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MODELING OF AIR FLOW THROUGH SINTER MIX BED

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ABSTRACT

The present work relates the flow of air through a packed sinter mix bed to the pressure drop using the Ergun's Equation. The velocity of air infiltration across the sinter mix charged into a pot was measured at different suction pressures. The parameters, void fraction and equivalent spherical diameter were calculated using the pressure drop and air velocity relationship. These have been interpreted in terms of the process variables vis-à-vis the mix permeability The validity of the Ergun's equation was checked while comparing the observed pressure drop with the computed one obtained by fitting the above parameters in the equations.

Key words : Ergun;s equation, Sinter mix permeability, Sinter basicity, Speed of sintering, Moisture, Equivalent diameter of sinter mix, Void fraction, Surface area

INTRODUCTION

The Sintering Process as used in the Iron & Steel Industry caters the special needs on burden materials used in the blast furnace iron making. The machine mainly used nowadays is Dwight-Lloyd sinter strand. In the process of iron ore sintering, a shallow bed of fine particles is agglomerated by heat exchange and partial fusion of the quiescent mass. Air is infiltrated through top of the bed. Heat is generated by combustion of a solid fuel admixed with the bed of fines being agglomerated. The sintering process consists of the passage of a heat and reaction front through a packed bed of solids. The gases following through the bed continuously carry the heat from the flame front further along the bed.

$$\text{The Velocity of heat transfer front} = h_g V/h_s (1-\epsilon) \qquad \text{---------} \qquad (1)$$

Where, h_g = the volumetric heat capacities of the gases (Kcal/m^3), h_s = the volumetric heat capacity of solids (Kcal/m^3), V = the volumetric flow of the gases (m^3/m^2-min.), and ϵ = void fraction of the bed.

The above relationship shows that the velocity of the heat transfer front is directly proportional to the gas velocity. Figure 1 , shown below, represents the schematic of the sintering reaction [1]

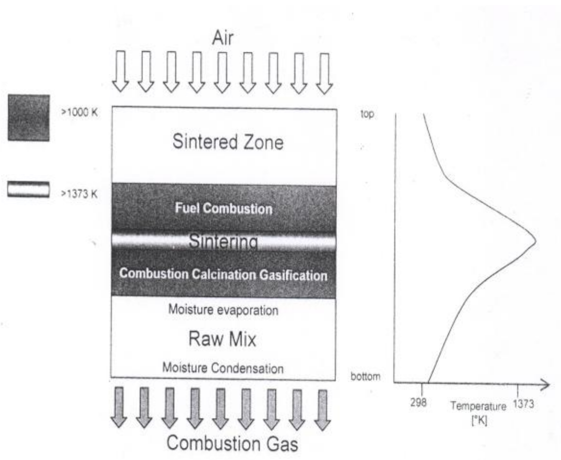

Figure 1 : **Schematic diagram of sintering reaction showing various zones**.

From top: Sintered Zone,
Fuel Combustion (> 1000K)
Sintering (>1373 K)
Combustion , Calcination
and Gasification (> 1000K)
Moisture evaporation
Raw Mix
Moisture condensation

The vertical rate of sintering, which is defined as shifting of sinter formation along the height of the layer of sinter charge over the grates in unit time, depends on how fast the air is blowing in. This is dependent on the permeability of the bed and its height as well as suction pressure. The velocity of gas infiltration varies in a complex manner with time as the sintering advances since the bed is composed of different sintering zones which have different permeability. Nevertheless, the parameter pre-ignition permeability has got significance in affecting pressure drop during and after sintering. In case of Bhilai ores, a close relationship have been found amongst sintering time, the permeability of the green mix [2]. The permeability is greatly affected by the two factors, namely, the moisture content [2] and the proportion of return fines in the sinter mix [3]. Kasai et al. [4] confirmed that pre-ignition permeability was related to the mean size of granules which was. In turn, related to moisture addition.

