KnE Engineering

TIM'2018
VII All- Russian Scientific and Practical Conference of Students,
Graduate Students and Young Scientists on
"Heat Engineering and Computer Science in Education, Science and Production"
Volume 2018

Conference Paper

Improvement of Calculation Methods for Heat Transfer Factor in Iron Ore Pellet Bed

E. G. Dmitrieva, V. S. Shvydkii, S. Ya. Zhuravlev, and I. V. Plesakin

Ural Federal University (UrFU), Ekaterinburg, Russia

Abstract

For the sake of improving the calculation procedure for heat transfer in metallurgical unit dense beds a number of experiments has been carried out that allow adjustment of the heat transfer factor between the gas flow and the pellets in the course of heating. In the course of analysis, a permanent channeling flow was detected in the pellet bed at Re = 100 – 1400. The heat transfer factor was calculated and the pellet temperature was determined in the course of heating within ± 11.4°C.

Keywords: heat transfer in bed, pellet firing, dense bed, heat transfer factor, hydrodynamic resistance, gas flow

Corresponding Author:
V. S. Shvydkii
v.s.shvid@gmail.com

Received: 6 June 2018
Accepted: 15 June 2018
Published: 17 July 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the TIM'2018 Conference Committee.

1. Introduction

Heat transfer between gas and granular solid bed to a considerable extent determines the unit performance and product quality. Heat transfer intensity is determined through density of heat flow from a hotter solid to a colder one and it in its turn is proportional to the heat transfer factor α_F and the temperature difference Δt. However, up to the present there are no mathematical expressions allowing heat transfer factor determination in dense beds of sintering and roast machines, blast furnaces and other metallurgical units with an accuracy sufficient for the engineering analysis.

For the pellet bed, the heat transfer factor is determined either by generalized observed dependences, proposed by V. N. Timofeev [1], or by formula of N. N. Berezhnoy [1], which is considered to be the most accurate:

$$Nu = 0.00028 Re^{1.8}, \tag{1}$$

where Nu = $\alpha_F d/\lambda_g$ – Nusselt criterion (number);

Re = wd/ν_g – Reynolds criterion (number);

d = particle diameter;

How to cite this article: E. G. Dmitrieva, V. S. Shvydkii, S. Ya. Zhuravlev, and I. V. Plesakin, (2018), "Improvement of Calculation Methods for Heat Transfer Factor in Iron Ore Pellet Bed" in *VII All- Russian Scientific and Practical Conference of Students, Graduate Students and Young Scientists on "Heat Engineering and Computer Science in Education, Science and Production"*, KnE Engineering, pages 1–9. DOI 10.18502/keg.v3i5.2649

λ_g = gas heat conductivity;

w = gas rate in clear opening; and

ν_g = gas kinematic viscosity.

Error in heat transfer factor determination using equation (1) may comprise 30–40%, what significantly reduces the thermotechnical calculation accuracy. Apparently, it is caused by the lack of a common approach to heat transfer and bed flow dynamics analysis.

Two approaches are known for analysis of heat transfer in the bed—with the use of a jet flow model around the particles and with the use of gas channeling flow model. However, as the experiments showed [2–4], jet stream in granular beds is more developed at Re > 2 103. As in the course of pellet firing Re < 2 103, the gas flow pattern remains vague. Based on the concept of dense bed flow dynamics, it can be expected that in this case a channeling gas flow takes place. To prove the aforementioned statement and obtain an exact dependence for the heat transfer factor in the bed, Reynolds analogy may be used [2].

2. Heat Exchange Equation in a Layer of Pellets

Let's consider the following equation of heat transfer in the bed [2] (for gasses the Prandtl number $\mathrm{Pr} = \nu_g/a = 1$, where a = gas thermal diffusivity):

$$Nu = C_d Re^n, \tag{2}$$

where C_d = nondimensional factor reflecting heat resistance of boundary layer on the particle surface and

n = a constant determined by the conditions of flow over particles in the bed.

