SCALE MODEL AND FULL SCALE TEST RESULTS OF A CIRCULATING FLUIDIZED BED COMBUSTOR

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ABSTRACT

A scaling method derived from the equations of motion for fluid and solids in a fluidized bed is applied to design a cold flow experiment of a circulating fluidized bed combustor operating at 1600°F. A quarter scale replica of Riley Stoker's Multi Solids Fluidized Bed (MSFB) lower combustor region was constructed and operated in accordance with the scaling method. In the lower combustor, the circulating entrained solid flow is superimposed on a dense bed - a unique feature allowing increased fuel residence time and greater combustor turndown ability.

As a result of the scaling, measured dense bed expansion and static pressure profiles made in the quarter scale model agreed with measurements made in an operating combustor in the field. Visual observations of the dense bed in the model agreed with limited field observations. When the scaling requirements were not followed, the dense bed pressure measurements and the visual observations did not match field data. This evaluation of the scaling method was not comprehensive, but supported the scaling method's applicability to model circulating fluidized beds.

INTRODUCTION

The development of scaling laws for fluidized beds have become necessary for designing experiments in fluidized bed combustion technology because of the difficulty in predicting full scale behavior of two phase* flow. There are much data from small experiments on the mixing and transport of solid particles with ambient temperature air. It is unclear, however, how the data compare to fluidized and entrained solid bed combustors at elevated temperature. This is because much of the solid and gas mixture properties change as the density and viscosity of the gas change with temperature.

In this paper, a scaling method which accounts for the different solid and gas conditions at elevated temperature is applied to the design of a cold flow experiment of a circulating fluidized bed process. The process is Riley Stoker's Multi-Solids Fluidized Bed (MSFB) Combustor. Unique to this process is a fluidized dense bed of large particles that remain in the lower combustor.

A quarter scale replica of the lower combustor of an operating MSFB unit was constructed and operated in accordance with the scaling method. Measurements made in the quarter scale model dense bed were then compared to measurements later made in the operating full scale combustor. At one point in operating the model, the scaling method was not followed. Model measurements in this case were also compared to full scale measurements in the field.

THE FULL SCALE CIRCULATING FLUIDIZED BED PROCESS

Riley Stoker Corporation's circulating fluidized bed process is called the Multi-Solids Fluidized Bed (MSFB) Combustor. As shown in the schematic illustration in Figure 1, fuel is fed to a fluidized bed of large particles called the dense bed. The fuel grinds and partially burns at a fixed temperature in the dense bed. Sorbent can be added here to remove offending elements of the fuel such as sulfur in coal. The combustor expands to an upper region where secondary air is added to complete combustion at the same fixed temperature. This two stage combustion process minimizes the emission of nitrogen oxides.

Superimposed on the dense bed in the combustor is a circulating loop of sand and ash. While the dense bed remains in the lower combustor, the sand transports through the combustor, separates from the gas in the cyclone, and drops into a gently fluidized reservoir called the external heat exchanger (EHE). This circulating sand serves as a medium to transport the heat of combustion to heat exchanger tubes in the EHE. Thus, in this process, removal of heat is essentially decoupled from the production of heat leading to greater combustion control. Heat is also removed from the gas exiting the cyclone with a conventional convection heat transfer sursface. Completing the solid circulating loop, sand is returned to the combustor through non-mechanical "L" valves.

Of interest is the dense bed in the lower combustor which is an unique feature of the process as compared to other circulating fluidized bed combustors. This bed serves to grind and mix the fuel as it burns minimizing fuel

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* solid and gas

quarter scale particle size keeps the remaining scaling groups the same as the full scale groups. In this way, the change in the gas density and viscosity at elevated temperatures is accounted for in the fluidized bed.

To extend the scaling method to circulating fluidized beds, another scaling group can be included to model entrained recycle solid flows, as suggested by Louge (5). A dimensionless solids flux is defined as

$$F = G_s \,/\, \rho_s\, u \tag{2}$$

where G_s is the solids flux of entrained material in the MSFB lower combustor. Given that the model solids density is 3-1/2 times the field solids density and the model gas velocity is one-half the field gas velocity, the recycle solids flux in the model is set at 1-3/4 times the solids flux in the field to keep the dimensionless solids flux between the model and the field the same.

