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Comparative scaling analysis of two different sized pilot-scale fluidized bed reactors operating with biomass substrates

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ABSTRACT

This paper presents a comparative scaling analysis of two different sized pilot-scale fluidized bed reactors operating with biomass substrates. A multiphase Eulerian-Eulerian 2-D mathematical model was implemented, coupled with in-house user-defined functions (UDF) built to enhance hydrodynamics and heat transfer phenomena. The model validation was attained by comparison to experimental data gathered from both reactors. A grid refinement study was carried out for both geometries to achieve an appropriate computational domain. Hydrodynamics was deeply studied for both reactors concerning the scale-up effect. Mixing and segregation phenomena, solid particle distribution and biomass velocity were matters of great concern. Results showed that UDF implementation successfully minimized deviations and increased the model's predictability. The largest deviations measured between experimental and numerical results for syngas composition were of about 20%. Solids mixing and segregation was found to be directly affected by the particles size, density, and superficial gas velocity, with the larger reactor revealing improved mixing ability. Improved mixing occurred for smaller particles size ratio ($d_{biomass} = 3$ mm), smaller particles density ratio ($\rho_{biomass} = 950$ kg/m^3), and higher dimensionless superficial gas velocities (U_0/U_{mf}=3.5). The larger unit showed an increase in near-wall velocity, lateral dispersion, and bubble size. As for the smaller reactor, higher velocities were obtained at the center region due to a more pronounced wall boundary layer. Similarities were found between the two reactors regarding the bubble distribution, dimensionless average bed pressure drop and biomass velocity vector profiles when dimensionless parameters were employed.

1. Introduction

The frightening rate of manmade climate change has led to a global effort to find sustainable energy answers to overcome fossil fuels dependency [1,2]. Biomass has been mentioned as a feasible solution, capable of contributing to the world's energy demands that are currently dominated by fossil fuels [3,4]. In the European Union alone, biomass dominates renewable energy consumption with a 68% stake and a 95.5% share for heat only applications and reached 8.4% of the total energy consumption in 2011 [5]. By the year of 2050, the global biomass energy supply contribution is estimated to be around 160 to 270 EJ/year [6]. The biomass energy sector offers numerous routes for its energetic conversion, achievable by various thermo-chemical processes, namely combustion, pyrolysis and gasification [7–9]. Biomass gasification as a promising process which results in highly valuable products from an apparent useless raw material can be efficiently performed in fluidized bed reactors [10].

Fluidized bed scale-up is a rather complex process which goes beyond simple reactor size enlargement. Such procedures may not be governed by a pre-established set of simple mathematical equations which will deliver a solution for each particular scaling scenario [11]. However, it must obey a set of key factors governing this transition from small-scale to commercial-scale, namely, guidelines, scaling laws and validation tools [12]. When moving from a small-scale to a large-scale fluidized bed, a set of scale-dependent parameters change drastically, such as hydrodynamics (i.e. particles properties and bubble growth), heat transfer, and

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residence time, which in turn will affect the chemical reactions leading to a distinct syngas composition [12]. Also, different particle sizes behave differently when scaled-up [11]. The first well known scale-up failure happened in 1950 in Brownsville, Texas (USA), with a bubbling Fischer-Tropsch fluidized bed reactor, where a reactor was scaled from 0.305 m to 5 m in diameter. This consequential scaling resulted in a serious void size increase, residence time discrepancies and considerable yield loss. Operational behavior depends upon the bubble size and the higher velocities in the larger reactor, which in turn, will also directly influence the gas-solid interaction and the reactor performance [13]. Because of this, scale-up effects in fluidized bed reactors constitutes an engineering challenge [11–13].

Computational fluid dynamics (CFD) gives a helping hand in modeling the complex phenomena behind the scale-up process, minimizing experimental effort, avoiding drawbacks associated with building an actual system and preventing the inappropriate waste of capital resources. Most of the information found in the literature presents laboratory scale-reactors studies. Handy operating controls and lower capital costs come as the main reasons for their general usage. Industrial scale reactor studies are seldom conducted, given to its complicated control parameters and high operation costs [14].

A scale-up review of bubbling fluidized bed reactors was presented by Rüdisüli et al. [12]. The author provides guidelines for a successful fluidized bed scaling from laboratory to industrial scale, highlighting the reactor's hydrodynamics and chemical conversion changes during the procedure. An overall insight into the scale dependence of major reactor parameters was assessed. The dimensionless scaling method was found to be the most appropriate to use, and phenomena such as wall effects and particle-particle interactions must be taken into account.