As per Reynolds analogy for the flow core at Pr = 1, formula [2] is true:

$$C_d = C_f/2 = aRe^{-0{,}5}, \tag{3}$$

where C_f = friction factor on solid surface.

Pressure drop at gas flow in tubes and channels is described by formula [2]:

$$\frac{\Delta p}{L} = f\frac{w^2}{2d}\rho, \tag{4}$$

where f = friction factor in channels with the length of L.

From the heat exchange theory it is known that

$$f = C_f/4. \tag{5}$$

For the ball particle bed, equation (4) is written as [1]:

$$\frac{\Delta p}{\Delta h} = \zeta_{\text{bed}} \left(\frac{w^2}{2d} \right) \rho, \tag{6}$$

where ζ_{bed} = bed resistance factor. It is easy to note that $\zeta_{bed} = f$ if L comprises with the bed height Δh. Then, by inserting equations (3) and (5) into (2) we obtain

$$Nu = C_d Re^n = (c_f/2)Re^n = 2fRe^n = 2\zeta_{bed} Re^n, \tag{7}$$

where $2\zeta_{bed} \sim \mathrm{Re}^{-0,5}$.

Thus, the task of heat transfer factor determination in the bed resolves itself into determination of ζ_{bed} factors in gas-dynamic resistance equation. To describe the pellet dense bed resistance, the equation describing the nonstationary filtration resistance of fluid or gas in void cannel is used [3]:

$$\rho dV/d\tau = -\partial p/dx + \mu \Delta V, \tag{8}$$

where dV = instant fluid or gas flow in time $d\tau$; p = fluid or gas density; $\Delta = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ – Laplace operator for flow field. Using the local gas flow and coming over to description of the whole bed, the following equation is obtained:

$$-\frac{\partial p}{\partial x} = \frac{\mu u}{k} + \frac{\rho u^2}{2l} + \rho \frac{\partial u}{\partial \tau}. \tag{9}$$

Here, the first term of the right side corresponds to the Darcy law, where k – penetrability factor – describes pressure drops due to fluid friction on void channel walls. The second term corresponds to the drops at inertial motion caused by channel unstraightness. The term includes parameter 1 having length dimension.

It is demonstrated in the work [3] that a binomial resistance law is the most reasonable from the physical standpoint for porous media and is observed at all Reynolds numbers. In dimensionless form for stationary motion ($du/d\tau = 0$), equation (9) may be written as follows:

$$-\frac{\partial p}{\partial x} \frac{2l}{\rho u^2} = \frac{\mu l}{\rho u k} + 1. \tag{10}$$

With $\zeta^* = d_{eq.}$ taken, a universal resistance equation is obtained [3]:

$$\zeta^* = \frac{\partial p}{\partial x}\frac{2d_{\text{eq}}}{\rho u^2}, \tag{11}$$

where ζ^* = universal resistance factor,

$$\zeta^* = 1/Re^* + 1(12), \tag{12}$$

where Re* = universal Reynolds number, having a unit order relative to external flow parameters determined by Reynolds number to the power of *m*:

$$Re^* = Re^m = \left(\rho\frac{uk}{\mu d_{\text{eq}}}\right)^m. \tag{13}$$

The resistance law in equation (11) may be approximately considered linear at Re* << 1 and quadratic at Re* >> 1. Switching over from a local gas rate to the filtration rate *w* and integrating equation (11) over the bed height, the following equation for the equivalent channel diameter is obtained.

$$\frac{\Delta p}{\Delta h} = \zeta_{\text{bed}}\frac{w^2}{2d_{\text{eq}}\varepsilon^2}\rho, \tag{14}$$

formally coinciding with equation (6).

