Particle Injection and Mixing Experiments in a One Quarter Scale Model Bubbling Fluidized Bed

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Abstract

One significant factor in the operation of a fluidized bed combustor is the manner in which coal particles disperse and mix with the bed material upon entering the bed. A thermal tracing technique was used to study the mixing characteristics in a 1/4 scale model of a pressurized bubbling fluidized bed combustor. Particles cooled by liquid nitrogen are injected into the bed in the same way that pulverized coal will be injected. An array of thermistors is mounted inside the bed. They are used to trace the path of the cooled particles as they enter the bed and mix with the other bed material. The approximate concentrations can also be determined since heat transfer from the cooled particles to the fluidizing gas is negligible during the course of the experiment. Time resolve images of the particle concentration show that the lateral motion of the injected particles is much greater than the lateral motion of an injected gas jet. The extended lateral motion is due to the substantial momentum of the injected particles.

Introduction

Bubbling fluidized bed combustors offer an alternative power generation technique that has several advantages over traditional pulverized coal combustors, including smaller boiler size and fewer harmful effects on the environment, such as a near complete elimination of sulfur dioxide emissions and a sizable reduction in nitrogen oxide emissions. One significant factor in the operation of a fluidized bed combustor is the manner in which coal particles mix with the bed particles upon entering the bed. This is a particular concern as the size of the units increase. Bubbling beds have a high particle concentration, making lateral mixing of coal feed particularly difficult. Although there have been considerable study of gas and liquid jet penetration and mixing in a fluidized there are very few studies of particle laden jets. In this paper, a thermal tracer technique was used to study the mixing characteristics in a one-quarter scale model of a pressurized bubbling fluidized bed combustor, the Tidd 70MWE plant in Brilliant, Ohio, that was operated by American Electric Power, Inc.

Apparatus

The mixing experiments carried out in this study made use of the one-quarter-scale, room-temperature, and one-atmosphere model of the Tidd plant. The constructed model matches to one-quarter scale all the linear dimensions of the actual bed (Figure 1). For scaling of a bubbling bed, Glicksman, et al. (1) showed that the following simplified set of dimensionless scaling parameters must be matched between the model and the actual plant:

$$\frac{\rho_s}{\rho_g}, \frac{U_0^{\,2}}{gD}, \frac{U_0}{U_{mf}}, \frac{L}{D}, \Phi_s, \textit{Particle Size Distribution} \qquad (1)$$

The model experiments were carried out with the bed fluidized with air at standard conditions while the combustor was operated at an elevated pressure. In order to match the solid to gas density ratio plastic particles were used in the model. Table 1 gives the dimensionless parameters used in the Tidd bed and the model.

Table 1. Dimensionless Parameters

DIMENSIONLESS PARAMETER	TIDD BED	MIT COLD MODEL
ρ_s / ρ_g	898	835
$U_0^{\,2} / gD$	0.025	0.025
U_0 / U_{mf}	3.8	3.8
L / D	geom. similar	geom. similar
Φ_s	0.82	0.85
PSD	matched	matched

Table 2 gives the dimensional values of the parameters used to obtain the correct dimensionless scaling ratios.

Table 2. Operating Parameters

OPERATING PARAMETER		TIDD BED	MIT COLD MODEL
temperature	T(K)	1135	311
abs. pressure	p(Pa-abs)	9.04×10^5	1.013×10^5
gas viscosity	kg/m-s	4.6×10^{-5}	1.9×10^{-5}
gas density	ρ_g (kg/m^3)	2.8	1.1
solid density	ρ_s (kg/m^3)	2513	918
particle sphericity	Φ_s	0.82	0.85
minimun fluidization velocity	Umf (m/s)	0.24	0.12
superficial gas velocity	U_0 (m/s)	0.91	0.46
bed dimension	D (m)	3.4	0.85
mean particle diameter	d (μm)	851	609

The dimensionless parameters match closely enough to achieve similitude between the two beds. Previous measurements on this model, Ferrell (2) indicated that results from experiments conducted on the model give an accurate representation of the results from the same experiments on the actual bed.