The independent variables set at one quarter scale geometry, half scale velocities, quarter scale particle size, and the choice of 3-1/2 times denser solids in the cold flow model give that time, a dependent variable, is half scale. This means that observed events in the cold flow model happen twice as fast as the hot full scale prototype. Also, when properly scaled, model pressure drops are nearly equal to full scale pressure drops. This can be seen for the case of the dense bed in the following equation for pressure drop due to the buoyant weight of the bed.

$$\Delta p = \frac{W}{A} = (\rho_s - \rho)\ (1 - \bar{\varepsilon})\ g\ H \tag{3}$$

Assuming the voidage is equivalent between model and prototype, the choice of 3-1/2 times denser model solids and quarter scale height gives the expected dense bed pressure drop in the prototype as nearly 90% of the dense bed pressure drop measured in the model.

Table 1 summarizes the requirements of the scaling method. The scaling groups used here are only as valid as the governing set of equations. Interparticle forces other than mechanical forces due to collisions were omitted in the equations used to derive the fluidized bed scaling groups. Fine particles may have significant electrostatic forces. This may be an important consideration when dealing with quarter scale material in a cold flow model.

THE COLD FLOW MODEL

To evaluate the scaling method, a quarter scale replica of the lower combustor of one of Riley Stoker's MSFB field units was built. The replica, shown in Figure 2, was placed in the replaceable test section of the experimental system shown in Figures 3 and 4. The test section was built with a minimum of dielectrics such as plexiglass to reduce static charges.

The model included a recirculation loop for the entrained recycle material. The recycle flow rate was measured by timing the fall of solid particles in a plexiglass section of the model L-valves. While not used to evaluate the

Table 2

SCALING GROUPS USED TO DESIGN THE COLD FLOW MODEL

Prototype Solids	Model Solids	Scaling Group	Full Scale Value	Model Value
Fuel:	Fuel:	Re_p	63	69
Coal	Iron Ore	ρ_s/ρ	4530	4250
		Ar	8400	9400
		Fr	5400	5400
		H/d_p	950	950
		D/d_p	1333	1333
Recycle Material:	Recycle Material:	Re_p	8.4	9.2
Sand	Copper Powder	ρ_s/ρ	8418	6667
		Ar	30.4	28.8
		Fr	43140	43140
		H/d_p	7600	7600
		D/d_p	10668	10668
		F	4.88×10^{-4}	4.68×10^{-4}
Dense Bed:	Dense Bed:	Re_p	1075	1175
Gravel	Steel Pellets	ρ_s/ρ	8418	6667
		Ar	30.4×10^6	29.4×10^6
		Fr	431	431
		H/d_p	76	100
		D/d_p	106	106

In maintaining the scaling group values, the model fluidizing velocities were set at one-half the full scale values. The particle size of the solids were one-quarter of full scale with approximately the same particle size distribution. The air supply to the model was operated differently from the full scale combustor in that the model was forced draft giving a static pressure slightly higher than atmospheric above the dense bed. The full scale combustor was run balanced at atmospheric pressure.

bed height in the field to fit the quarter scale geometry of the model. The gravel bed in the model had an average particle size about half the particle size in the field. At the time of these tests, the static pressure profile in the model gravel bed was measured by wall pressure taps instead of a pressure lance. In these early tests, two gravel bed pressure profiles were measured at similar dense bed pressure drops.