BED PERMEABILITY AND ERGUN'S EQUATION

Several investigators have derived equations relating the flow of gas through a packed bed to the pressure drop across the bed including Carman [5] and Ergun [6]. With regard to bed permeability, air flow through packed bed, before a sinter bed is ignited, can be described by the Ergun's equation.

$$\Delta P/h = A * \acute{\eta}\, Vo(1-\varepsilon)^2 / \varphi^2 d^2_p \varepsilon^3 + B* pV^2_o(1-\varepsilon) / \varphi\, d_p \varepsilon^3 \qquad \text{-----} \quad (2)$$

Where,

d_p = the equivalent spherical diameter of the packing (m)
h = the bed depth (m)
ΔP = the pressure drop across the bed (Pa) and its
Vo = the superficial gas velocity (m/s)
ε = the void fraction of the bed (-)
ή , p = the dynamic viscosity of the gas (Pa.s) and its density (kg/cu.m)
φ = the shape factor.

The initial voidage may be estimated from the measurements of the bulk density and the real density of the mix at the loading stage on the machine. The value of d_p , the harmonic mean diameter of the pellets , is obtainable from a size analysis of the raw mix using the equation

$$1 / d_p = f_1 / d_1 + f_2 / d_2 + \text{-------} + f_n / d_n \qquad \text{------ (3)}$$

Where f_n is the fraction of the pellets between two sieve sizes with a mean diameter d_n. The pellets are not perfectly spherical , and the effective diameter is related to the harmonic mean diameter by a shape factor φ.

Factors A and B in Eq. (2) have, according to Ergun, values 150 and 1.75 respectively. The Equation shows that for a given pressure drop, air flow is increased if there is an increase in φ , ε, or dp. An analysis of the permeability of the sinter mix bed on the basis of Ergun's equation was done by Rankin et al. [7] who observed that the permeability depends on the type of sinter feed .

Calculation of the Shape Factor and Voidage

The shape factor φ and the voidage ε for the raw mix at sintering suction may be calculated using the Ergun's equation which can be rewritten as :

$$\Delta P = C\, Vo + D\, V^2_o \quad \text{, or} \quad \Delta P / Vo = C + D\, V_o \qquad \text{-----------} \quad (4)$$

Where, $C = 150\, ή\, (1-\varepsilon)^2 * h \;/\; \varphi^2 d^2_p\, \varepsilon^3$, and

$$D = 1.75\, p\, (1-\varepsilon) * h \;/\; \varphi\, d_p\, \varepsilon^3 \qquad \text{--------} \ (5)$$

Values of the parameters, D and C can be found from the pressure drop (ΔP) and velocity (Vo) observations at points 1 and 2 using the Equations (4) and (5) as follows.

$$D = (\Delta P1/ Vo1 - \Delta P2/ Vo2) \;/\; (Vo1 - V_o 2) \qquad \text{-----} \ (6)$$
$$C = (\Delta P1/ Vo1) - D * Vo1, \quad \text{or} \quad C = (\Delta P2/ Vo2) - D * Vo2 \qquad \text{----} \ (7)$$

To cross check validity of the equation ΔP3 can be calculated using the value of gas velocity at point 3 : $\Delta P3 = C\, Vo3 + D\, V^2_o 3$, and

$$\%\ \text{Difference} = 100 * (\Delta P3\ \text{calc.} - \Delta P3\ \text{obs.}) \;/\; (\Delta P3\ \text{obs}) \qquad \text{--------} \ (8)$$

The parameter

$$(0.07)\,(C/D) = 0.07 * [150\, ή\, (1-\varepsilon)^2 * h \;/\; (\varphi^2 d^2_p\, \varepsilon^3)\,] \;/\; [(1.75\, p\, (1-\varepsilon) * h \;/\; \varphi\, d_p\, \varepsilon^3)\,]$$
$$= [\,6\,(1-\varepsilon) / \varphi * d_p\,] * [\,ή \,/\, p\,] \qquad \text{------} \ (9)$$

$$(0.07)\,(C/D) = SSA * [\,ή \,/\, p\,] \qquad \text{---------} \ (10$$

Where, SSA, the specific surface area the granules can be computed from the ratio, [C / D] using Eq. (10.