In the Tidd plant, pulverized coal is injected into a bed of crushed limestone, while in the model, a small amount of cryogenically cooled plastic bed particles is injected into a bed of plastic particles. A small amount of particles is suctioned from the bed into the injector body, figure 2, where they are cooled to about 100 degrees below the temperature of the bed. A foam-insulated trough is filled with liquid nitrogen in order to cool the particles in the injector tube well below the bed temperature. The injector tube is completely submerged in the liquid nitrogen. The particles remain in the injector long enough to reach the nitrogen temperature.

The cooled particles are injected into the bed under the horizontal tube bank in the same way that the pulverized coal is injected. The injected particles mix with the bed particles lowering the local particle temperature. An array of thermistors mounted on the inside of the bed is used to trace the path of the cooled particles and give a good indication of mixing between the injected particles and the bed material since heat transfer to the air is negligible for the short time period after injection. After a modest time period the bed returns to its initial temperature and another test can be performed. This technique eliminates the need to separate permanently marked tracers from the bed before further testing can be done.

The thermistors are arranged in a two-dimensional array in a plane that contains the centerline of the injector tube axis. Figure 3 illustrates the arrangement of the thermistors and the injector tube. The copper injection tube is lined up with the first row of thermistors and is always parallel to that row. The tube can be pulled back up to 14 cm from the first thermistor, all the way to the bed wall.

A high-speed camera was used to determine the speeds at which the particles entered the bed. The thermistors are monitored for 10 seconds after the particles are injected. Multiple runs at the same test conditions were made. Sufficient time was allowed between runs for the bed temperature to reach a uniform condition. For each thermistor, the temperature results at each time increment were averaged over the multiple runs. The temperature was non-dimensionalized as,

$$\theta(t) = \frac{T(t) - T_{BED}}{T_{INJECTION} - T_{BED}} \qquad (2)$$

where T_{BED} is the average bed temperature at that location before injection, T (t) is the temperature measured by thermistor at that location at time t after injection, $T_{INJECTION}$ is the temperature of the cooled particles in the injector as determined by the initial measurements of the thermistor adjacent to the injector exit.

Table 3 shows the test conditions in the model.

Table 3. Test Conditions in Model.

Data Set	Injection Speed	Superficial Velocity	Injection Point
MI	0.3 m/s	0.46 m/s	at thermistor 1
M2	0.3 m/s	0.23 m/s	at thermistor 1
M3	0.9 ms	0.46 m/s	at thermistor 1
M4	0.9 m/s	0.46 m/s	pulled back 7 cm from thermistor 1
M5	0.9 m/s	0.46 m/s	pulled back 14 cm from thermistor 1
EI	0.3 m/s	0.46 m/s	pulled back 14 cm from thermistor 1
E2	2.2 m/s	0.46 m/s	pulled back 14 cm from thermistor 1

A commercial plotting program, AXUM, using interpolation algorithms between the data points converted the 16 x 1000 array of data values into approximate contour plot of the dimensionless temperature, θ, distribution over the bed area at each time interval. Since heat transfer to the air is small and θ is proportional to the tracer concentration, the plots depict tracer concentration over the bed.

Results

For test conditions MI, M2, and M3, 20 runs were conducted for each condition. For conditions M4, M5, EI, and E2, seven runs were conducted for each. The temperature values at each thermistor were averaged to give an average temperature/time curve at each location. An average is more informative, since results from test to test varied due to the random bubble pattern in the region

The contours indicate roughly the behavior of the jet. No program gave entirely satisfactory results in the interpolations over the entire field. AXUM gave the fewest problems. Some places in the plots, namely where there are few thermistors, the interpolation algorithm gives incorrect contours. In a separate experiment, Glicksman and Farrell (3) determined the bubble rise velocity in the bed to be 0.5 m/s. Estimates of the momentum of the bubble wakes indicate that the injected particles should rapidly acquire the vertical velocity of the bubbles.

Figures 4 through 7 show results for test M3, with bed superficial velocity of 0.46 m/s (typical Tidd conditions) and injection velocity of 0.9 m/s. Over the roughly 50 ms interval depicted, at successive times, the tracers progress further into the bed both vertically and horizontally. The vertical displacement appears to be equivalent to the horizontal displacement. This is somewhat surprising, considering that the horizontal injection velocity is greater than the vertical bubble rise velocity.

