Chemical Engineering Journal 148 (2009) 41–49

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Effect of secondary fluidizing medium on hydrodynamics of gas–solid fluidized bed—Statistical and ANN approaches

Y.K. Mohanty [a,*], B.P. Mohanty [a], G.K. Roy [b], K.C. Biswal [b]

[a] Department of Chemical Engineering, G.I.E.T., Gunupur, Rayagada, Orissa 765022, India
[b] Department of Chemical Engineering, N.I.T, Rourkela, Orissa 769008, India

ARTICLE INFO

Article history:
Received 30 October 2007
Received in revised form 10 July 2008
Accepted 16 July 2008

Keywords:
Gas–solid fluidized bed
Fluctuation ratio
Expansion ratio
Artificial neural network
Factorial design

ABSTRACT

Investigations have been carried out in a cylindrical gas–solid fluidized bed to study the effect of secondary fluidizing medium on bed pressure drop, fluctuation and expansion ratios. Artificial neural network (ANN) and factorial design (statistical approach) models have been developed to predict pressure drop, fluctuation and expansion ratios with varying gas flow rates, bed heights, particle sizes and particle densities. The values of pressure drop, fluctuation and expansion ratios predicted by the developed models for primary, and simultaneous primary and secondary fluidizing media have been found to agree well with the corresponding experimental values. Owing to secondary air supply, the column is divided into two sections, viz., the upper and the lower. In order to improve the quality of fluidization and to increase its applicability, the fluidizer can be operated in higher velocity ranges, i.e., $G_f \geq 2G_{mf}$, in the case of simultaneous primary and secondary air supply.

1. Introduction

Fluidization is an established fluid–solid contacting technique, which finds extensive applications in combustion, gasification, carbonization, drying of solids, coating of objects and many other processes. With the flow of gas more than the minimum fluidization mass velocity, the top of the fluidized bed fluctuates considerably leading to instability in operation. The use of secondary air in fluidized bed offers several advantages, viz., creation of oxidation and reduction zone in the fluidized bed combustor, control over particle residence time, reduction of toxic gases like SO_X and NO_X in the flue gas, control over reaction rates, etc.

Many thermal power-generating units are, of late, increasingly following the concept of circulating fluidized bed and are using secondary air in the fluidizer for the improvement of quality of fluidization and combustion. Owing to the scarcity of good quality coal and an ever-increasing demand for electricity, for the complete combustion of low-grade coal, the introduction of secondary air is one of the best solutions. Several sponge iron units have been entangled with the problem of converting carbon into carbon dioxide. Bed fluctuation, expansion and pressure drop are interrelated with the fluidization quality. Out of the four important methods, viz., uniformity index, pressure fluctuation, fluctuation ratio and expansion ratio, the later three have been widely used to quantify fluidization quality.

Gas–solid fluidized bed, generally of aggregative nature, is marked by occurrence of bubbles of varied sizes. This results in a non-uniform bed expansion and a poor fluidization phenomenon. Keeping in view the aforesaid inherent drawbacks, the present study aims at investigating the influence of primary as well as simultaneous primary and secondary fluidizing media on bed pressure drop, fluctuation ratio and expansion ratio.

Davis [1] explained the statistical approach as one of the important methods for processing of experimental data due to its interaction effects among the variables and a less number of data are required for the development of model equations.

Ghosh and Saha [2] showed that the quality of bubble formation is strongly influenced by the type of distributor used. Wasserman [3] defined artificial neural network model as a computing system made up of a number of simple, highly inter-connected nodes or processing elements, which processes information by its dynamic system response to external inputs.

Buyevich and Kapbasov [4] worked out a mathematical model to treat random small-scale fluctuations of particles and fluid in a macroscopically uniform disperse mixture. Mastellone and Arena [5] studied the effect of particle size and density on solid distribution along the riser of a circulating fluidized bed and concluded that an increase in particle density from 1800 to 2600 kg/m^3 led to a higher solid concentration at the riser bottom.

* Corresponding author. Tel.: +91 9437372631.
E-mail address: yashobantkumar@yahoo.com (Y.K. Mohanty).

1385-8947/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2008.07.037

Nomenclature

ANN	artificial neural network
d_p	diameter of particle (m)
D_c	diameter of column (m)
G_f	mass velocity corresponding to fluidization (kg/m^2 s)
G_{mf}	mass velocity corresponding to minimum fluidization (kg/m^2 s)
G_p	mass velocity of the medium due to primary air = G_{mf} + 0.17 (kg/m^2 s)
G_s	additional mass velocity of the fluidizing medium due to secondary air (kg/m^2 s)
h_S	static bed height (m)
h_1	lower height of the expanded bed (m)
h_2	upper height of the expanded bed (m)
ΔP_{mfs}	pressure drop at minimum fluidization for secondary air supply (N/m^2)
r	fluctuation ratio
r_1	fluctuation ratio calculated through dimensional analysis approach at primary air supply
r_2	fluctuation ratio calculated through dimensional analysis approach at simultaneous primary and secondary air supply
r_p	fluctuation ratio calculated through factorial analysis approach at primary air supply
r_s	fluctuation ratio calculated through factorial analysis at simultaneous primary and secondary air supply
r_{cal}	fluctuation ratio calculated from the developed equations
r_{exp}	fluctuation ratio obtained from the experiments
R	expansion ratio
R_p	expansion ratio calculated through factorial analysis at primary air supply
R_s	expansion ratio calculated through factorial analysis at simultaneous primary and secondary air supply
R_{cal}	expansion ratio calculated from the developed equations
R_{exp}	expansion ratio obtained from the experiments
X_1, X_4	factorial design symbols

Greek symbols

ρ_f	density of fluid (kg/m^3)
ρ_s	density of solid particle (kg/m^3)

Grace et al. [6] studied the effect of high density (HDCFB) and low density (LDCFB) particles in a circulating fluidized bed and found that HDCFB systems offer significant advantages for reactions involving gas and particles, in particular, for low back mixing of gas and solids coupled with high solids loading and excellent gas particle contacting. Zhao et al. [7] proposed a model for determination and predictability of dynamics underlying pressure fluctuations by measuring and analyzing the time series of pressure signals at different locations in a bubble bed. Singh and Singh [8] predicted the expanded bed height and reported that the expansion ratio is a function of particle Reynold's number as well as fluid characteristics.