The value of void fraction (ε) can be found out using the following relationship:

$$SSA / D = [\,6\,(1-\varepsilon) / \varphi * d_p\,] \;/\; [1.75\, p\, (1-\varepsilon) * h \;/\; \varphi\, d_p\, \varepsilon^3\,]$$
$$SSA / D = (6 * \varepsilon^{3)} \;/\; (1.75\, ^* p * h\,), \quad \text{------------------------}$$

$$\text{or } \varepsilon^3 = [1.75\, ^* p * h / 6\,] * [SSA / D] \qquad \text{----} \ (11)$$

The value of equivalent spherical diameter, d_p, can be computed as follows :

$$d_p = 6\, (1-\varepsilon) / \varphi * (1/ SSA) \qquad \text{------} \ (12)$$

EXPERIMENTAL

The iron ore fines (-10 mm size) from the following sources were collected. Table 1 shows the chemical analysis of these samples. The chemical analysis of these ores and other sintering ingredients, fluxes, coke breeze etc.. are reported elsewhere [2] .

Rajhara : Hard laminated to massive (hematite)
Dalli unwashed : Soft laminated containing higher amount of laterite
Dalli Washed : Soft laminated containing higher amount of laterite
Blue dust : high grade hematite fines
Manual : Mixed varieties of hematite ores from hard laminated to lateritic

Table 1: Sieve analysis of different iron ore fines

SIZE (mm)	Weight %				
	HLO	SLO (Dry)	SLO (Washed)	Blue dust	Manual
+10 mm	6.5		10.0	9.5	6.0
- 10 mm+5 mm	13.4		19.6	10.5	22.8
-5 mm+3 mm	10.8	24.2	20.4	10.2	16.4
-3 mm+1 mm	13.8	14.8	19.7	20.3	14.0
-1 mm	55.5	28.8	30.3	49.5	40.8

The sintering study was carried out in a pot unit of 0.0625 sq. m cross sectional area and 0.3 m height. The sinter mix constituting of ore fines along with fluxes so as to maintain sinter basicity ($CaO/SiO2$): 2.5/3.1 was prepared in a balling drum and fed into the pot. The velocities of the air infiltration through the bed of sinter mix before ignition (pre-ignition permeability) were measured at different suction pressure. Effect of moisture and basicity on the permeability was established and the parameters, Dp, φ and ε were computed using Ergun's equation.

RESULTS AND DISCUSSION

Application of Ergun's Equation to Sinter Mix Bed

The process of sintering takes place in a narrow range and the velocity of gas infiltration varies in a complex manner as the sintering progresses since the bed is composed of different sintering zones which have different permeability. The present work is restricted to the validation of Ergun's equation in computing the granule characteristic (size , void- age and shape factor) before the bed is ignited (pre-ignition permeability) which has got significance in affecting the sintering speed as in case of Bhilai Steel Plant (SAIL) [2]. Hinkley and Waters [8] showed that the Ergun equation accurately predicted bed permeability over a wide range of moisture addition in case of green sinter mix. The Ergun's equation, which pertains to the isothermal flow of an incompressible fluid, may be applied to the bed of sinter mix before ignition because changes in gas volume caused by the pressure gradient across the bed have a negligible effect on gas flow[9].

The parameters, dp, φ and ε were calculated from the set of pressure drop and air velocity relationship data, before ignition over wide range of moisture and sinter basicity. The validity of Ergun's equation was checked while comparing the observed ΔP (third set of data) with the computed one by fitting the above parameters in the equations. Fig. 2 shows the calculated values of pressure drop using the Ergun's equation against the observed ones. A close matching shows that the pre-ignition permeability can be accurately predicted by the Ergun equation over a wide range of moisture addition Annexure 1 lists typical calculation in the present case.