COMPARISON OF THE COLD FLOW MODEL TEST RESULTS TO THE FULL SCALE TEST RESULTS

Since the minimum fluidization velocity and the settled bed height were not directly measured in the field, we compared the model data to calculated values for the full scale combusor. The minimum fluidization velocity for the field was calculated using the following equation [6].

$$u_{mf} = \frac{\mu}{\rho d_p} \left[(33.7)^2 + 0.0408 \frac{d_p^3 \rho(\rho s - \rho) g}{\mu^2}\right]^{1/2} - 33.7 \qquad (5)$$

The results of this equation exactly matched the minimum fluidization velocity measured for the gravel bed in the cold flow model. The full scale settled bed height was estimated using equation (3) for the two dense bed pressure drops observed in the field assuming a voidage of 0.5 at minimum fluidization conditions.

The minimum fluidization velocity measured in the model steel pellet dense bed was 43% of the calculated full scale value. The settled bed height measured in the model was a little under a third of the calculated full scale dense bed height for both pressure drops. Strict application of the scaling method requires that the measured minimum fluidization velocity be one half the full scale value and the settled bed height be one quarter. However, the steel pellets used in the model were only 3 times the solids density of the full scale solids rather than 3-1/2 as required. This led to slightly lower fluidization point and a higher bed. The measured fluidization velocity for the gravel bed at half the particle size and a quarter scale settled height in the cold flow model was 37% of the full scale value.

The contrast between the use of steel pellets and fluidizing raw gravel in the cold flow model became apparent in the measured expanded bed heights. Figure 5 shows the ratio of the expanded bed height and the settled bed height versus the ratio of the fluidization velocity and the minimum fluidization velocity as measured in the full scale combustor and the quarter scale model. As the figure shows, the model steel pellet bed expansion closely approximated the expansion measured in the field at a velocity ratio between 1.75 and 2.0. The model gravel bed, however, expanded over twice its settled height at a velocity ratio of 2.2 - much more than the steel pellet bed and the field data. Figure 5 shows that the model steel pellet bed did not double its settled height until at a higher velocity ratio than the gravel bed.

The gravel in the cold flow model was thrown higher as compared to what could be seen in the full scale combustor. The steel pellet dense bed flow behavior observed without entrained recycle flow appeared similar to the limited observations in the field made at start-up with no recycle flow. At one point, gables were installed inside the windows of the cold flow model in an attempt to part the apparent curtain of flowing entrained material with

Other geometry changes based on the test program have been incorporated in several of Riley Stoker's MSFB combustors which are coming on line now.

CONCLUSIONS

Measurements made in a cold flow model designed according to the fluidized bed scaling method matched similar measurements made in the dense bed of the Multi-Solids Fluidized Bed Combustor. Fluidizing steel pellets in a quarter scale model in accordance with the scaling method resulted in similar bed expansions and similar static pressure profiles. The visual activity of the dense bed in the model appeared similar to limited field observations at low load conditions. Fluidizing gravel in the cold flow model, on the other hand, resulted in bed expansions greater than what was observed in the full scale combustor. Static pressure profiles of the model gravel bed did not match profiles in the field. These observations are not proof, yet support the applicability of the scaling method for modeling circulating fluidized beds.

Riley Stoker Corporation is now working with support from the U.S. Department of Energy to develop a small industrial package boiler based on the MSFB combustion process [7]. In the first phase of the project, a quarter scale cold flow model of a prototype package boiler is being built using the scaling method for fluidized beds. The cold flow model will be used to simulate the whole package boiler circulation loop including solid entrainment, separation, collection, and return to the combustor.

REFERENCES

1. Nack, H.; Liu, K.T., and Falton, G.W. Battelle's Multi-Solid Fluidized Bed Combustion. Proceedings Fifth Int. Conf. on Fluidized Bed Combustion III, p.233, 1977.

2. Nack, H. Fluidized Bed Combustion - Industrial Application Demonstration Projects Battelle's Multi-Solid Fluidized Bed Combustion Process. Final Report, U.S. DOE, Contract No. EX-76-C-01-2472, Oct. 1979.

3. Glicksman, L.R. Scaling Relationships for Fluidized Beds. Chem. Eng. Sci., 39 (9): 1373-1379, 1984.

4. Nicastro, M.T. and Glicksman, L.R. Experimental Verification of Scaling Relationships for Fluidized Beds. Chem. Eng. Sci., 39, (9): 1381-1391, 1984.