Kumar and Roy [9] found that correlations with dimensional analysis approach as well as ANN-models can satisfactorily be used for the prediction of bed expansion ratio. Tarelho Luis et al. [10] studied the effect of secondary air in a bubbling fluidized bed, for the combustion of bituminous and anthracite coal, and reported that due to less operational temperature the NO_X emission can be suitably controlled. The NO flue gas concentration is strongly determined by the secondary combustion zone.

Murthy and Chandra Sekhar [11] used statistical approach method and found that at minimum fluidization velocity the pressure drop and the power consumption decreases and increases respectively with increase in stirrer speed. Link et al. [12] reported results of a combined experimental and simulation study on the various regimes of a fluidized bed that the fluid particle drag obtained from lattice Boltzmann simulations is reasonably accurate for homogeneous systems.

Kumar and Roy [13] predicted a model equation by using statistical approach method for the bed fluctuation ratio as under:

$$r = 1.668 + 0.309X_1 + 0.173X_2 - 0.114X_3 + 0.112X_4 + 0.079X_1X_2 \quad (1)$$

Mohanty et al. [14] have found that a distributor plate having 10% open area of cross-section of the column cross-section gives better results (lower fluctuation and higher expansion) as compared to 6%, 8% and 12% open areas of cross-section. They also developed a model equation using factorial design method for pressure drop at minimum fluidization for only primary air supply as under:

$$\begin{aligned}\Delta P_{mf} = {} & 2.712 + 0.2437A - 0.0562B + 0.4625C + 1.525D \\ & + 0.1625AB + 0.1187AC + 0.1812AD + 0.1312BC \\ & - 0.0562BD + 0.65CD - 0.025ABC + 0.1625ABD \\ & + 0.1812ACD + 0.1312BCD - 0.025ABCD \quad (2)\end{aligned}$$

Mohanty et al. [15] studied the effect of secondary air on mixing and found that the introduction of secondary air into the bed enhances mixing as compared to both promoted and unpromoted beds. Instead of using any bed internals, the mixing can be enhanced through the use of secondary air. Cabral et al. [16] studied the pressure drop in a vibrating and non-vibrating fluidized bed and found that the pressure drop across the fluidized bed with no vibration is more than that at vibrating condition.

Fan et al. [17] proposed a dynamic model, which was based on the assumption that fluctuations of the bed height are affected by both the present and time delayed fluctuations of the gas flow rate through the distributor. The dominant frequency of pressure fluctuations in a fluidized bed corresponds to the marginal frequency of bed instability. Narvaez et al. [18] studied biomass gasification with air in an atmospheric bubbling fluidized bed, 6 cm in internal diameter and found that the use of secondary air improves the quality of raw gas produced and reduces the tar yield.

The objective of the present work is to understand the hydrodynamics of both primary and simultaneous primary and secondary air supplies and to increase its applicability in fluidized bed. A mathematical model has also been developed for determining pressure drop at minimum fluidization, fluctuation and expansion ratios. Many researchers have developed different methods for the calculation of pressure fluctuations, whereas a very little literature is available on fluctuation ratio and expansion ratio. Computing through neural networks is one of the recently growing areas of artificial intelligence. It is also evident from the literature that the ANN approach can be suitably applied for the calculation of the same. In the present case, a software package for artificial neural network in Mat Lab [19] has been used for ANN simulation. A typical three layers, viz., (i) input (I), (ii) hidden (H) and (iii) output

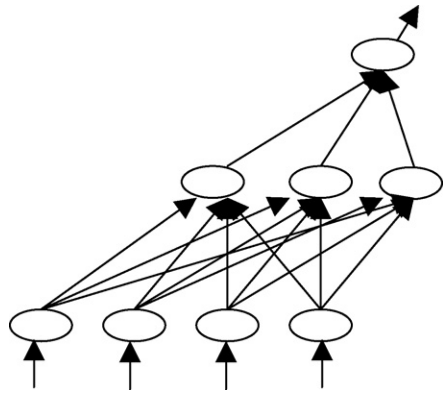

Fig. 1. A typical three layer Neural Network.

(O) have been chosen. Four nodes in the input layer, three neurons in the hidden layer and one node in the output layer have been taken as shown in Fig. 1.

2. Material and method

2.1. Experimental

The experimental set-up consists of an air compressor of capacity 1297 kPa, an air accumulator for storage of air at constant pressure and a silica gel column placed after the accumulator to arrest moisture. The schematic representation of the experimental set-up is given in Fig. 2. Two rotameters (one for primary air and the other one for secondary air) have been used to measure the airflow rates. The calming section consisting of a cylindrical portion followed by a truncated conical bottom (which is filled with glass beads of diameter 5 mm for uniform distribution of gas) and a distributor plate having a free area of 10% of the column cross-section is fixed at its top.

The fluidizer is a transparent Perspex column 99 mm in internal diameter and 960 mm in height, with one of its ends fixed to the Perspex flange. Two pressure tappings have also been provided with to measure the bed pressure drop through a differential manometer filled with carbon tetrachloride.

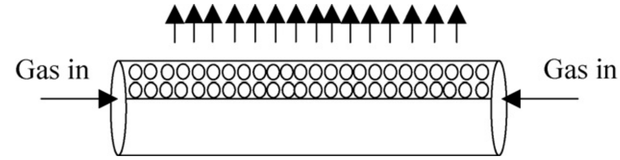

Fig. 3. Schematic representation of air distributor for secondary air supply, 1 mm in orifice diameter and 2.0 mm in pitch.

2.2. Procedure

The method of experimentation is based on statistical design of experiments (Factorial Design and Analysis) in order to bring out the interaction effects of variables, which would not be otherwise found by conventional experimentation, and to explicitly find out the effect of each of the variables quantitatively on the response. Four different bed materials, viz., dolomite, sand, refractory brick and coal have been considered for the experimentation. Out of which, coal and dolomite have been considered for the calculation of the model equations, as these two have the lowest and highest densities respectively. Apart from this, particles of sizes 0.00055 and 0.0017 m, bed heights 0.08 and 0.14 m, and mass velocities at the lowest and the highest ranges have been considered for the development of the mathematical model. It has been observed that all the different particles in the bed start to fluidize at different mass velocities called minimum fluidization mass velocity.