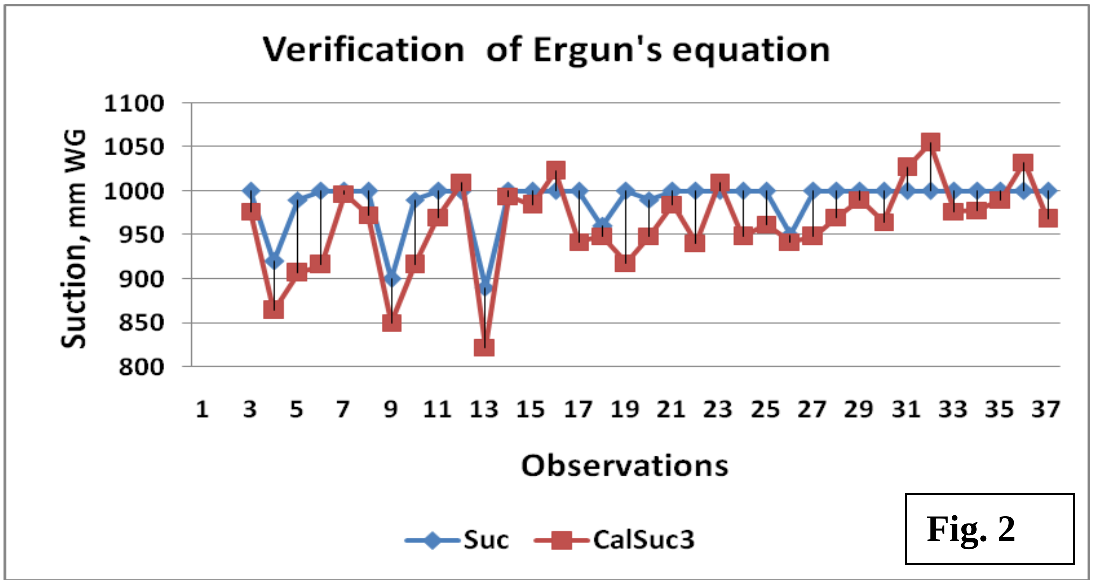

Fig. 2

Effect of Moisture

Moisture in the sinter mix owing to its balling effect increases the gas permeability and decreases the amount of very fine particles of the mix. With proper agglomeration of the fines, the voids in the dry and wet zones, could be prevented to be filled up. Figures 3 and 4 show the effect of moisture content on the equivalent spherical diameter, Dp of sinter mix, respectively, at 3.1 and 2.5 sinter basicity.

