Chapter 2
Approach

Keywords Fluidized-bed combustion · Metal wastage · Erosion · Design guidelines · Operating parameters · Design parameters · Computer programs · Hydrodynamics

The methodologies used to develop metal wastage guidelines and procedures are described in this chapter.

Parameters that are known to have or that are suspected of having an influence on metal wastage in fluidized-bed combustion (FBC) units are grouped into (1) those that are related to the design of the unit and (2) those that are related to the operation of the unit. Examples of the first group of parameters include tube size, tube spacing and pitch, tube bundle and fluidized bed height, distributor type, and heat exchanger tube material properties. Examples of the second group of parameters include fluidizing velocity, particle size and distribution, and particle hardness and angularity.

Each of the above parameters can be controlled by FBC designers and, therefore, can be considered independent. Another set of parameters, including solids velocity and flow patterns, bubble frequency, size and flow patterns, and pressure fluctuation frequency, is determined by the first set and, therefore, can be considered dependent. The interaction between the independent and dependent variables is shown in Table 2.1. A change in any one of the independent variables will likely result in changes in all of the dependent variables and perhaps in the amount of metal wastage as well.

The approach taken by the Cooperative Research and Development Venture referred to in the acknowledgments and presented herein has been to closely couple hydrodynamic and erosion modeling efforts with experimental activities at the participating organizations in order to provide hydrodynamic and erosion data that can be used to validate the models.

This approach adopted to develop metal wastage guidelines and scale up procedures can be summarized as follows:

R. W. Lyczkowski et al., *Thermo-Hydrodynamic Design of Fluidized Bed Combustors*, SpringerBriefs in Thermal Engineering and Applied Science,
DOI: 10.1007/978-1-4614-3591-4_2,

Table 2.1 FBC Metal wastage dependencies

Independent variables		Dependent variables		
Design parameters				
Tube size				
Tube spacing/pitch				
Tube bundle/bed height				
Tube inclination				
Height from distributor				
Type of distributor	→	Solids velocity	→	Metal wastage
		Bubble frequency		
Operating parameters		Bubble size		
		Bubble velocity		
Particle size/size distribution		Pressure fluctuations		
Particle shape/angularity		Bed porosity		
Particle hardness/density				
Fluidizing velocity				
Bed/tube temperature				
Chemical environment				

1. Apply hydrodynamic and erosion codes to generic and specific FBC geometries.
2. Simplify the models to their essential components and place them in dimensionless form.
3. Define input parameters for simplified models and correlations.
4. Develop procedures and recommendations for model calculations.
5. Develop calculation procedures to relate simplified models for any geometry.
6. Validate guidelines, procedures, and scaling.

As mentioned in Chap. 1, Argonne national laboratory (ANL) developed the FLUFIX/MOD2 computer code [1] to predict hydrodynamics in fluidized-bed combustors. This code is based on the hydrodynamic model of fluidization and can be used to predict frequency of bubble formation, bubble size and growth, bubble frequency and rise-velocity, solids volume fraction, and gas and solids velocities. The results of the hydrodynamic model are used as inputs to ANL's EROSION/MOD1 computer program, which contains various erosion models, [2, 3] including the monolayer energy dissipation (MED) erosion model developed by ANL [4, 5].

Babcock & Wilcox (B&W), with ASEA-B funding, in close collaboration with ANL, developed the FORCE2 [6] computer code, which is a three-dimensional transient and steady-state version of FLUFIX/MOD2 [1]. ANL then implemented the FORCE2 computer program on its mainframe vector, the so-called supercomputer at the time, CRAY X-MP/18 and performed quality assurance and validation using some of the experimental results [7]. Good agreement of the computed overall solids flow patterns, major porosity and pressure frequencies, bubble sizes and frequencies, and time-averaged porosity profiles with experimental data were achieved [2–5, 7–10].

Advanced graphics were implemented that served to speed up the validation process and to render the computer simulations more comprehensible to the users of the FLUFIX/MOD2, FORCE2, and EROSION/MOD1 computer programs [11] which are all available from the energy science and technology software center (ESTSC) [1, 2, 6].

Data on erosion rates at particle sizes, velocities, and loadings typically found in FBCs were obtained in the Ash Erosion Test Facility at ABB/CE [12]. In these experiments, sand and/or crushed quartz was dropped through a vertical tube onto a heated carbon steel target in order to determine the erosion rate as a function of particle size, loading, and impact velocity.