5. Louge, M.HY. Circulating Fluidization Research at Cornell. A Study of Hydrodynamic Scale-Up Effects; 1987 Int. Conference on Fluidized Bed Combustor.

6. Kunii, D.; Levenspiel, O. Fluidization Engineering Krieger Publishing Co., Huntington, NY, 1977.

7. DOE Contract 87MC 23295: Atmospheric Fluidized-Bed Combustion Advanced Concepts Applicable to Small Industrial and Commercial Markets. U.S. DOE, Morgantown Energy Technology Center, Sep. 29, 1987.

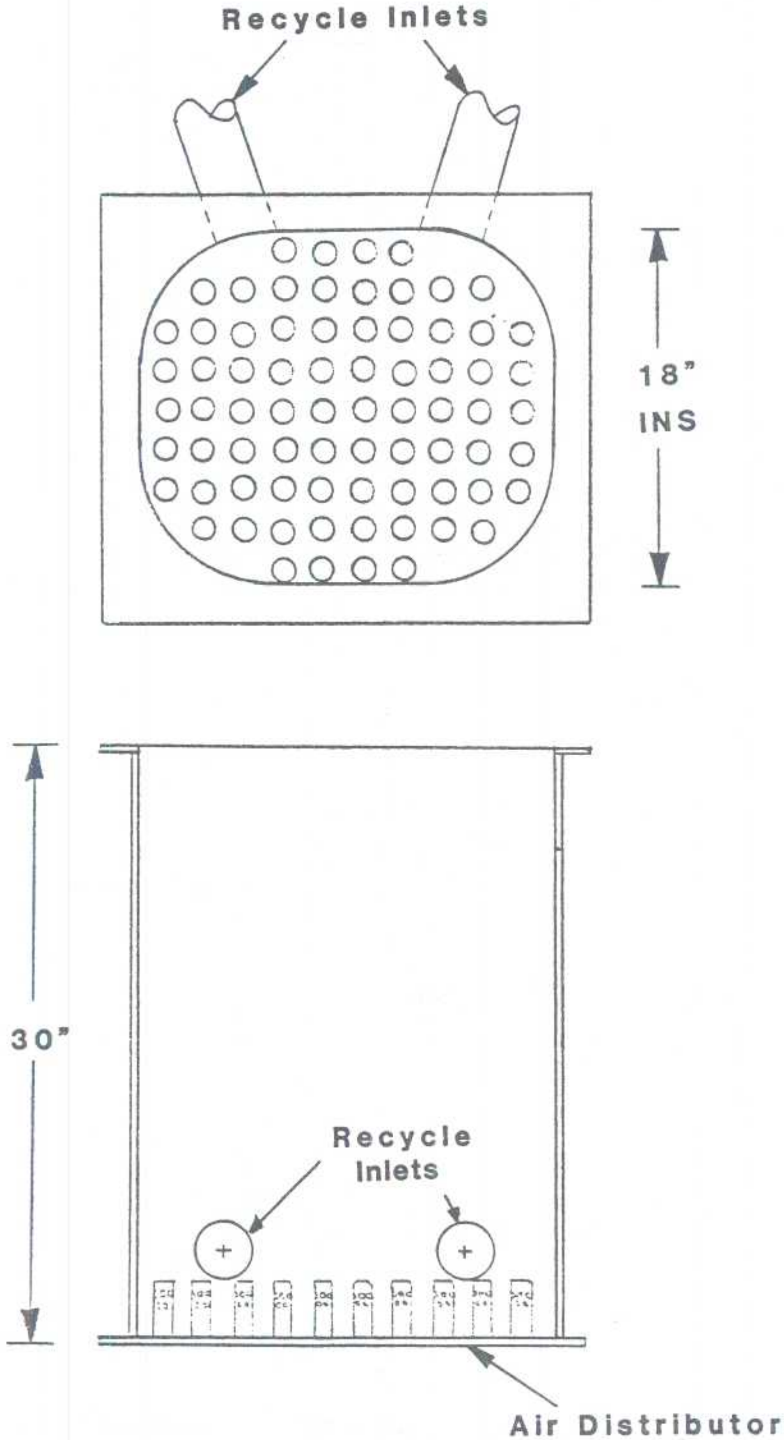

Figure 2. Test Section Used to Evaluate the Scaling Method