Figures 8 and 9 show contours from M1 and M2 tests with injection velocity of 0.3 m/s, and superficial velocities of 0.46 m/s and 0.23 m/s, respectively. Due to the lower injection velocity, the horizontal displacement is much lower than the tests shown on figure 4 though 7. Note that both the vertical and horizontal displacement is lower for test M2 compared to test M1. M2 has a lower superficial gas velocity than M1 although they have the same injection velocity. It appears that the higher superficial bed velocity encourages horizontal displacement by the action of the bubbles, probably though bubble coalescences.

In test condition E2, figure 10, the injector was pulled back 14 centimeters to the bed wall, to allow study of the particles at greater distances from the injector. At the high injection velocity of 2.2 m/s the particles penetrated almost 25 cm in 100 ms indicating that the injected momentum was sufficient to have the material span the entire bed width in a short time.

It is interesting that the extent of the injected jet penetration approximately agrees with the correlation of Merry (4) for horizontal gas jets in a fluidized bed.

Conclusions

Thermal tracers are a convenient method to obtain statistically relevant data about solids mixing in a fluidized bed since tests can be easily repeated without requiring the separation of tracers from the bed.

High velocity horizontal injection allows the particles to traverse an extensive distance due to the high initial jet momentum. Both horizontal and vertical mixing is aided by the bubble behavior. Particles are probably drawn vertically upward in the bubble wakes. Horizontal mixing appears to be augmented by bubble coalescences.

Changes in the injector geometry need to be investigated to achieve a wider spread mixing in the bed.

Acknowledgment
Ezra Carr was supported by the Department of Energy University Coal Research Internship Program.

Nomenclature

d	Mean particle diameter
D	Bed width
g	Acceleration of gravity
L	Bed height
p	Pressure
t	Time
T	Temperature
T_{BED}	Bed Temperature before injection
$T_{INJECTION}$	Temperature of injected particles and gas
U_0	Superficial gas velocity
U_{mf}	Minimum fluidization velocity
θ	Dimensionless temperature
ρ_g	Gas density
ρ_s	Solid density
Φs	Particle sphericity

References

1] Glicksman, L.R., M. Hyre, K. Wolshun, "Simplified Scaling Relationships for Fluidized Beds," Powder Technology, 77, 2, pp. 177-199, 1993.

2] Glicksman, L.R. & P. Farrell, "Verification of Simplified Hydrodynamic Scaling Laws for Pressurized Fluidized Beds: Part I Bubbling Fluidized Beds", Proc. 13th Int. Conference for Fluidized Bed Combustion, pp. 981-990, 1995, Kissimmee, Fl.

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4] Merry J.D., “Penetration of a Horizontal Jet into a Fluidized Bed”, Trans. Instn. Chem. Eng., Vol. 49, 189-195, 1975