Other experiments sponsored by the consortium provided hydrodynamic and erosion data from several fluidized beds. Experiments at the Illinois institute of technology (IIT) measured fluctuating and time-averaged porosities in a thin, "two-dimensional," fluidized bed containing single obstacles of various shapes [8, 13]. A computer-aided particle tracking facility (CAPTF) was employed at the university of illinois at Urbana-champaign (UI-UC) to track the movement of a radioactive tracer particle in two- and three-dimensional fluidized beds containing single obstacles that were round, square, or rectangular in cross-section. Other experiments employed small arrays of round tubes immersed in the fluidized bed [14]. In addition, pressure fluctuations were measured at numerous locations in both two- and three-dimensional beds [10, 12–14]. Erosion measurements of tubes in the three-dimensional experiment were also performed [13]. The particle motion data were processed to provide direction and speed distribution information [12].

Experiments in a variable-thickness (thickness increased from thin, square to full between experiments), large-scale cold model fluidized bed at FWDC provided information on the significance of erosion data from experiments in small-scale fluidized beds [12, 15]. Metal wastage of tubes in small arrays were measured and compared with calculated erosion rates [13]. The simulation of experiments at FWDC forms a basis from which the sensitivity of metal wastage to changes in various parameters can be assessed.

A comparison of model predictions with other data reported in the literature has resulted in order of magnitude and better agreement with wastage rates and correct prediction of observed trends [2–5, 7, 13, 16]. The comparison of model predictions with data involves the simulation of each experiment to obtain detailed hydrodynamic and erosion predictions. Each simulation requires extensive computer time and subsequent analysis of the detailed computations in order to present results that can be directly compared with data. This type of analysis was necessary in order to validate the models and to develop confidence in their predictive capability and to provide insights used to simplify the models for design applications.

This Cooperative Research and Development Venture was the most comprehensive and integrated effort to identify the causes and remedies of metal wastage in FBCs. In fact, it was an international venture with the membership of the British Coal Corporation from the U. K. and CISE from Italy. Quite independently, Chalmers University of Technology in Sweden started an ambitious research effort circa 1990 to understand fluidized-bed hydrodynamics, heat transfer, and erosion in pressurized FBCs also coupled with numerical modeling. This effort, reviewed by Lyczkowski and Bouillard, [5] extended to about 2005 at which time economic and reorganization issues caused the program to be terminated and the equipment to be dismantled.

The group at Chalmers University of Technology was the first to adopt the MED erosion model to analyze their metal wastage experiments of in-bed cooling tubes. Recently He et al. [17] from the group at Harbin Institute of Technology in China have also adopted the MED erosion model to numerically simulate erosion, to compare with Chalmers erosion experiments, and to compare with the results reported by Lyczkowski and Bouillard [5]. In the years since the Cooperative Research and Development Venture, these are, to our knowledge, the only two major groups which have performed erosion simulations coupled with experiments. The reason for this is that erosion experiments require significant capital expense and long running times and the simulations are complex, requiring extensive and long running computations. However, with advances in computer speed, there continue to appear studies which perform two-and three-dimensional hydrodynamic simulations and comparison with fluidized-beds experiments containing tubes [18, 19].

A simplified, yet mechanistic, means of developing design guidelines is necessary to provide design engineers with easy-to-use procedures and to avoid the necessity of detailed computation for each design variation. Therefore, the detailed hydrodynamic and erosion models were distilled down to contain the essential parameters in dimensionless form. When results obtained using the simplified models were compared with the detailed model calculations, agreement was close. Thus, the simplified models can, with a small amount of hand calculation, capture the essence of the detailed models and provide the means for developing design guidelines.

The dimensionless erosion rates calculated using the simplified models can then be translated into erosion rates by using appropriate constants as shown in Chap. 3.

Because all of the parameters listed in Table 2.1 are not explicitly contained in the simplified model, a primarily empirical approach is taken in Chap. 5 to understand the influence of the design parameters on erosion. The empirical approach can, in principle, be validated by performing sensitivity studies using the detailed models. The simplified models can then be extended to incorporate the results of these sensitivity studies.

The subsections in Chaps. 4 and 5 are written as if the parameters are independent of each other, and the reader can refer to a specific subsection when seeking information on the influence of that parameter on erosion. Where there is significant interdependence between variables, the reader is cautioned not to neglect the effect of the other variables on erosion, Studies by Foster Wheeler Power Products [20] indicate that no single parameter is solely responsible for metal wastage, but rather the wastage in a particular location is related to a combination of the main parameters. Some parameters, principally fluidizing velocity, are more important than others. No simple remedy exists, and only by careful consideration of all the parameters, in the correct combination, can acceptable solutions be offered.

The discussions in each subsection of Chaps. 4 and 5 describe the data that were used to validate the guidelines and the limitations on the range of applicability. The final validation of the models and the guidelines developed from them will be achieved when they are compared with field data. In order to accomplish the final validation, some details of the hydrodynamics, as well as erosion, must be determined from units in the field.

Parameters that have uncertain effects on metal wastage and the remaining information gaps are identified in Chap. 7.

We consider this book to be a companion to Engel's [21] which is an excellent reference for single-particle erosion theory and data. However, it has long been out of print.

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