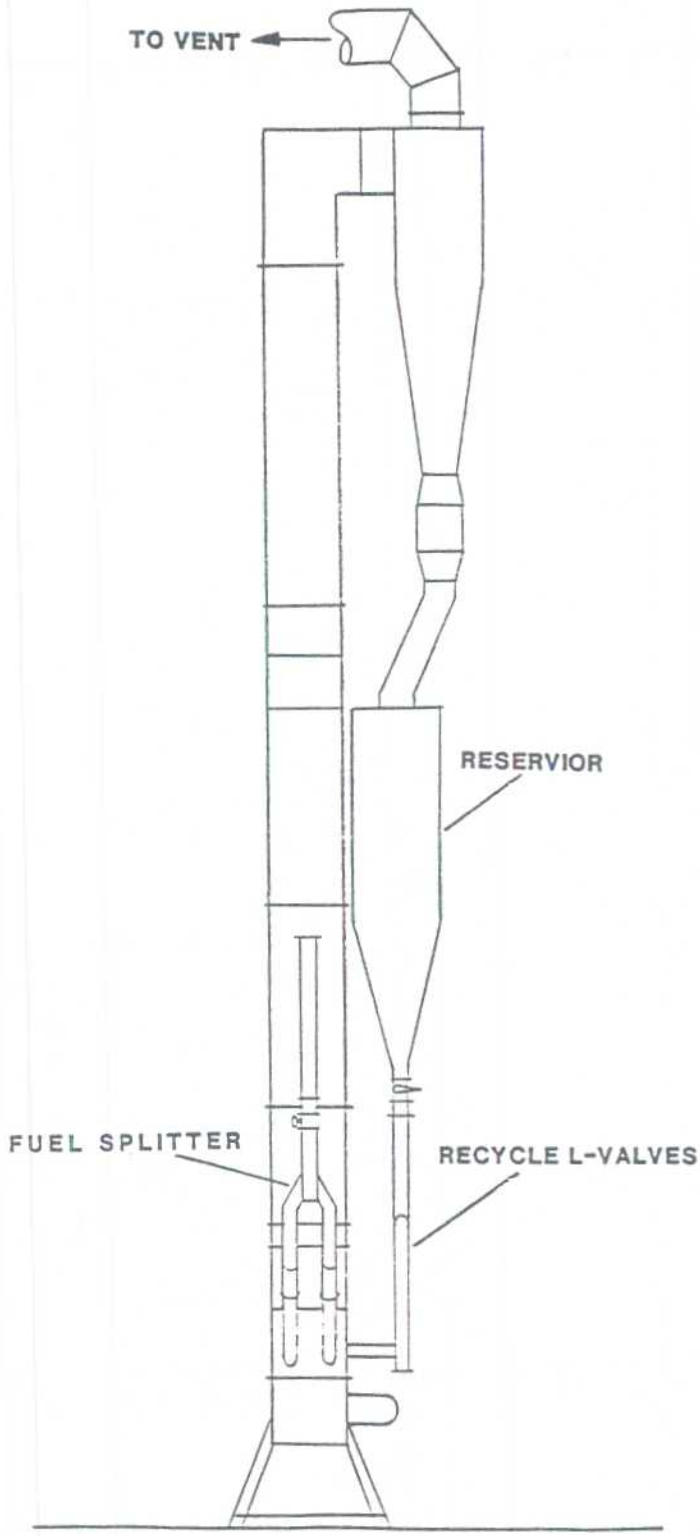

Figure 4. The Experimental System, Side View

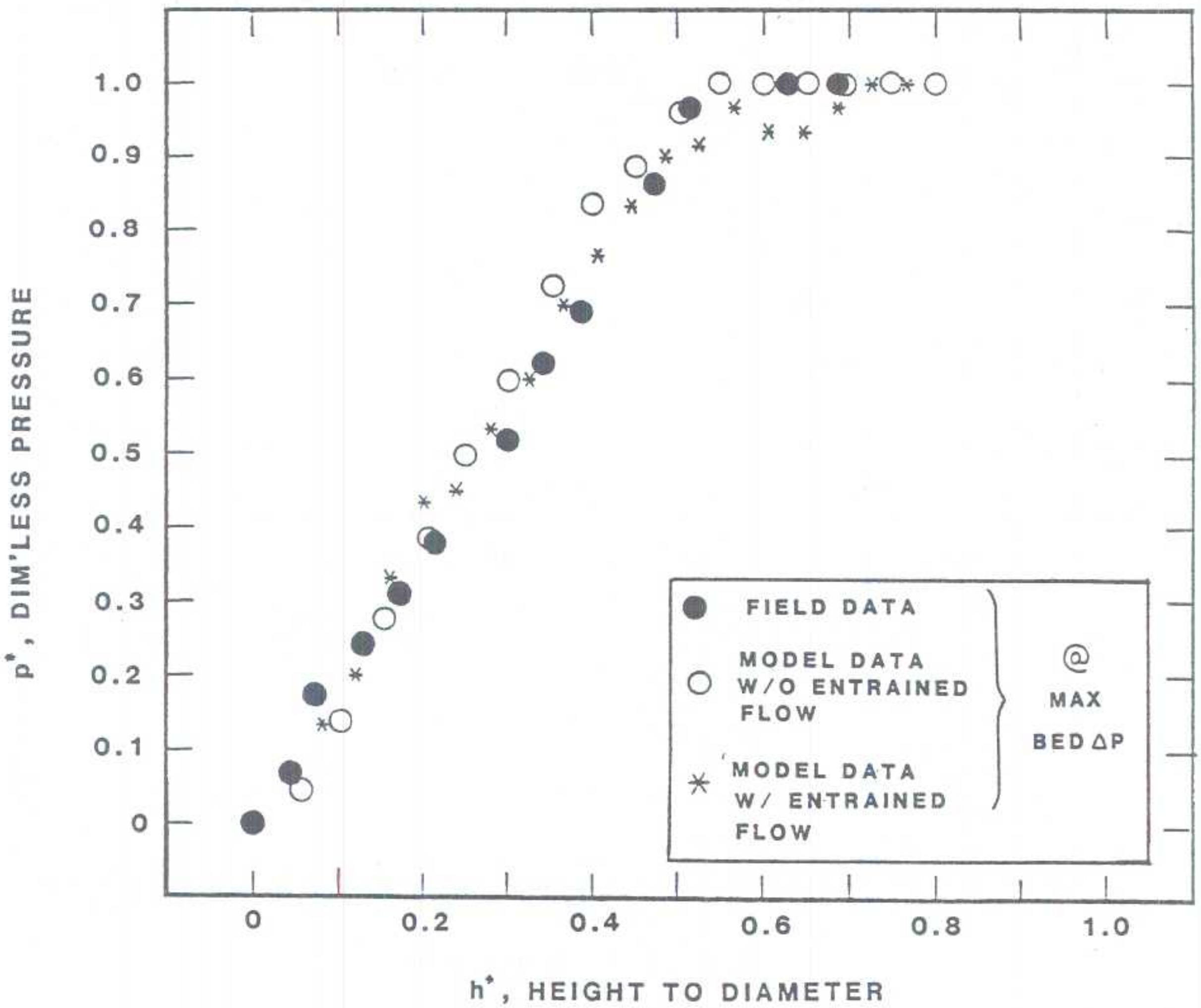

Figure 6. Comparison of the Normalized Model and Field Static Pressure Profiles Fluidizing Steel Pellets in the Model

