same volume flow rate ratio with different flow rates.
Location of injection

Fig. 7 shows the effect of location of injection on the mixing efficiency for different volume flow rate ratios. The two locations of injection 0.156 m and 0.312 m were shifted to the location 0 m, it means the injection always started at 0 m. In case of $V_R = 0.625$, it is obvious that all profiles fell together and formed a jet of $N_2$. The flow from lance location 0.312 m formed a symmetrical wide jet, and the flow from the lance locations 0, 0.156 m are on the right side. Therefore, it can be concluded that the
shape of the jet is independent from the lance location. For $V_r = 0.06$, this case shows that if we decrees the injected amount of $N_2$, the width of the jet will be smaller (the distance between the first two side flat points on the top of the curve).

Compared with the CFD simulation

The comparison with the CFD simulation has shown that even a same trend of Concentration propagation can be seen in the model, Figure 8. However, the mixing efficiency in the process simulation is higher than that determined by the data. It can be recommended to use a porous media model for modelling a whole shaft kiln to study the flow behavior inside the bed.

Average mixing efficiency

Fig. 9 explain the average mixing efficiency $X_{av}$ for different operation condition at the same volume flow rate ratio 0.625 and at measuring level $Z = 0.473$ m, the main parameter has the strong effect is the volume flow rate ratio depending on the amount of supplying air and nitrogen.

CONCLUSIONS

In this paper, an experimental work of cross flow mixing in unstructured packed beds was researched experimentally and validated with porous media model using CFD. Various parameters of measurement height, injection velocity, volume flow rate ratio, flow conditions and location of injection) were studied. From the reported results, the following conclusions were drawn:

- The measurements are independent of the height of the bed and the lance diameter.
- The lower $V_r$ is, the higher the mixing efficiency (width of the jet) is.
- For $V_r = 0.625$, the width of the jet is approximately 0.4 m as double value of its width at $V_r = 0.06$.
- The location of injection has a great influence on the mixing efficiency profiles in the bed. Moreover, the mixing displacement is wider than that with a low volume ratio.
- The jet penetration and widths only depend on the ratios of the two flows, not on their absolute value.
- The shape of the jet is independent from the lance location.
- The simulation results and measurement results are in a good fit.

REFERENCES

15. S. Bu, J. Yang, Q. Dong, Q. Wang, Experimental study of mass transfer and flow transition in simple cubic packings with the electrochemical technique, Electrochimica Acta, Available online 1 February 2015.
22. M. Hatch, W. Sowa, G. Samuelsen, Geometry flow influences on jet mixing I a cylindrical duct, Journal of