Focusing on the hydrodynamics, Che et al. [15] explored the hydrodynamics of scale-up in a pilot-scale fluidized bed reactor. Meaningful hydrodynamic differences provoked by the scale-up were found during the first steps of the fluidization process. Also, gas and solid volume fractions showed considerable changes in the structure of the core region when scaled from a laboratory to a pilot plant size.

When a proper scaling rule is applied, dimensionless parameters reveal a good agreement between geometries. Wu et al. [16] followed this methodology by developing a CFD numerical model, employing a similarity method ruled by nondimensionalized governing equations. Hydrodynamics and heat transfer parameters were discussed for their influence on the fluidized bed scaling. Results showed reasonable similarities when dimensionless parameters were matched for the time-mean radial void distribution and heat transfer coefficients.

The scale-up effect with multiple fluidized bed reactor sizes was investigated by Lu et al. [17]. Fluidization characteristics such as flow structures, velocity distribution, and gaseous product mass fractions were compared versus experimental data from differently sized reactors. The hydrodynamics were reasonably predicted for the different sizes, however, the chemical behavior demonstrated increased disparity with increasing reactor size.

Couto and Silva [14] studied the potential of numerical models to properly predict the scale-up effect from a laboratory scale to a pilot-scale reactor. The authors analyzed the influence of operating parameters in both reactors and their result in the produced gas. Results showed higher gas residence time, temperature, syngas calorific value, carbon monoxide and hydrogen content, for the larger scale reactor, where residence time was found to have a major influence on the final product. Biomass characteristics such as volatiles concentrations and particle size were also strongly influenced.

This early study allowed the research group to determine the scale-up effect over the syngas composition, however, the analysis was based only considering the syngas composition with no particular analysis on hydrodynamics. In the present study hydrodynamics is the subject of major interest. Experimental data retrieved from two different sized pilot-scale reactors (75 kW_{th} and 250 kW_{th}) were used and compared in an attempt to add proper scale-up information to the limited data regarding biomass gasification in this matter.

This paper aims to study the scale-up biomass gasification in two different sized pilot-scale bubbling fluidized bed reactors. The numerical model, extended to the two different sized biomass gasifiers, was validated against experimental data gathered from biomass gasification runs in both reactors and fluidization curves for the 75 kW_{th} reactor. Both reactors hydrodynamics was studied focusing on the particle size, particle density, and superficial gas velocity. The additional influence of these factors was considered on the mixing and segregation phenomena. The solids volume fraction distribution and biomass velocity were also assessed for scale-up. The variations concerning the solids and gas distribution profiles were compared and discussed regarding the two fluidized bed geometry sizes.

2. Experimental setup

2.1. Description of fluidized bed reactors

The analysis was performed in two different sized bubbling fluidized bed biomass gasifiers, a 75 kW_{th} gasifier located at the University of Aveiro and a 250 kW_{th} gasifier located at the Polytechnic Institute of Portalegre. Fig. 1a and b display the comparative geometries of the aforementioned biomass gasification reactors.

The unit placed at the University of Aveiro resides in a 75 kW_{th} thermally insulated pilot-scale bubbling fluidized bed gasifier, with 0.25 m wide and 2.3 m height. 17 kg of quartz sand, with particles size range between 355 μm and 1000 μm, gives the bed a static height of 0.23 m. Dry atmospheric air enters throughout the distributor plate from the bottom of the bed. A pre-heating system heats this air stream before its injection into the gasifier vessel. A screw feeder placed at 0.30 m above the distributor plate, discharged the biomass into the reactor. Eight water-cooled probes arranged along the bed maintain the bed temperature within the desired range. Nine water-cooled sampling probes placed at different heights along the reactor (two immersed in the bed, and seven along the reactor freeboard) monitor the temperature and pressure inside the reactor.

The unit placed at the Polytechnic Institute of Portalegre is composed of a 250 kW_{th} tubular fluidized bed reactor, 0.5 m wide and 4.15 m height, internally coated with a ceramic refractory material. The bottom bed comprises 70 kg of quartz sand with a particle size range between 300 μm and 700 μm, and a static bed height of about 0.15 m. A screw feeder delivers the biomass into the reactor 0.4 m above the distributor plate, and preheated atmospheric air enters the reactor from the distributor plate throughout a set of diffusers, with a delivery flow of about 70 Nm^3/h.

2.2. Experimental conditions and syngas analysis

From the described biomass fluidized bed reactors, gasification runs with varying experimental conditions were performed. Table 1 shows the experimental operating conditions and the results for syngas composition analysis for the 75 kW_{th} pilot-scale reactor. Here, five experimental gasification runs using eucalyptus wood as fuel and atmospheric air as gasification agent were employed to acquire the syngas composition. The experimental