Experiments have been carried out by supplying primary air from below and secondary air [which is only a fraction (a maximum of 0.2) of the primary air supplied through the side ports of column at different heights of the column, i.e., 30%, 50% and 70% of each static bed] through a pipe having fine holes directed only towards the top of the column like a sparger pipe (1 cm in internal diameter) as shown in Fig. 3. The experiments have been carried out up to 2.5 times the minimum fluidization mass velocity with a continual increment of 0.085 kg/m^2 s. The flow of secondary air begins after the bed starts to fluidize due to primary air supply through the bottom of the fluidizer. It has been observed that the secondary air exerts an axial thrust on the bottom of the bed and owing to this effect, the primary air supply is maintained at more than the minimum fluidization mass velocity, i.e., G_{mf} + 0.17 for all the experiments (experimentally found). If this extra amount of primary air (0.17 kg/m^2 s) is not supplied, then the lower half of the bed will

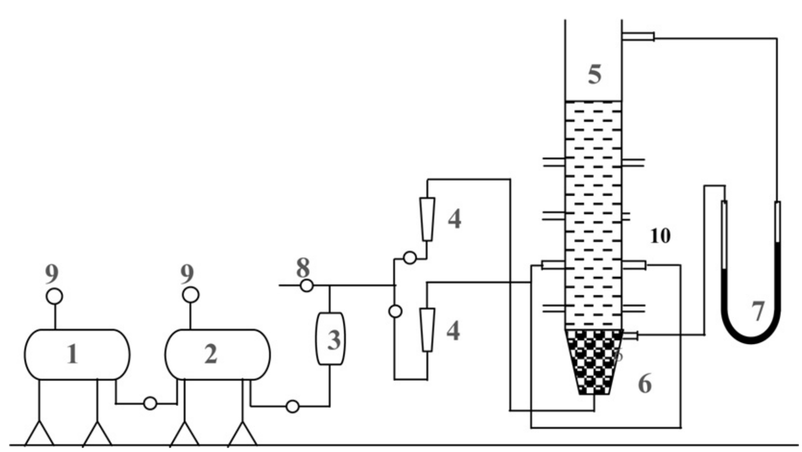

Fig. 2. Schematic representation of the experimental set-up: (1) compressor (2) storage tank (3) silica gel column (4) rotameter (5) fluidizer (6) calming section (7) manometer (8) valve (9) pressure gauge (10) side ports for secondary air (8-No.s).

Table 1
Scope of the experiment

Properties of the bed materials					
Materials			$d_p \times 10^3$ (m)		$\rho_s \times 10^{-3}$ (kg/m^3)
Dolomite			0.55, 0.725, 1.3, 1.7		2.817
Sand			0.55		2.61
Refractory brick			0.55, 0.725, 1.3, 1.7		2.5
Coal			0.55, 0.725, 1.3, 1.7		1.6
Density of fluid (ρ_f)				1.18 kg/m^3 at 25 °C	
Diameter of column (D_c)				0.099 m	
Bed parameter					
Initial static bed height, $h_s \times 10^2$ (m)				8, 10, 12, 14	
Flow property					
Materials	A	$B \times 10^{-3}$	$C \times 10^2$	D (G_f/G_{mf})	D (G_p/G_s)
Coal	0.808, 1.414	1.356	0.55	1.2, 1.6	1.7, 5.77
Coal	0.808, 1.414	1.356	1.7	1.2, 1.6	1.7, 5.77
Dolomite	0.808, 1.414	2.387	0.55	1.2, 1.6	1.7, 5.77
Dolomite	0.808, 1.414	2.387	1.7	1.2, 1.6	1.7, 5.77

not fluidize properly, i.e., the bed will behave like a fixed bed. For any bed material this is the minimum required extra amount of air that has to be supplied in addition to the amount of minimum fluidization mass velocity, i.e., G_{mf}.

Experiments have been carried out under two different conditions, viz.,

(i) Primary air supply and
(ii) Simultaneous primary and secondary air supplies.

The variables affecting pressure drop, fluctuation ratio and expansion ratio are static bed height, particle density, particle size and mass velocity of air. The scope of the experiment is presented in Table 1. The total number of experiments required at two levels (minimum and maximum) for four variables are ($2^n = 2^4 = 16$; n = number of variables/dimensionless parameters) sixteen for responses in the case of factorial design method. Each experiment is repeated three times and the arithmetic average of three values is reported as response value. The various values of a factor examined in an experiment are known as levels. The set of levels of all factors employed in a given trial is called the treatment combination. The treatment combination gives a full description of the conditions under which the trial is carried out, so far as these are affected by the various factors being studied. The numerical result of a trial based on a given treatment is called the response corresponding to that treatment.

3. Development of models

The fluctuation ratio (r) is defined as the ratio of highest to the lowest bed heights of the fluidized bed in expansion, i.e., $r = h_2/h_1$. The expansion ratio (R) is defined as the ratio of average of highest

Table 2
Factorial design and analysis data

S. no.	Name of the variable	Variable general symbol	Factorial design symbol	Minimum level (−1)	Maximum level (+1)	Magnitude of variables
1	Static bed height	h_s/D_c	A	0.808	1.414	0.808, 1.01, 1.212, 1.414
2	Density	ρ_s/ρ_f	$B \times 10^{-3}$	1.356	2.387	1.356, 2.118, 2.211, 2.387
3	Average particle size	d_P/D_c	C	0.0055	0.017	0.0055, .00732, 0.013, 0.017
4	Mass velocity	G_f/G_{mf}	D	1.2	1.6	1.05–3.0
		G_p/G_s		1.7	5.77	0.875–22.0

