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Abstract
The electrical resistance of fluidized beds of conducting particles is of both theoretical and practical interest. The bed resistance of carbonaceous solids has been measuredinseveral different laboratory systems using a four-point probe technique, It is a function of gas velocity, column diameter, particle size and other properties of the bed material. Also, as temperature is increased, the bed resistance decreases continuously at least in the temperature range between room temperature and 700°C.

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Comments
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THE ELECTRICAL RESISTANCE OF GAS FLUIDIZED BEDS

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SYNOPSIS

The electrical resistance of fluidized beds of conducting particles is of both theoretical and practical interest. The bed resistance of carbonaceous solids has been measured in several different laboratory systems using a four-point probe technique. It is a function of gas velocity, column diameter, particle size and other properties of the bed material. Also, as temperature is increased, the bed resistance decreases continuously at least in the temperature range between room temperature and 700°C.

NOTATION

D_b	column diameter, cm
I	current flow in bed, amps
L	distance between measuring electrodes, cm
R_b	bed resistance, ohm
S	cross section area for current flow, cm^2
V	superficial gas velocity, cm/sec
V_{mf}	minimum fluidization velocity, cm/sec
V_{fs}	velocity at which bed is fully supported, cm/sec
ΔV	voltage drop between measuring electrodes, volts
ρ	bed resistivity, ohm-cm
ρ_m	minimum fluidized bed resistivity, ohm-cm
ρ_s	bed resistivity with no gas flow, ohm-cm
σ	standard deviation of particle size, microns
Θ	angle of repose of bed material, degree

INTRODUCTION

The electrical properties of fluidized beds of conducting particles are of interest for several reasons. One of these is that conducting fluidized beds may be used as resistance heaters to supply energy for high temperature endothermic reactions which may be carried out conveniently within such beds. Another reason is that a study of the electrical properties of these beds provides some insight into the general phenomenon of fluidization (Goldschmidt and Le Goff, 1967).

Electrofluid reactors which utilize electrodes to supply power to a conducting fluidized bed have been used in both experimental (Beeson, et al., 1974) and commercial reaction (Shine, 1971) systems. Design of these reactors requires an understanding of the basic electrical properties of fluidized beds. The electrical characteristics of such beds can be predicted for simple electrode arrangements where the bed resistivity is constant and known (Knowlton, et al., 1973).

Current flow in fluidized beds appears to be along continuous chains of conducting particles, at least at low voltages (Goldschmidt and Le Goff, 1963). The resistance, and hence the current flow, fluctuate as the particle chains are broken by passing bubbles. However, the time-averaged resistance appears to be constant at steady state. The total interelectrode resistance is the sum of two resistances, the bed resistance and the contact resistance between the fluidized bed and the electrodes.

The bed resistance obeys the well-known resistance equation (Reed and Goldberger, 1966),

$$R_b = \rho \; L/S \qquad (1)$$

and therefore it is the behavior of the resistivity which is of most interest. This paper reports data which illustrate the effects of gas velocity, bed material, particle size, column diameter and temperature on bed resistivity. In particular, the results reported extend the work of Jones and Wheelock (1968) on the effect of column diameter to larger size columns and measurements of the effect of temperature on bed resisitivity are presented for the first time.

EXPERIMENTAL METHOD

The bed resistance has been measured by a four-point probe method which isolates the bed resistance from the total interelectrode resistance (Jones and Wheelock, 1968). With this method, the electrodes used to measure the voltage drop across the fluidized bed are separate from the current supplying electrodes. Since there is no current flow in the voltage-measuring electrodes, the voltage drop between these electrodes is unaffected by any contact resistance.

The bed resistance is determined by applying Ohms Law and the bed resistivity by applying equation (1) modified to reflect the geometry. Details of the equipment used to measure resistivity both at room and elevated temperatures are reported elsewhere (Pulsifer and Wheelock, 1975).

During our investigation, the resistivity of beds of graphite, calcined coke and coal char were measured under a variety of conditions. Nitrogen was the fluidizing gas in all cases, with the reactor pressure being atmospheric.

