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Ecological Electricity Supply through CFB Boilers: Suggestion for Design Improvement

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The aim of this communication is to advocate for use of high density powders (more than 5000 kg/m^3) in experimental simulation of gas-particles flows of Circulating Fluidized Bed (CFB) boilers. These industrial facilities are used as ecological electricity suppliers with effective pollutants capture for a high thermal net efficiency. Usually, as illustrated by the results available in the literature, solid particles used for experimental simulation in the aim of industrial design of these plants are sand, glass beads or FCC (about 1200 kg/m^3 or less). We give here arguments for re-orientation of applied research in the field of energy production by CFB, suggesting that powders with higher density would lead to a better design of industrial facilities through more adapted similitude laws. Improving such technology is challenging since CFB plants are only at their second stage of development and could be advantageously combined to another ecological electricity supply technology based on gasification process of biomass.

The Question

Circulating Fluidized Beds (CFBs) combine the principle of fluidization with a circulating process. Circulation inside the boilers is obtained during combustion by forcing mixed inert-oxidizer gases through a solid inventory of fuel in the shape of powder. The circulating character of CFBs makes the particles of fuel crossing the furnace several times until full combustion. Depending on the gas velocity (or fluidization velocity), the fluidized beds refer to different kinds of flow regimes which obviously influence the combustion quality and consequently the energy production. The knowledge of the flow regimes and associated thermal exchanges is therefore fundamental.

Fluidized beds are employed in a wide variety of industrial applications such as combustors for electricity supply or chemical reactors. In many commercial applications, size of fluidized beds is large and they are operated at high temperature (more than 800°C) and pressure (several tens of bar). There must be an understanding of the fluid dynamics for the proper design of fluidized beds as directly influences the boiler performance. Designers are thus particularly concerned with the relationship between the performance of large commercial beds and the results obtained from much smaller pilot plants or experimental mock-ups: there is a critical need to understand and predict the fluid dynamics of large fluidized beds in order to optimize performance. This is provided by characterizing flow regimes and characteristic velocities for flow transitions.

However, on the one hand there is a dearth of relevant information available in the field of large commercial beds; on the other hand there is a large amount of data and approximate analytical models based on results from small experimental beds. But, these data are collected under a fairly restricted range of operating conditions and it is not obvious how the data can be applied to large commercial designs especially due to the powder characteristics used for experimental flows. Boilers, which are the main focus of the present communication, are normally operated with particles of group B (40 and 500 µm and particle density between 1400 to 400 kg/m^3) and group D (above 600 µm and particle densities above 2000 kg/m^3) in the Geldart classification. Boilers usually have a square or rectangular cross section and are wider than the height of the bottom bed. Experimental mock-ups are usually operated with light particles whereas to be representative of industrial beds, experimental plants and related materials must have certain particular similitude [1] among which is the ratio between the solid and gas densities. If similitude relationships match for most of them, the one regarding densities does not. In such conditions, what can be said about extrapolation of characterizing flow regimes and transition velocities from experimental to industrial cases? Are not there any possibilities to refine the similitude relationships?

Facts

The scientific literature proposes numerous correlations associated with regime transitions, most of them developed for non-circulating fluidized beds and then applied to Circulating Fluidized Bed (CFB). However, in some cases it is apparent that the authors disagree regarding the types of regime on either side of identified transitions. This can be due to the disparity of the geometrical aspect of CFBs (with particular reference to riser section) from one author to another, although the powder used and the operating conditions are very similar.

Bai and co-authors [2] stressed the need for clear identification of the fluidization regimes in the riser of a

CFB, to ensure better comprehension of the thermohydraulic context, and thus correctly design the loop. They emphasize the ambiguity of definitions proposed in the literature, both in qualitative and quantitative terms, and demonstrate a number of contradictions between theoretical predictions and experimental results.

Furthermore, the available correlations for CFBs have been developed for Fluid Catalytic Cracking (FCC) type powders which density is around 2000 kg/m^3 and for which extrapolated studies concern at least densities less than 5000 kg/m^3 [3]. For example, among the recent compilation made by Yang & Leu [4] gathering 29 experimental cases, only 2 of them involve powder density higher than 5000 kg/m^3 (less than 7% of all cases). As a consequence, extrapolation of fluidization regimes observations and results appears to be not so easy.