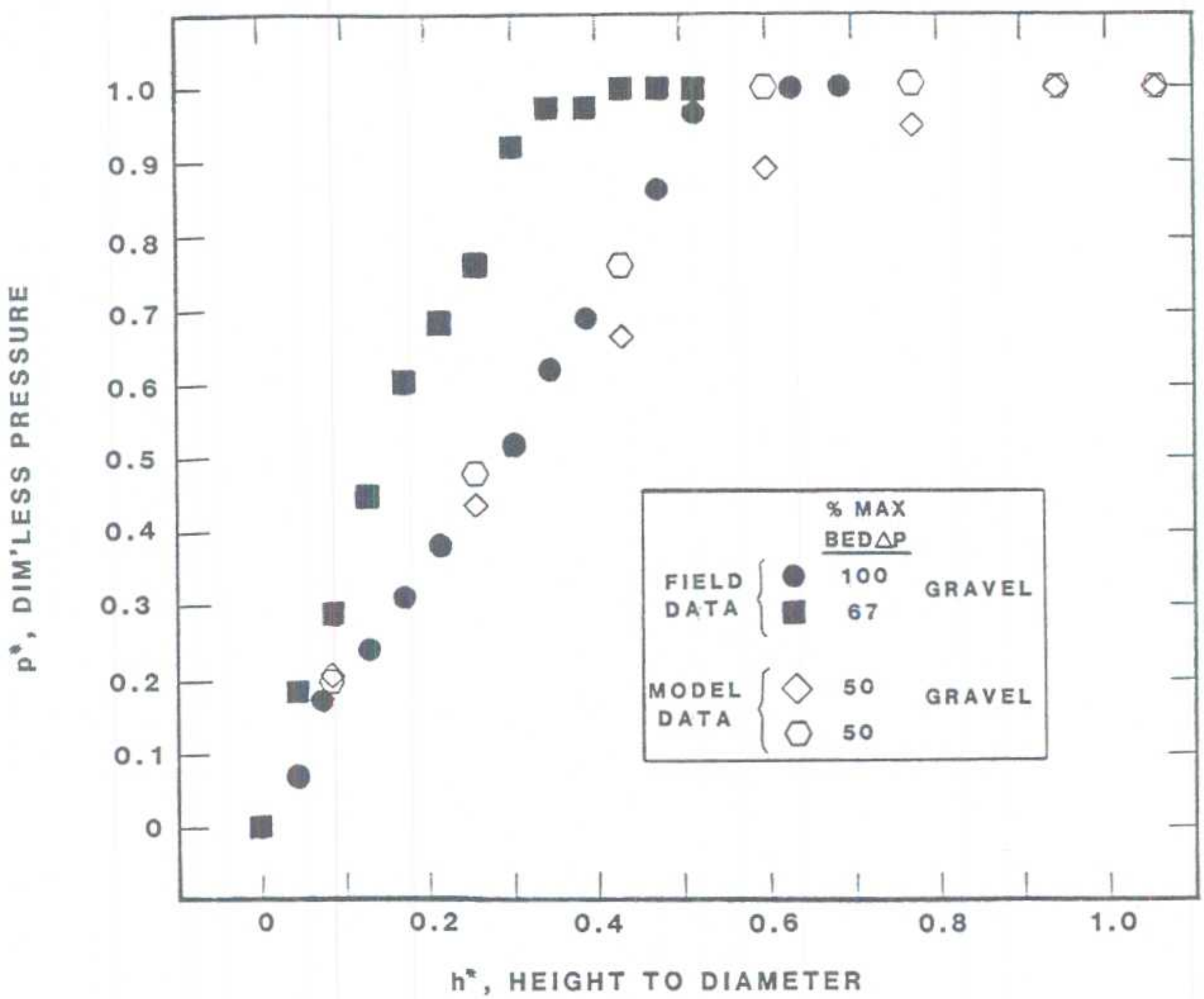

Figure 8. Comparison of Normalized Model and Field Static Pressure Profiles Using Gravel Instead of Steel Pellets in the Model