ROOM TEMPERATURE MEASUREMENTS

Shown in Fig. 1 are bed resistivities for two different materials measured at room temperature in a 15.2-cm. diameter column with current flow in a horizontal direction between a 2.5-cm. diameter center electrode and the column wall. As illustrated in this figure, the bed resistivity remains fairly constant as gas flow rate is increased until the minimum fluidization velocity is reached. As the bed becomes fluidized, the bed resistivity increases sharply and reaches a peak value at the point where the first bubbles are formed and the bed becomes fully supported by the gas stream. The resistivity then decreases somewhat with further increases in gas velocity. The sharp increase in bed resistivity is accompanied by an increase in bed height which presumably decreases the number of conducting chains, thus increasing the resistivity. As bubbles form, the void fraction of the dense phase decreases leading to a small decrease in the resistivity.

Fig. 1 also illustrates the effect of bed material on resistivity. Calcined coke gives a higher bed resistivity than graphite, caused at least partly by the higher resistivity of the coke particles. The inherent resistivity of the particles used in the experimental work was unknown, but the resistivity of petroleum coke is reported to be 4-5 times that of graphite. The difference between the resistivties of the graphite and coke beds with no gas flow was about a factor of four. With gas flow in the bed, the resistivity of the coke bed was 4-8 times that of the graphite bed. Since current flow occurs along chains of particles, this indicates that material properties that affect the resistance of particle-to-particle contacts such as hardness and surface roughness contribute somewhat to the observed difference between beds of graphite and calcined coke.

In Fig. 2, bed resistivity-gas velocity data for calcined coke beds in both 10.2-cm. and 15.2-cm. diameter columns are compared to data collected by Jones and Wheelock (1968) in 5.1-cm. and 10.2-cm. diameter columns. All these measurements were made with vertical current flow in the fluidized bed using two needle probes spaced 3.8-cm. apart in the bed for measuring the voltage drop. The curves in Fig. 2 are aimilar in shape to those in Fig. 1, except that the resistivity of the smaller diameter beds increases significantly at higher velocities beyond the trough which follows the peak resistivity. The difference in these curves due to differing column diameter is not surprising since the rise in resistivity beyond the minimum point in the curves seemed to coincide with the onset of slugging in the bed. The fluidized bed resistivity at the minimum point in the curves fits the empirical correlation developed by Jones and Wheelock (1970) for data taken in smaller columns, namely

$$\frac{\rho_m}{\rho_s} = \frac{38.07\ \sigma^{0.21}}{D_b^{\ 0.765}(\tan\Theta)^{3.47}} \qquad (2)$$

This equation relates the minimum fluidized bed resistivity to the settled bed resistivity and shows that the relation of one to the other depends on particle properties as well as column diameter.

ELEVATED TEMPERATURE MEASUREMENTS

Fluidized bed resistivity is affected by temperature and this effect has been investigated with a 14.0-cm. I.D. Vycor glass fluidization column over the temperature range from room temperature to 700°C. The current flow in the bed was in the vertical direction and the resistivity was determined from the voltage drop over a 2.5-cm. section of the bed. The glass column was externally heated so that the bed temperature could be varied independently of the current flow in the column.

During the study, the effect of temperature on the resistivity of fluidized beds of several carbon containing materials was investigated. The materials included calcined coke, graphite and several coal chars. Except in one case where no gas flow was used, the resistivity was always measured at a relative fluidization velocity of 1.6 and, generally, the effect on the resistivity of heating and cooling the bed several times was determined.

Typical results, in this case for a partially gasified coal char with an ash content of 13.1%, are shown in Fig. 3. The data tend to be somewhat scattered; however, the relationship between the fluidized bed resistivity and temperature is generally linear with the resistivity decreasing as the temperature increases. This same linear trend between bed resistivity and temperature was observed with all of the bed materials, although the resistivity of the graphite and calcined coke beds were significantly less than those of the coal char beds.