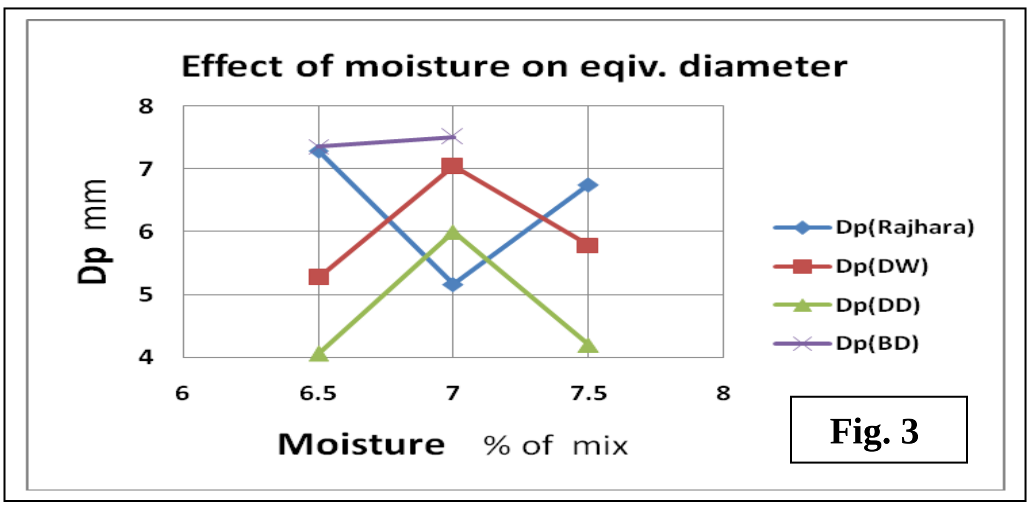

Fig. 3

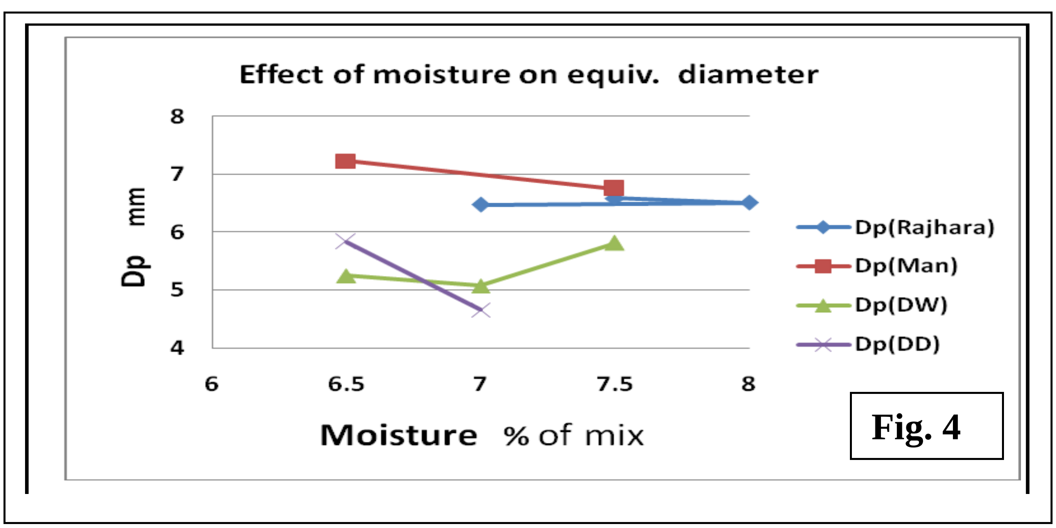

Fig. 4

Too little moisture restricts the green granule growth , whereas too much water can saturate and collapse the lower bed and decreases permeability, hence the Dp. 6.5 % moisture seems to be optimum at 2.5 sinter basicity, whereas 7 % moisture was optimum at 3.1 sinter basicity (except Rajhara ore). At 2.5 sinter basicity (Fig. 3) Dalli dry and wet has the lowest Dp. It is apparent from these figures that the optimum moisture content depends on the size and nature of ores. The iron ore granule grows up with increasing the water content added into the mix. The mass fraction of the particles with smaller size decreases wit increasing the water content , and that of particles with bigger size increases with increasing the water content. With reference to blue dust and the ores from manual mines, which are dried ones, the same / higher permeability value can be achieved at lower mix moisture which was 6.5% compared to Dalli washed ores.

Figures 5 and 6 show the effect of moisture content on the sinter mix void fraction, **ε**, respectively, at 3.1 and 2.5 sinter basicity. 7 % moisture seems to be optimum for the void fraction also. Blue dust and Rajhara ore fines has lowest void fraction. This was because of better granulation in case of high grade (Fe_2O_3) ores.