3. Experimental Determination of the m Factor

To determine the factor *m* in equation (13) and calculate ζ_{bed} for the roast pellet bed, a number of research works has been carried out on a pilot plant for pellet firing in the Uralmechanobr JSC lab. The plant (**Figure 1**) consisted of a vertical cylinder channel 1 with the diameter of 100 mm on a metal grid. Pellets with the diameters of 14.5 and 11.0 mm were used as filling material 3; the diameter ratio changed in various experiments as well as mixture of different fractions with an average diameter of 12.9 corresponding to the real pellet bed. Fill layer height of 0.3 m was constant. Discharging under the bed was created by a liquid piston pump. Air (gas) flow and temperature at the bed input were measured by a heat loss anemometer 2 or a thermocouple 7.

To measure the bed static pressure, a number of openings was provided for pulse tubes 4 or thermocouples 7, spaced 65.0 mm apart. Static pressure and its drop Δp

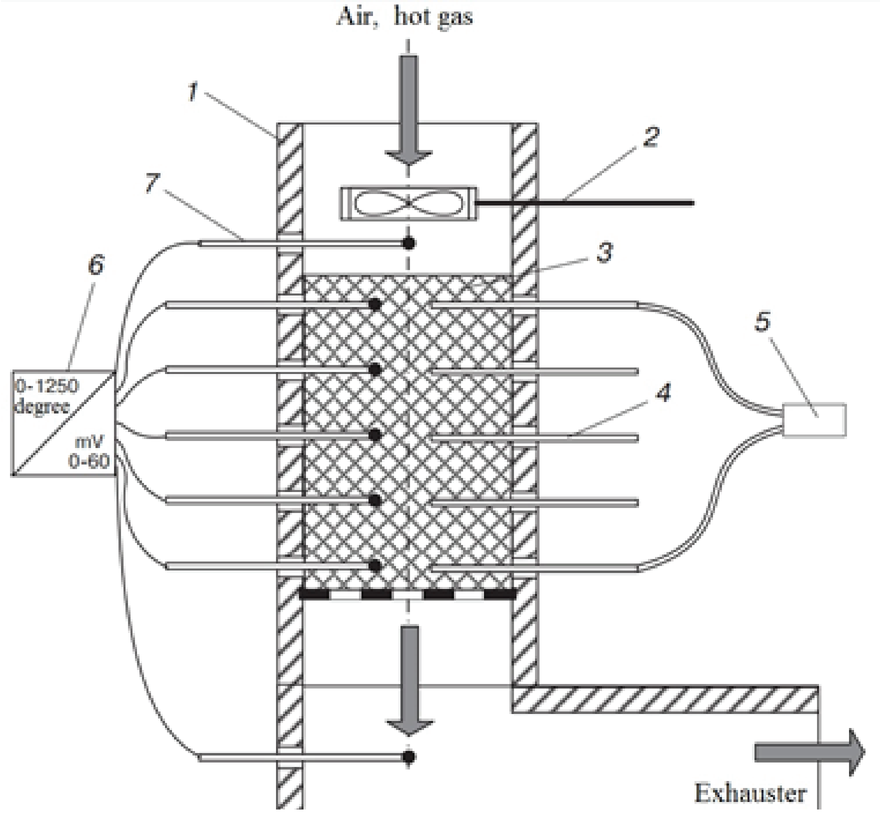

Figure 1: Experimental plant for the study of gas dynamics and heat transfer.

through the bed height at$h$ = 0.245 m were measured by a differential manometer 5, the bed temperature values were received by thermal converter 6 and were registered in data base. In the experiments, the air flow and gas temperature as well as the fractional makeup varied at the bed input. The resistance measurement results are given in **Table 1** and in **Figure 2**.

If we approximate the obtained relations, we get the index of power m in equation (13) atRe = 100 – 1400 equal to 0.5, what coincides with the value for the friction factor $C_f \approx \mathrm{Re}^{-0,5}$ for gas laminar flow along the channel wall [4].