When the bed of char was cooled, the bed resistivity increased in an apparent linear manner but along a line of lesser slope than that obtained while heating. Consequently, the resistivity of the bed at room temperature was less than before the heating and cooling cycle was performed. Upon standing for a time at room temperature, the bed material seemed to regain its former level of resistivity so that when another heating and cooling cycle was carried out, the same resistivity versus temperature path was retraced (Fig. 3). Thus the changes in the bed material which took place during the cycle seemed to be reversible. It is not clear whether these changes which affected the resistivity of the fluidized bed were due to adsorption and desorption of permanent gases or to changes in the structure of the char. However, it may be noteworthy that the beds of graphite did not display as much hysteresis as the beds of char over a heating and cooling cycle although the percentage decrease in resistivity for a given increase in temperature was about the same for both types of beds.

The change in resistivity of fluidized beds of carbonaceous materials is probably due in part to changes in the inherent resistivity of the materials. Thus it is well established that the resistivity of coal chars (Waters, 1963) and petroleum coke (Mrozowski, 1952) decreases with rising temperature in the range of our measurements. Also the resistivity of polycrystalline graphite decreases with rising temperature up to about 450°C before the trend reverses and the resistivity increases (Mrozowski, 1952).

Waters (1963) found that the resistivity of coal char carbonized at a temperature near 800°C, about 70°C less than the carbonization temperature of our material, decreased by a factor of 7-8 when it was heated to 700°C. This is somewhat less than the decrease shown in Fig. 3 indicating that additional factors besides changes in material resistivity affect the resistivity of fluidized beds when the temperature is changed. This also is demonstrated by a comparison of the effect of temperature on the resistivity of a fluidized bed of coal char with that of a fixed bed; the resistivity of the fluidized bed declined much more than the resisitvity of the fixed bed between 25°C and 525°C (Fig. 4). It would appear that temperature affects the particle-to-particle contact resistance which must play a greater role in a fluidized bed than in a fixed bed. The reduction in fluidized bed resistivity at higher temperatures may also be due to an increase in arcing between particles which in effect would reduce the contact resistance.

CONCLUSIONS

The electrical resistivity of a bed of conducting particles increases sharply as the bed passes from the fixed state to the fluidized state and it reaches a maximum as the bed becomes fully supported by the gas. At higher velocities the resistivity declines, but if the velocity is increased to the point where slugs develop, the resistivity will rise again. The resistivity is also affected by the properties of the particles, bed dimensions, and temperature. The resistivity of fluidized beds of carbonaceous materials appears to decrease linearly with increasing temperature, at least up to 700°C. Although this effect of temperature is probably due in part to the influence of temperature on the inherent resistivity of the materials, it may also be due in part to the influence of temperature on the particle-to-particle contact resistance and/or arcing between particles.

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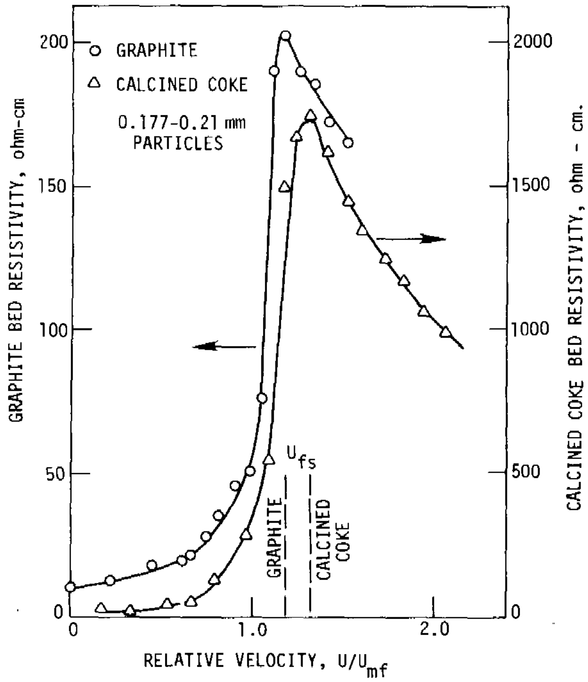

Fig. 1. Effect of relative gas velocity on the resistivity of graphite and calcined coke beds.