Table 3
Analysis of fluctuation ratio (r) and expansion ratio (R) data

A	B	C	D (G_f/G_{mf})	r_p exp	D (G_p/G_s)	r_s exp	D (G_f/G_{mf})	R_p exp	D (G_p/G_s)	R_s exp	D (G_p/G_s)	$\Delta P_{mfs}/100$
0.808	1.356	0.0055	1.2	1.052	1.7	1.2	1.2	1.218	1.7	2.062	4.5	1.4
1.414	1.356	0.0055	1.2	1.075	1.7	1.23	1.2	1.082	1.7	1.553	4.5	1.675
0.808	2.387	0.0055	1.2	1.11	1.7	1.2	1.2	1.187	1.7	2	4.5	2.52
1.414	2.387	0.0055	1.2	1.133	1.7	1.24	1.2	1.142	1.7	1.803	4.5	2.85
0.808	1.356	0.017	1.2	1.157	1.7	1.102	1.2	1.281	1.7	2.562	4.5	1.65
1.414	1.356	0.017	1.2	1.138	1.7	1.121	1.2	1.375	1.7	2.5	4.5	1.75
0.808	2.387	0.017	1.2	1.075	1.7	1.088	1.2	1.206	1.7	2.937	4.5	3.87
1.414	2.387	0.017	1.2	1.091	1.7	1.105	1.2	1.262	1.7	2.142	4.5	4.25
0.808	1.356	0.0055	1.6	1.13	5.77	1.13	1.6	1.531	5.77	1.468	5	1.38
1.414	1.356	0.0055	1.6	1.117	5.77	1.17	1.6	1.285	5.77	1.225	5	1.625
0.808	2.387	0.0055	1.6	1.175	5.77	1.14	1.6	1.562	5.77	1.406	5	2.5
1.414	2.387	0.0055	1.6	1.133	5.77	1.205	1.6	1.142	5.77	1.339	5	2.75
0.808	1.356	0.017	1.6	1.121	5.77	1.17	1.6	2.187	5.77	1.562	5	1.55
1.414	1.356	0.017	1.6	1.12	5.77	1.2	1.6	2.196	5.77	1.571	5	1.7
0.808	2.387	0.017	1.6	1.129	5.77	1.2	1.6	2.062	5.77	1.656	5	3.65
1.414	2.387	0.017	1.6	1.058	5.77	1.25	1.6	1.875	5.77	1.41	5	3.95

Columns indicating A, B and C are common.

and lowest bed heights to the static bed height for a particular gas flow rate, i.e., $R=(h_2+h_1)/2h_s$.

In this work, a mathematical model has been developed for the prediction of bed pressure drop, fluctuation ratio and expansion ratio. The model equations are assumed to be linear and the equations take the general form:

$$Y = a_0 + a_1A + a_2B + a_3C + a_4D + \cdots + a_{12}ABD + a_{13}ACD + \cdots + a_{15}ABCD \quad (3)$$

where Y stands for pressure drop, fluctuation ratio and expansion ratio; A, B, C and D are the factorial design symbols.

The coefficients are calculated by the Yate's technique

$$a_i = \sum \frac{\alpha_i y_i}{N} \quad (4)$$

where a_i is the coefficient, y_i is the response, α_i is the level of variables and N is the total number of treatments (Kumar and Roy [13], Davis [1]).

The experimental data based on factorial design, nature of the effects and its analysis are presented for fluctuation and expansion ratios in Tables 2 and 3 respectively.

The levels of variables for primary as well as simultaneous primary and secondary air supplies have been calculated from Table 2 as:

$$\left.\begin{array}{l}
\text{Level of static bed height} = \dfrac{A-1.111}{0.303} \\
\text{Level of density} = \dfrac{B-1.871}{0.515} \\
\text{Level of particle size} = \dfrac{C-0.01125}{0.00575} \\
\text{Level of mass velocity} = \dfrac{D-1.4}{0.2} \quad \text{(For fluctuation and} \\
\quad \text{expansion ratios in the case of primary air supply only)} \\
\text{Level of mass velocity} = \dfrac{D-3.735}{2.035} \quad \text{(For fluctuation and} \\
\quad \text{expansion ratios in the case of simultaneous primary} \\
\quad \text{and secondary air supply)}
\end{array}\right\} \quad (5)$$

The effect of a factor is the change in response produced by a change in the level of a factor. When a factor is examined at two levels only, the effect is simply the difference between the average response of all trials carried out at the first level of the factor and that of all trials at the second level.

Eqs. (6) and (7) have been developed for fluctuation and expansion ratios respectively for primary air supply. Similarly, Eqs. (8)–(10) have been developed for fluctuation ratio, expansion ratio and pressure drop at minimum fluidization respectively for simultaneous primary and secondary air supplies.

$$r_p = 1.113 - 0.0052A - 0.00037B - 0.0022C + 0.0095D - 0.004AB - 0.004AC - 0.01AD - 0.022BC + 0.02BD - 0.0136CD - 0.0003ABC - 0.008ABD + 0.002ACD + 0.008BCD - 0.004ABCD \quad (6)$$

$$R_p = 1.474 - 0.0565A - 0.0466B + 0.204C + 0.2573D - 0.0216AB + 0.0493AC - 0.0489AD - 0.0363BC - 0.023BD + 0.1459CD - 0.009ABC - 0.0245ABD + 0.009ACD - 0.007BCD + 0.006ABCD \quad (7)$$

Table 4
Selected structures of ANN-models

Net train parameter	500 (for 'r' and 'R') and 100 (for pressure drop)
Percentage set learning rate	0.2–10
Net train parameter learning	0.2–10
Percentage set error goal	0.001
Net train parameter epochs	50,000
Performance	$0.02368/1e^{-005}$

Bed particular	Input nodes	Hidden nodes	Output nodes	No. of cycles
Primary air	4	3	1	50,000
Secondary air	4	3	1	50,000

$$r_s = 1.172 + 0.0181A + 0.0065B - 0.0174C + 0.01118D + 0.003AB - 0.003AC + 0.0049AD - 0.0003BC + 0.0215BD + 0.0393CD - 0.001ABC + 0.002ABD + 0.0005ACD + 0.004BCD + 0.0004ABCD \quad (8)$$

$$R_s = 1.824 - 0.1318A + 0.0118B + 0.2177C - 0.37D - 0.0312AB - 0.004AC + 0.0635AD - 0.018BC - 0.013BD - 0.1226CD - 0.0982ABC + 0.021ABD + 0.014ACD + 0.003BCD + 0.0383ABCD \quad (9)$$

$$\Delta P_{mfs} = 2.441 + 0.1268A + 0.85B + 0.3543C - 0.0537D + 0.03AB - 0.01AC - 0.008AD + 0.2831BC - 0.0262BD - 0.03CD + 0.023ABC - 0.011ABD + 0.005ACD - 0.02BCD - 0.005ABCD \quad (10)$$

In the present communication, the ANN-model based on supervised feed forward neural network with back propagation algorithm for the calculation of pressure drop, fluctuation ratio and expansion ratio in the case of primary air and simultaneous primary and secondary air have been developed. Factorial design techniques are used initially to represent the dependent and independent variables/parameters through model equations. Later on an ANN-model is developed to test these data for its authentication. In all the cases, a three layer feed forward ANN structures (Input layer × Hidden layer × Output layer) have been tested at constant epochs (cycles), learning rate, error goal and net trained parameter. The selected structures of the ANN-model are considered for the training of the input and output (after normalizing the data, i.e., values in the range of 0.1–0.999) data in each case as shown in Table 4. The network is trained for a given set of input and target data sets. These data were obtained from the experimental observations. The network is trained with 500 data sets in the case of fluctuation and expansion ratios, but 100 data sets for pressure drop (in case of pressure drop less data are available, because pressure drop remains constant after minimum fluidization condition is reached).