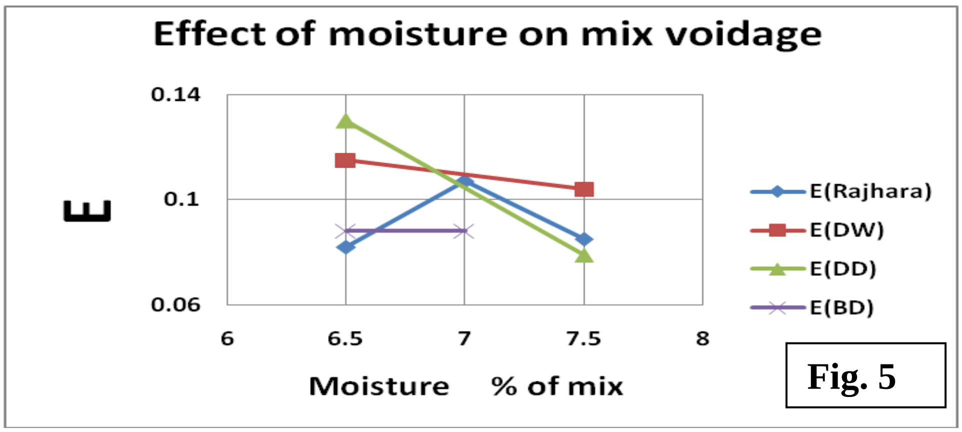

Fig. 5

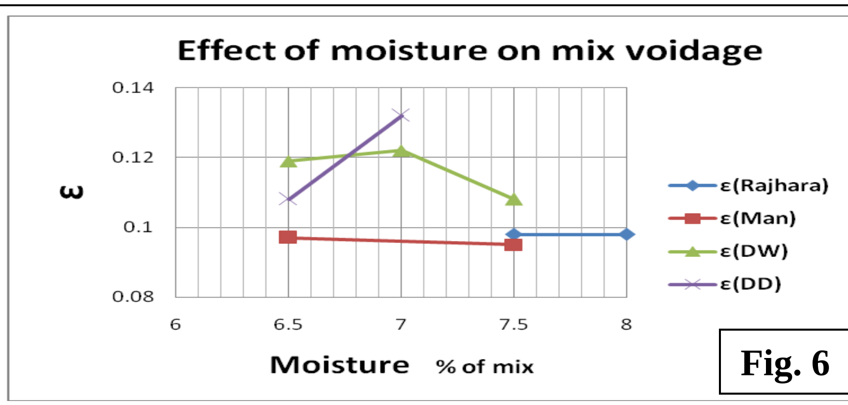

Fig. 6

The relationship between mix moisture and green permeability is extremely complex. It is most likely that at the highest mix moisture value, the granules became very compressible resulting in a sharp decline in green bed permeability. This fact possibly explains sharp decline in mix voidage at 7.5 wt.% moisture. The sphericity or shape factor of the granule also has significant effect, the more spherical granules giving highest permeability. Deviation at high moisture addition, in case of Rajhara ores was probably due to changes to the shape factor, which had been assumed constant over the range of the moisture contents.

Effect of Sinter Basicity

Figures 7 and 8 show the effect of sinter basicity on the equivalent spherical diameter, Dp of sinter mix, and its void fraction, **ε**, at 7 % moisture content. Marginal increase in Dp with the increase in sinter basicity was observed. For Rajhara (hard laminated hematite) the increase was more than that of Dalli (soft laminated more of goethite). Blue dust has highest Dp The sinter mix voidage, E, decreases with the increase in sinter basicity. At sinter basicity 2.5 also 7 % moisture seems to be optimum