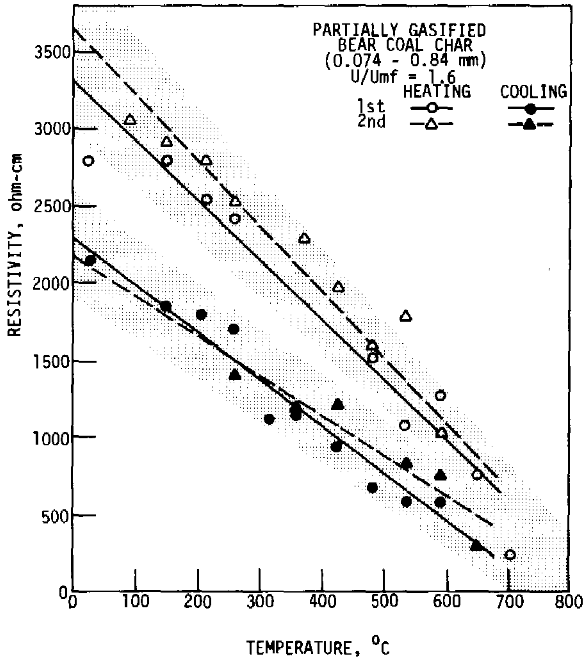

Fig. 3. Effect of temperature on the resistivity of a bed of partially gasified coal char.

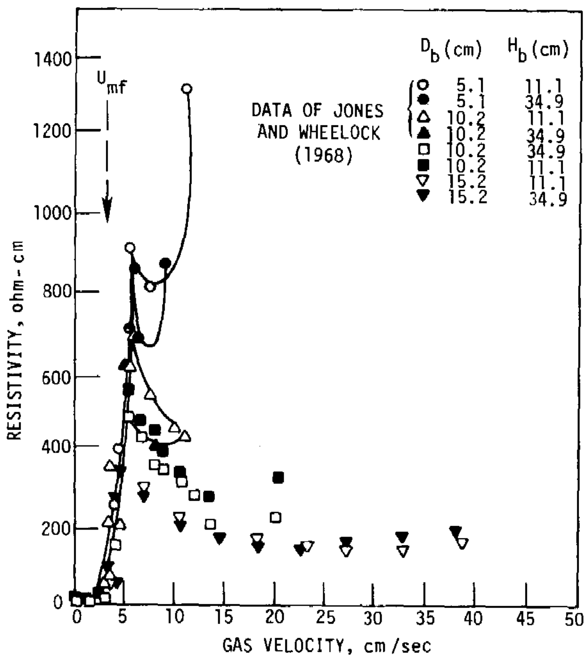

Fig. 2. Resistivity of calcined coke beds fluidized in different diameter columns.

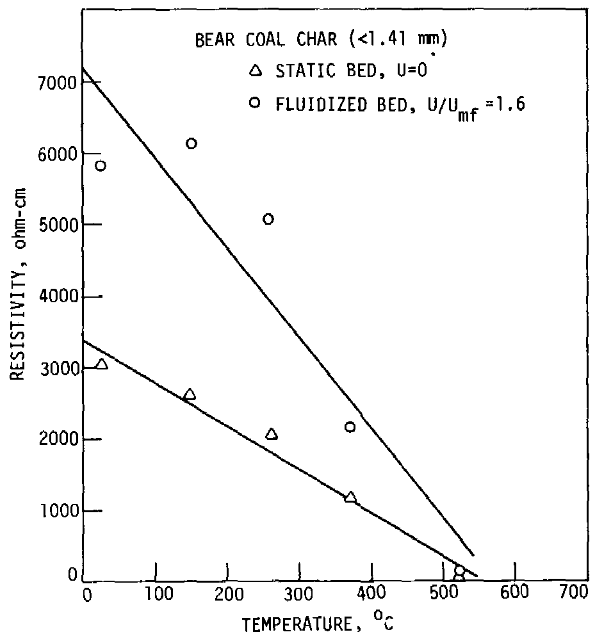

Fig. 4. Comparison of the resistivities of fluidized and static beds of coal char.