The data were scaled down and then the network was exposed to those scaled data sets. The network weights were updated using the back propagation algorithm. The algorithm is implemented using MAT LAB [19] programming language. In this back propagation the network corrects its weights to decrease the observed error as described by Kumar and Roy [9] and Wassermann [3]. The network structure together with the learning rate was varied to obtain

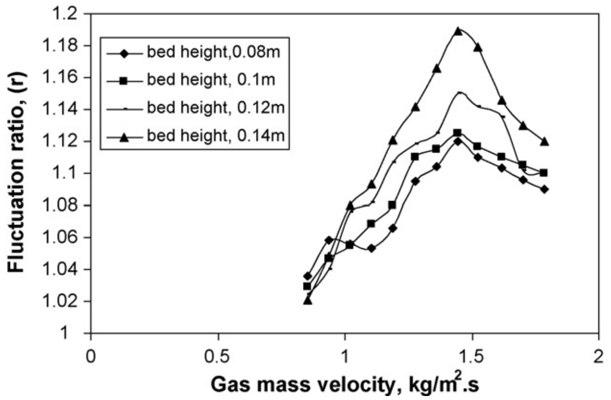

Fig. 4. Effect of bed height on fluctuation ratio for primary air for dolomite of size 0.000725 m.

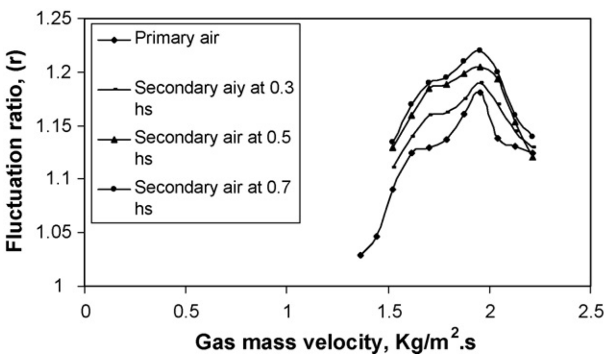

Fig. 5. Effect of primary and simultaneous primary and secondary air on fluctuation ratio for dolomite of size = 0.0013 m and bed height = 0.12 m.

an optimum structure with a view to minimize the mean percentage set error goal to 0.001. The training data sets were impressed repeatedly for a maximum of 50,000 numbers of epochs till the percentage set error goal is achieved. The network with the weights obtained from the training is now exposed to the prediction data set and thereby 500 (for fluctuation and expansion ratios) and 100 (for pressure drop) sets of output data were computed. Then the out put data were multiplied with the normalized data to get the final out put.

4. Results and discussion

Fluctuation ratio increases with an increase in bed height as evident from Fig. 4, up to about twice the minimum fluidization mass

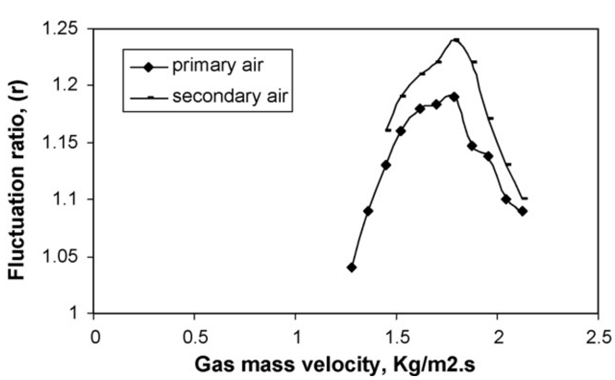

Fig. 6. Effect of primary and simultaneous primary and secondary air (at the middle of the bed) on fluctuation ratio for coal of size = 0.0017 m and bed height = 0.1 m.

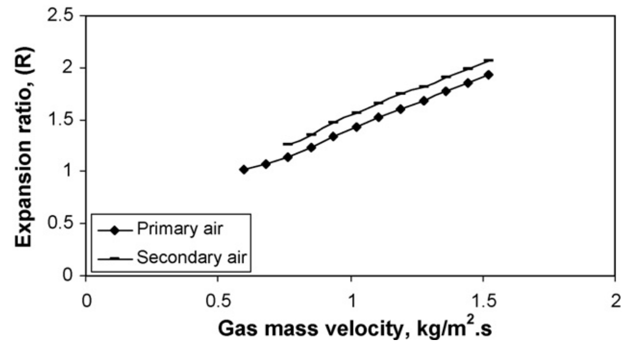

Fig. 7. Effect of primary and simultaneous primary and secondary air on expansion ratio for sand size = 0.00055 m bed height = 0.14 m (secondary air introduced at 70% of the static bed).

velocity and then reduces a little at higher mass velocities, as gas bubbles break up at greater heights (after achieving the column diameter). In lieu of taking only the primary air supply, additional secondary air has also been supplied to improve the mixing of particles by creating greater turbulence in the bed (Mohanty et al. [15]). Initially with only primary air supply, the bubbles grow at normal rates when they detach from the distributor plate and then burst when it achieves the column diameter. But due to the introduction of secondary air, the bed is divided into two sections each of about 50% by weight. The entire bed is supported by the primary air, while the upper section (about 50% by weight) by the secondary air. As the secondary air exerts an axial thrust on the lower portion of the bed, for which the lower level, i.e., h_1 maintains a lower value whereas the value of h_2 remains almost unchanged. Hence, fluctuation ratio is more in the case of simultaneous primary and secondary air supply. Owing to the fact that lowering of weight of the bed material (because the upper portion of the bed is supported by secondary air) being supported by the primary air predominates over the effect of early bursting of the bubbles due to secondary air, the fluctuation ratio is more in the case of secondary air supply as evident from Figs. 5 and 6. This phenomenon is obtained up to $G_f \geq 2G_{mf}$ and thereafter due to bursting of bubbles, the fluctuation ratio first decreases and then remains approximately same with that under only primary air supply condition. It is also observed that with an increase in the height of the secondary air inlet (above 50% of the static bed) the fluctuation ratio increases (due to higher value of h_2).