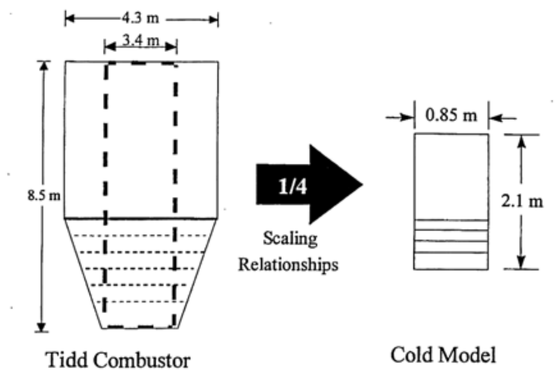

Figure 1 Scaling from Tidd Combustor to Cold model

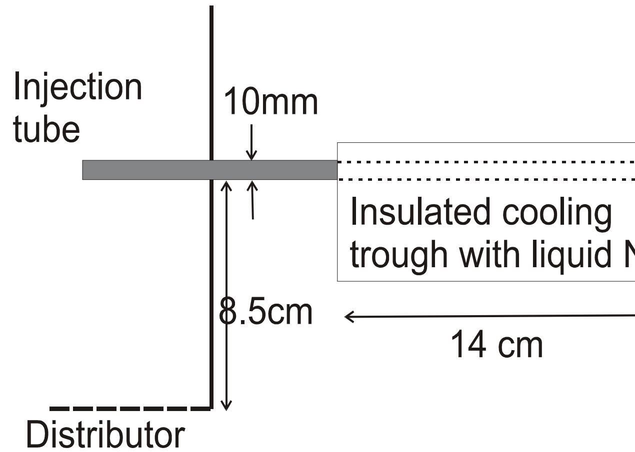

Fig. 2 Injector and Cooling Apparatus

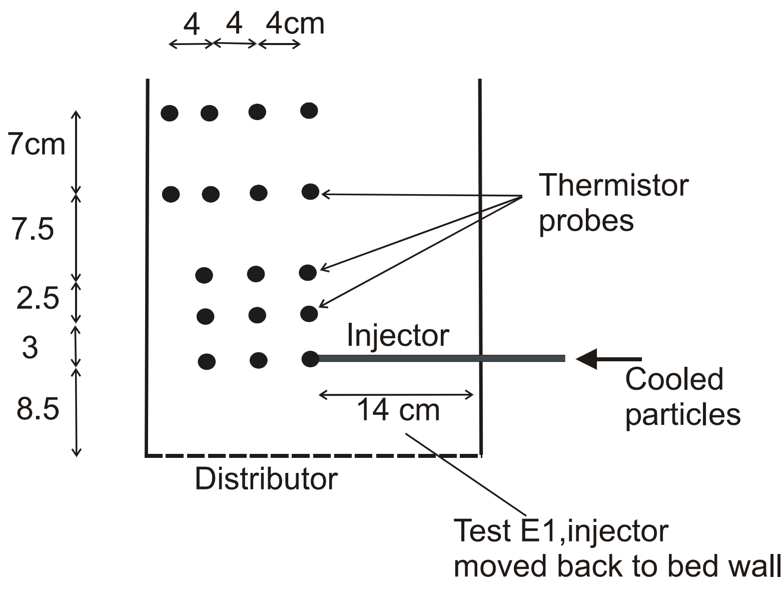

Fig.3 Thermistor probe arrangement. All dimensions in cm