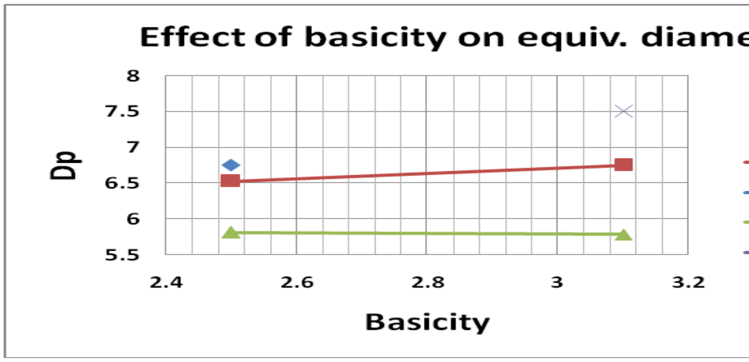

Fig. 7

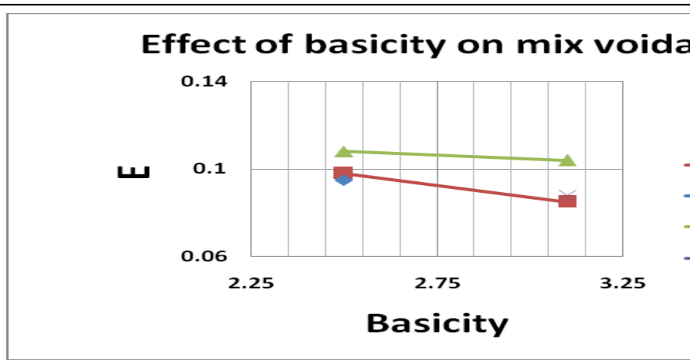

Fig. 8

CONCLUSIONS

- The spherical average diameter of the sinter mix granules, Dp and void fraction , **ε** have been computed for the sinter mix constituting different ore fines from Bhilai Steel Plant (SAIL) & the parameters affecting these have been established. These are greatly affected by (a) the type of ore fines, (b) the moisture content of sinter mix, and (c) the sinter basicity (proportion of ore to flux in the mix)

- The sphericity or shape factor of the granule has significant effect on these parameters. Deviation at high moisture addition in case of some ore fines could be probably due to changes to the shape factor, which had been assumed constant (0.9 in this case) over the range of the moisture contents.

Acknowledgement

The experimental data used in the present work for the modeling of the gas flow have been taken from the experimental studies reported elsewhere [2]. The author expresses his deep sense of gratitude to his co-workers who did participate in the experiments. He also acknowledges Steel Authority of India Limited for the support to the experiments.

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Annexure : Typical Calculation using Ergun's Equation

For air the viscosity, ή, and density, p, at 25 degree C :

ή = 1750 *10 (E-8) Pa. s = 1750 *10 (E-8) (N/sq. m) * s
= 1750 *10 (E-8) * (0.102 *9.81) kg / (m s) [1 N = 0.102 kgf = 1 kg*9.81 m/(sq.s)]
= 1.75 * 10 (E-5) kg/ (m s)
p = 1. 293 kg/ cu.m

With regards to a typical hematite ore fines (100 % -0 mm size) along with 1% lime, 30% return sinter fines 7 % moisture and fluxes (limestone and dolomite) so as to maintain sinter basicity at 2.5 typical observations on the velocities of the air infiltration through the bed of sinter mix, 0.3 m height were 0.835 m/s and 0.712 m/s, respectively when subjected to the pressure drop , ΔP across the bed (through vacuum pump) 800 mm [78480 kg/ (m sq.s)] and 600 mm WG [58860 kg/ (m sq.s)].

D (using Eq. 6) = [(78480/0.835 – 58860/0.712)] / (0.835-0.712) = 91060 (kg / cu.m)
C (using Eq. 7) = [(78480/0.835) – D *0.835] , or
= [(58860/0.712)] – D *0.835] = 17867 [(kg / (sq.m*s)]

(0.07) * (C / D) = SSA * (ή / p) , Or
(0.07) * (17867/91060) (m/s) = SSA (sq.m/cu.m) * [(1.75* 10E(-5) / 1.293) (sq.m/s)]
SSA = 1014.8 (sq.m/cu.m)

The void fraction, ε, can be found out using Eq. (xi) :
ε^3 = [1.75 * 1.293 (kg/cu.m) *0.3(m) / 6] * [1014.8 (sq.m/cu.m) /91060 (kg / cu.m)], [--]
= 0.0012608 [--] , Or , ε = 0.108 [--]

The value of shape factor, φ, varies along with the mix composition and nature of iron ore fines. Typically for φ = 0.9:
The spherical equivalent diameter, d_p, can be computed from Eq. (12)
d_p = 6 (1-0.108) / 0.9 * (1/ 1014.8) = 0.0059 m = 5.9 mm