The fluctuation ratio, expansion ratio and pressure drop at different conditions (primary air and simultaneous primary and secondary air) can be calculated by using Eqs. (11)–(15), which are obtained after neglecting the smaller coefficients of Eqs. (6)–(10)

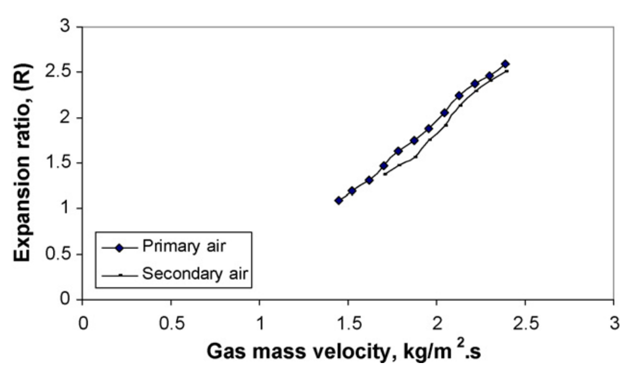

Fig. 8. Effect of primary and simultaneous primary and secondary air on expansion ratio for refractory brick of size = 0.0013 m bed height = 0.1 m (secondary air introduced at 50% of the static bed).

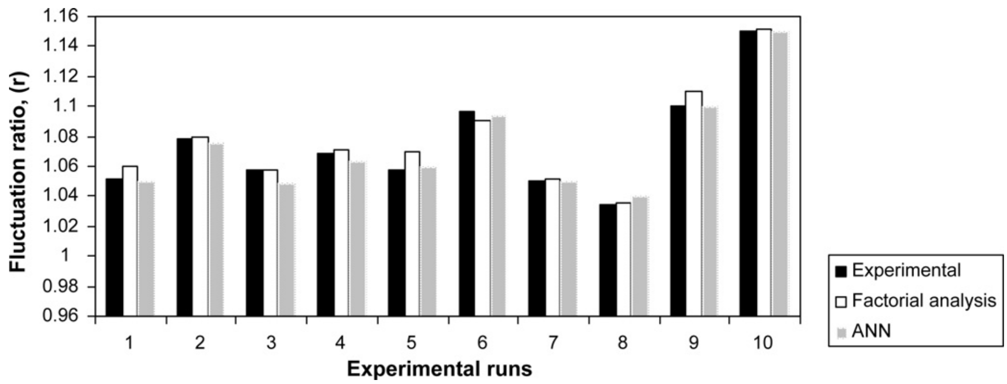

Fig. 9. Comparison of fluctuation ratio for primary air supply.

respectively.

$$r_p = 1.113 - 0.0052A - 0.00037B - 0.0022C + 0.0095D - 0.01AD - 0.022BC - 0.0136CD \quad (11)$$

$$R_p = 1.474 - 0.0565A - 0.0466B + 0.204C + 0.2573D - 0.0216AB + 0.0493AC - 0.0489AD - 0.0363BC - 0.023BD + 0.1459CD - 0.0245ABD \quad (12)$$

$$r_s = 1.172 + 0.0181A + 0.0065B - 0.0174C + 0.01118D + 0.0215BD + 0.0393CD \quad (13)$$

$$R_s = 1.824 - 0.1318A + 0.0118B + 0.2177C - 0.37D - 0.0312AB + 0.0635AD - 0.1226CD - 0.0982ABC + 0.0383ABCD \quad (14)$$

$$\Delta P_{mfs} = 2.441 + 0.1268A + 0.85B + 0.3543C - 0.0537D + 0.03AB + 0.2831BC - 0.0262BD - 0.03CD \quad (15)$$

The expansion ratio is more in the case of secondary air as compared to that in primary air, when secondary air is introduced at 70% of the static bed as is evident from Fig. 7. It is attributed to the fact that h_2 has got a higher value in the case of secondary air. On the contrary, Fig. 8 reveals that the expansion ratio is less in the case of secondary air as compared to primary air when the secondary air is introduced at 50% of the static bed, which is due to an axial thrust by the secondary air on the bottom part of the bed thereby leading to a lower value of h_1 and negligible change in h_2. It has also been observed during experimentation that the introduction of secondary air below 50%, i.e., at 30% of the static bed makes the expansion ratio less.

It is also evident from Eqs. (11) and (13) that the mass velocity has a larger effect on fluctuation ratio than on bed height, density and particle size for primary as well as simultaneous primary and secondary air supplies. The fluctuation ratio increases with an increase in mass velocity but decreases with increase in particle size and density in the case of only primary air supply as evident from Eq. (11). Whereas in the case of simultaneous primary and secondary air supplies, the fluctuation ratio increases with an increase in static bed height, density and gas mass velocity, and decreases with an increase in particle size as evident from Eq. (13). The predicted values of fluctuation and expansion ratios using ANN and statistical approaches have been compared with the experimental values for primary (Figs. 9 and 11) as well as simultaneous primary and secondary air supplies as shown in Figs. 10 and 12. It has been observed that both ANN and statistical approaches hold good for the entire mass velocity range, which is an authentication to the developed model and experimentation.

It is also evident from Eq. (12) that in the case of only primary air supply, mass velocity and particle size is direct functions of expansion ratio but static bed height and density are inverse functions of it. Whereas Eq. (14) represents that in the case of simultaneous primary and secondary air supply, expansion ratio varies inversely with mass velocity and static bed height but directly with density and particle size. It shows from Eq. (15) that static bed height, density and average particle size are direct functions of pressure drop. In case of interaction effects, the dominating parameter (higher

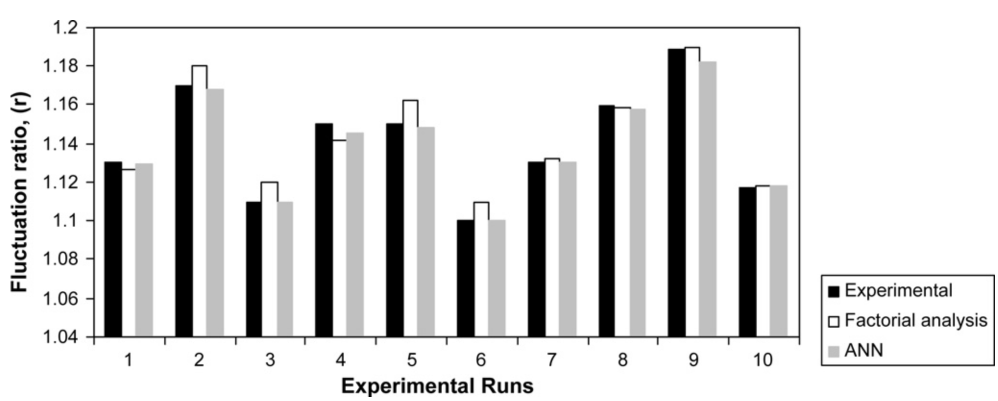

Fig. 10. Comparison of fluctuation ratio for simultaneous primary and secondary air supply.