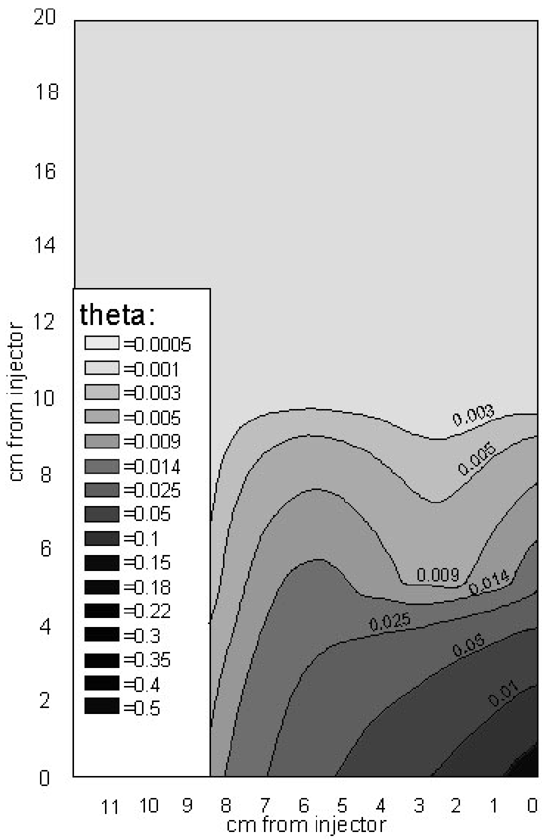

Fig. 4: Series M3 - 0.06 s after Injection

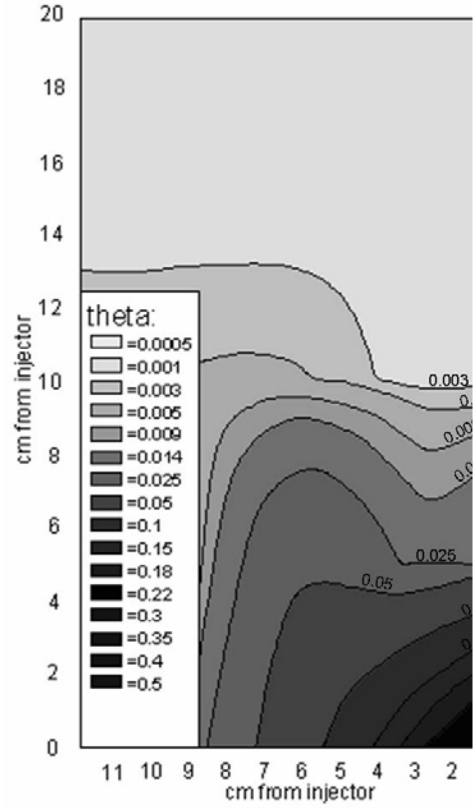

Fig. 5: Series M3 – 0.10 s after Injection

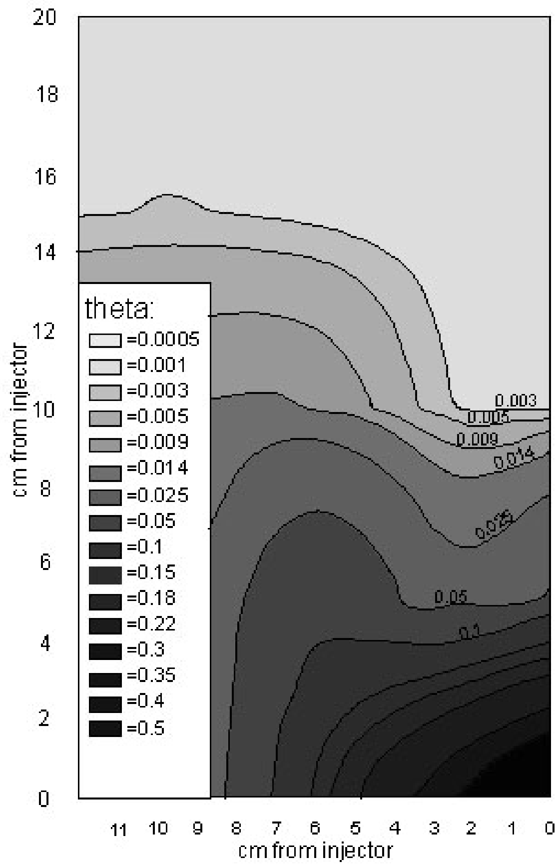

Fig. 6: Series M3 – 0.16 s after Injection

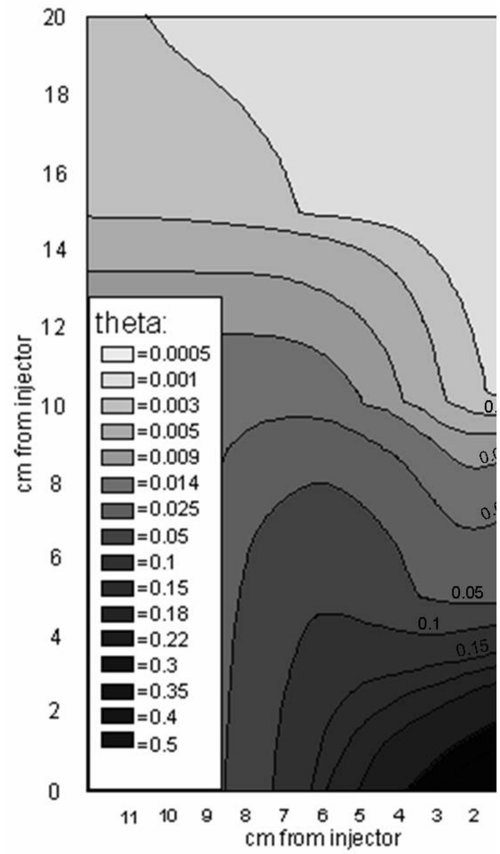