Yet, high density powders such as bronze are of interest since bronze and air present the same density ratio than ashes and hot gas on industrial CFB combustor plants. High density powder can thus help to work with better hydrodynamic similitude regarding density ratio whilst other similitude relationships remain satisfactory. Experimental identification of regime transitions for those types of gas/particle flow have been carried out in a CFB experimental loop (internal height of riser: 6.61m from the fluidization grid to the roof; square section: 0.175m x 0.175m) [5]. Analysis of pressure drop fluctuations in the riser to identify the various fluidization regimes and transition velocities [4], [6], [7-17] made it possible to show that gas/particles flows with high density powders (namely air/bronze) could positively be observed and described [5] in a similitude framework of industrial CFB boilers. Bronze and air presented the same density ratio than ashes and hot gas on industrial CFB combustor plants. Besides, visual observations were performed through the perspex walls of the riser in order to confirm fluidization regime transitions and a change of the two-phase flow behavior with changing fluidization velocity.

Furthermore, it was shown [5] that the transition flows such as onset of turbulent flow and choking limits could be successfully described with dense powder using established correlations for lower density powders: Yang & Leu's correlation [4] for onset of turbulent flow, Yang [18] and Bi et al. [19] correlations for choking limits.

Concluding Discussion

The disadvantages of extensive exploitation of the fossil fuel resources and its consequences have become obvious: “Rapid development of the human society over the last two centuries was based on the excessive and uncontrollable use of fossil, non-renewable energy resources. As modern society developed, the need for energy has grown bigger, while the reserves of the non-renewable energy resources have lessened” [20].

Nuclear electricity supply, despite its zero CO_2 production, and a high level of safety in operating companies [21], becomes quickly and easily unpopular in case of major accident due to its immediate consequences at the international level. “Fukushima woke up the world nuclear industry, not just the U.S.,” said in an interview Allison M. Macfarlane, chairwoman of the U.S. Nuclear Regulatory Commission.

In such an energetic context, alternative renewable and sustainable energy processes have to be found among which Circulating Fluidized Bed (CFB) technology have been identified. Its strengths are mainly related to the acceptance of a wide variety of fuels in terms of size and composition and to the possible additives to improve the conversion process [22, 23]. Yet, CFB technology is only at its second stage of development: compared to the first generation, facilities now provide a more efficient pollutants capture whereas the industrial process design has been simplified [24]. The most powerful generator is just giving less than half electric power of the biggest nuclear power reactor. To date, the operating temperature within the furnace lies between 800 and 900°C (compared with more than 1000°C in a nuclear reactor core). The first supercritical (and world's largest) CFB boiler was constructed by Foster Wheeler at the PKE's Lagisza power plant (Poland), successfully operated since early 2009, producing 460 MWe with a net efficiency of 43% [25].

To improve the concept of CFB boiler, refine experiments in good similitude design with industrial plants are needed.

Furthermore, CFB has been shown as the most suitable for another ecological electricity supply technology based on gasification process of biomass: “On the basis of the information presented above [the authors’ review] it can be concluded that at present [2011], the fluidized bed reactor complies the best with the requirements for the production of bio-syngas [a mixture of hydrogen, carbon monoxide and dioxide, gas water] for the synthesis of liquid transportation fuels via thermochemical gasification route” [22].

The growing environmental norms have augmented the development of the CFB boilers, inducing techno-economical challenges [25, 26] and, according to some analysts, this technology may drive the market with Supercritical CFBs and now Ultra Supercritical CFBs currently in their pilot phase and expected on the market by 2015 [23].

Indeed, knowledge of CFBs is worth to be refined. Our suggestion for design improvement is just one point. High density particles combined with air effectively help similitude relationships to match between industrial CFB boilers and experimental mock-ups: dimensionless quantities regarding mass ratio are improved compared with light powders and other dimensionless quantities required to describe the flow remain satisfactory.

Results in terms of correlations to describe the flow regimes and their transitions are satisfactory. High density particles appear to be a possibility to refine the similitude relationships and therefore the understanding, and consequently the improvement of CFB technology. We therefore promote use of high density powders (more than 5000 kg/m^3) in experimental simulation of gas-particles flows of Circulating Fluidized Bed (CFB) boilers. ■

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