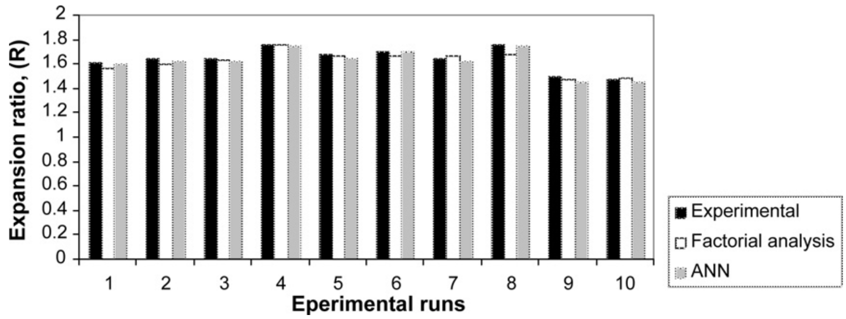

Fig. 11. Comparison of expansion ratio for primary air supply.

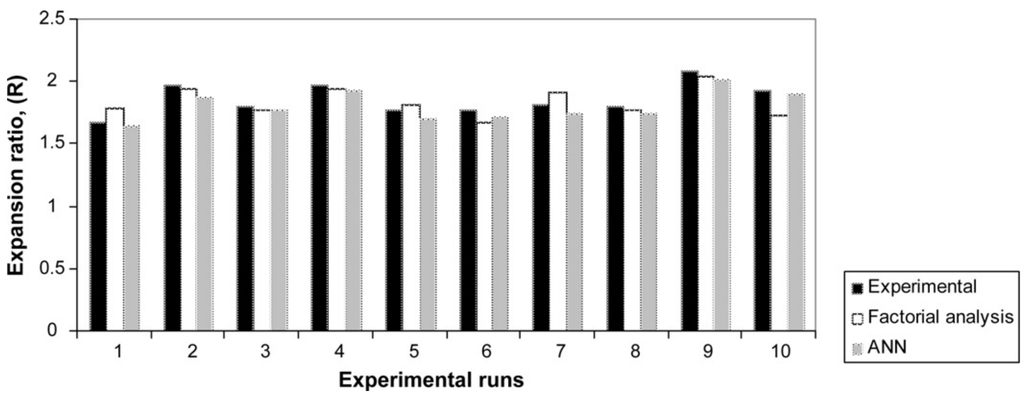

Fig. 12. Comparison of expansion ratio for simultaneous primary and secondary air supply.

coefficient of *A*, *B*, *C* or *D*) will control the effect. With an increase in mass velocity, pressure drop first increases up to the minimum fluidization mass velocity (G_{mf}) and then remains constant in all the cases as evident from Fig. 13. It is also evident from the same figure that the pressure drop is more in the case of simultaneous primary and secondary air supplies as compared to only primary air supply. Furthermore, it is also observed that with a decrease in height of secondary air inlet, the pressure drop increases, which is due to an axial thrust on the bottom part of the bed and hence on the distributor plate. Fig. 14 represents a comparison of fluctuation ratio between experimental and ANN output values and the R^2 value indicated in this case is an authentication to the developed model.

For development of the model equations through factorial design approach, the intermediate values for the bed expansion have been considered in lieu of the largest one, i.e., for (+1) range, for both primary, and simultaneous primary and secondary air supplies. In the case of fluctuation ratio, the smallest and largest experimental values have been considered for the development of model equations. Owing to the fact that the fluctuation ratio first increases up to about twice the minimum fluidization mass velocity ($G_f \geq 2G_{mf}$), then decreases and or remains constant in some cases, but expansion ratio increases linearly with mass velocity. The values of fluctuation and expansion ratios obtained by the statistical approach compare well with their experimental counterparts as presented in Table 5.

The standard deviations for fluctuation and expansion ratios (in percentage) have been found to be ±4.37 and ±13.86 for primary, and ±6.03 and ±25.49 for simultaneous primary and secondary air supplies respectively for values other than those taken for the development of model equations. The standard deviation for pressure drop (in percentage) has been found to be ±14.16.

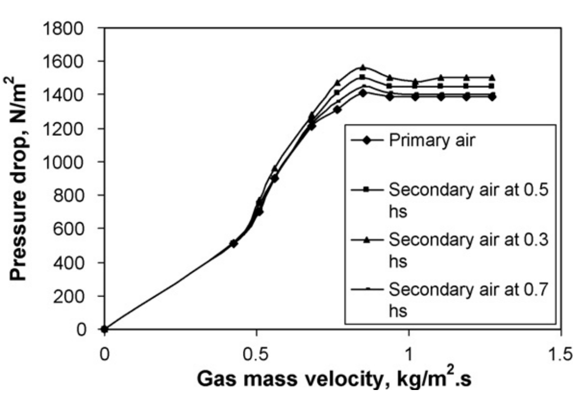

Fig. 13. Effect of primary air and secondary air on pressure drop for dolomite of size = 0.000725 m, static bed height = 0.1 m.

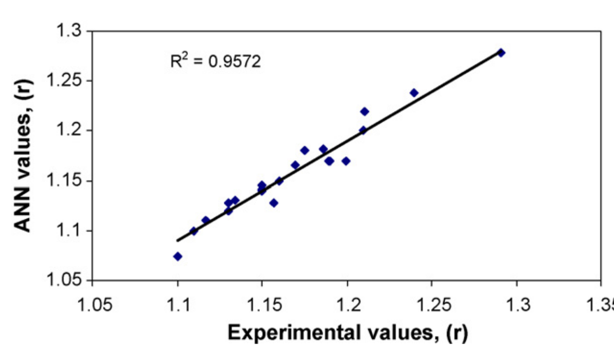

Fig. 14. Comparison of fluctuation ratio in the case of simultaneous primary and secondary air supply.