Fig. 7: M3 – 0.2 s after Injection

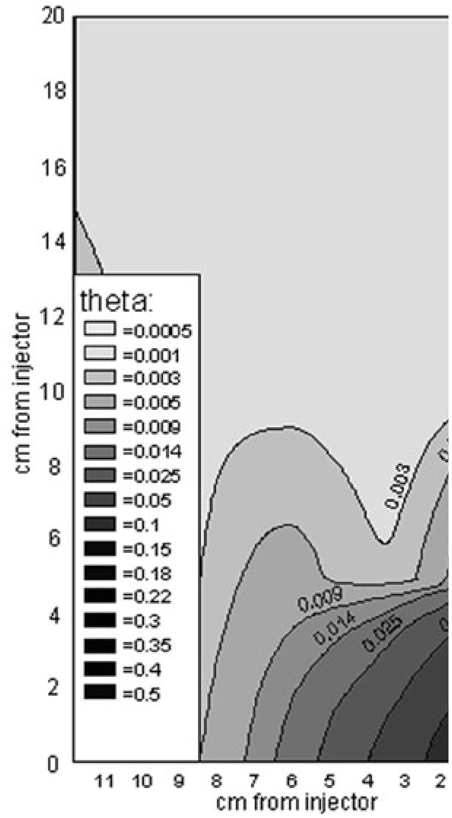

Fig 8 Series M1 0.2s after Injection

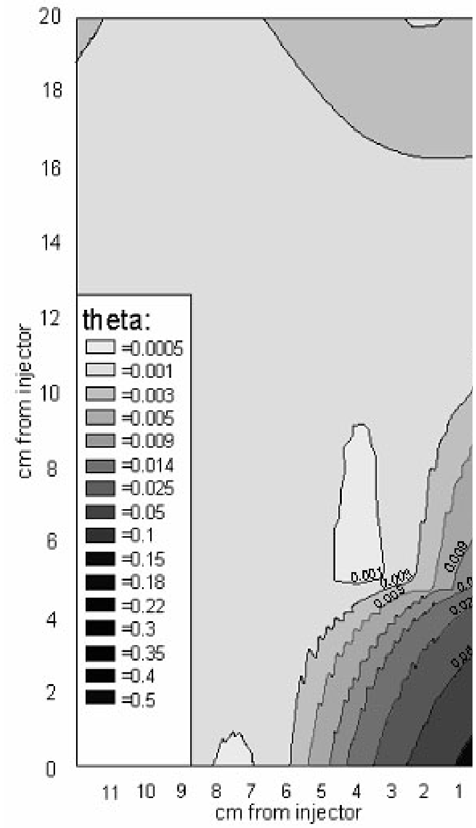

Fig 9 Series M2 0.2s after Injection

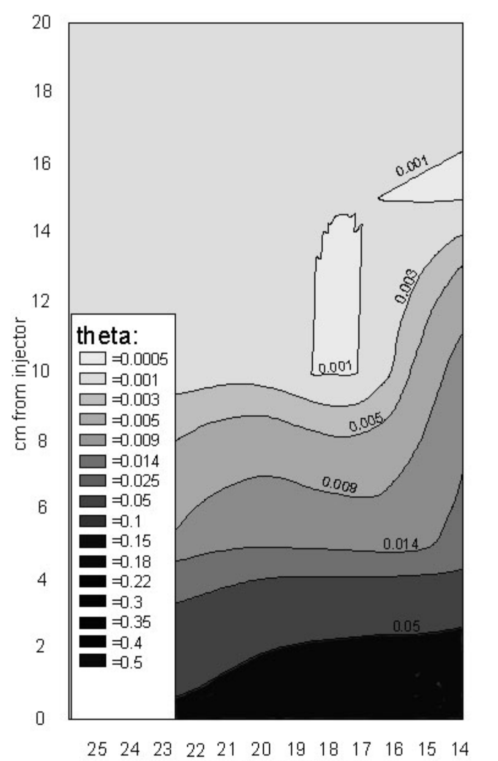

Fig 10 Series E2 0.1s after Injection