Table 5
Comparison of fluctuation ratio and expansion ratio calculated through factorial analysis approach

S. no.	$r_{p\ cal}$	$r_{p\ exp}$	$r_{s\ cal}$	$r_{s\ exp}$	$R_{p\ cal}$	$R_{p\ exp}$	$R_{s\ cal}$	$R_{s\ exp}$
1	1.065	1.052	1.126	1.2	1.204	1.218	2.101	2.062
2	1.075	1.076	1.162	1.23	1.085	1.082	1.554	1.553
3	1.109	1.11	1.114	1.2	1.223	1.187	1.996	2
4	1.118	1.133	1.150	1.24	1.116	1.142	1.762	1.803
5	1.131	1.157	1.170	1.102	1.294	1.281	2.517	2.562
6	1.141	1.16	1.206	1.121	1.369	1.392	2.488	2.5
7	1.087	1.075	1.158	1.088	1.169	1.206	2.930	2.937
8	1.097	1.125	1.194	1.105	1.256	1.214	2.177	2.142
9	1.131	1.13	1.202	1.13	1.521	1.531	1.473	1.468
10	1.101	1.117	1.238	1.17	1.305	1.285	1.248	1.225
11	1.175	1.17	1.240	1.14	1.547	1.562	1.381	1.406
12	1.144	1.25	1.276	1.205	1.146	1.25	1.332	1.339
13	1.144	1.08	1.090	1.205	2.190	2.281	1.554	1.562
14	1.113	1.06	1.126	1.17	2.167	2.321	1.543	1.571
15	1.100	1.103	1.128	1.2	2.071	1.906	1.676	1.656

5. Conclusions

For identical operating parameters, bed fluctuation and expansion ratios increase with an increase in mass velocity with the exception that expansion ratio decreases under simultaneous primary and secondary air supply conditions. Knowledge of fluctuation ratio and bed pressure drop in gas–solid fluidization is of importance in the design of fluidized bed reactors and combustors, specifically for the calculation of bed height. The above equations can be successfully utilized for the prediction of bed pressure drop, fluctuation and expansion ratios in the specified ranges of densities and particle sizes studied. The concept of secondary air may be made use of to reduce iron ore for production of sponge iron, sulfide ore, complete combustion of coal, etc., as part of industrial applications. Introduction of secondary air in the middle of each static bed height gives better results in terms of moderate pressure drop and fluctuation ratio.

Owing to greater turbulence, the bed provides a better contact between particles in the bed. The use of secondary air at different heights of the column will have a direct impact on residence time of the particle, pressure drop, fluctuation ratio and expansion ratio. It may be attributed to better mixing of particles of wide ranges of particle sizes and densities. The factorial design and ANN approaches can be suitably used for the prediction of pressure drop, fluctuation ratio and expansion ratio.

Acknowledgement

The authors are grateful to the Ministry of Human Resources Development, Govt. of India, for having provided the necessary financial support to carry out the above investigation.

References

[1] O.L. Davis, Design and Analysis of Industrial Experiments, second ed., Longman Publishers, 1978.
[2] A. Ghosh, R.K. Saha, Multiorifice distributor plates in a gas–solid fluidized bed, Ind. Chem. Eng. 29 (1987) 50–53.
[3] P.D. Wasserman, Neural Computing: Theory and Practice, first ed., Van Nastrank Reinhold, New York, 1989.
[4] A.Yu. Buyevich, S.H.K. Kapbasov, Random fluctuations in a fluidized bed, Chem. Eng. Sci. 49 (1994) 1229–1243.
[5] M.L. Mastellone, U. Arena, The effect of particle size and density on solids distribution along the riser of a circulating fluidized bed, Chem. Eng. Sci. 54 (1999) 5383–5391.
[6] J.R. Grace, A.S. Issangya, D. Bai, H. Bi, Situating the high density circulating fluidized bed, AIChE 45 (1999) 2108–2116.
[7] G.B. Zhao, J.Z. Chen, Y.R. Yang, Predictive model and deterministic mechanism in a bubbling fluidized bed, AIChE 47 (7) (2001) 1524–1532.
[8] S.P. Singh, A.N. Singh, Direct prediction of expanded bed height in gas–solid fluidization, Ind. Chem. Eng. 45 (2003) 268–272.
[9] A. Kumar, G.K. Roy, Artificial neural network-based prediction of bed expansion ratio in gas–solid fluidized beds with disk and blade promoters, Inst. Engrs. Ind. 85 (2004) 12–16.
[10] A.C. Tarelho Luis, A.A. Matos Manuel, J.M.A. Perira Fernando, Axial concentration profiles and NO flue gas in a pilot-scale bubbling fluidized bed coal combustor, Energy Fuels 18 (6) (2004) 1615–1624.
[11] J.S.N. Murthy, P. Chandra Sekhar, Studies on hydrodynamics of mechanically stirred fluidized beds—a statistical approach, Ind. Chem. Eng. 46 (2004) 84–89.
[12] J.M. Link, L.A. Cuypers, N.G. Deen, J.A.M. Kuipers, Flow regimes in a spout-fluid: a combined experimental and simulation study, Chem. Eng. Sci. 60 (2005) 3425–3442.
[13] A. Kumar, G.K. Roy, Statistical analysis of bed fluctuation ratio in gas–solid fluidized bed with rod promoter, Inst. Engrs. Ind. 86 (2005) 119–122.
[14] Y.K. Mohanty, K.C. Biswal, G.K. Roy, Effect of distributor area on the dynamics of gas–solid fluidized beds—a statistical approach, Ind. Chem. Eng. 49 (1) (2007) 1–10.
[15] Y.K. Mohanty, K.C. Biswal, G.K. Roy, Mixing characteristics of binary mixtures using promoters and secondary fluidizing medium, Powder Technol. online 11 February (2008).
[16] R.A.F. Cabral, J. Telis-Romero, V.R.N. Telis, J.R.D. Finzer, Effect of apparent viscosity on fluidized bed drying process parameters of guava pulp, J. Food Eng. 80 (4) (2007) 1096–1106.
[17] L.T. Fan, S. Hiraoka, S.H. Shin, Analysis of pressure fluctuations in a gas–solid fluidized bed, AIChE J. 30 (1984) 346–349.
[18] I. Narvaez, A. Orio, M.P. Aznar, J. Corella, Biomasa gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas, Ind. Eng. Chem. Res. 35 (1996) 2110–2120.
[19] Mat Lab Version, 6.5.0.180913a Release 13.