Gas permeability factor k, m^2, in expression for the Reynolds number was calculated byKozeny–Karman formula [5]:

$$k = b\varepsilon^2 d^2/(1-\varepsilon)^2. \tag{15}$$

In formula (15) b = 2.25 for rhombohedral particle alignment, b = 1.78 for octahedral. Note that for the bed with an average diameter of 12.9 mm, a value of b = 2.25 was obtained, which corresponds to the rhombohedral alignment – the most typical for

Table 1: Experimental/calculated values of bed hydrodynamic resistance Δp, Pa.

Filtration rate, m/sec	$\Delta p_{exp}/\Delta p_{calc.}$ at average particle diameter,		mm, (bed fractional void volume)	
	14.5 (0.419)	14.15 (0.419)	13.8 (0.404)	12.9 (0.417)
0.2	10/8	11/10	13/11	17/14
0.4	22/22	31/27	33/31	45/40
0.6	40/41	50/49	57/57	75/73
0.8	60/63	81/76	83/88	110/113
1	90/88	108/106	117/122	153/158
1.2	120/118	144/140	157/161	200/208
1.4	160/151	189/184	203/203	253/262
σ*	± 7	± 8	± 9	± 12

Note: *Standard deviation.

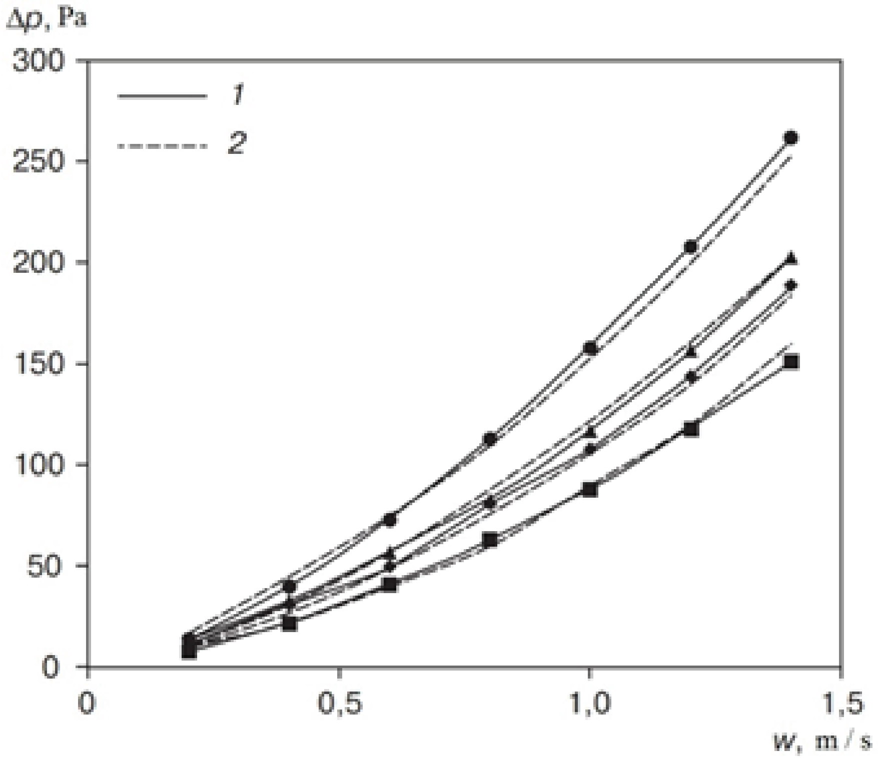

Figure 2: Dependence of the hydrodynamic resistance of the layer on the filtration rate. Note: 1 = experimental data; 2 = calculated data.

random alignment [1]. Thus, for the pellet bed, an equation may be written, describing the bed flow dynamics:

$$\frac{\Delta p}{\Delta h} = \frac{\rho w^2}{2\sqrt{Re_{\text{eq}}}\varepsilon^2 d_{\text{eq}}}, \tag{16}$$

where the bed resistance factor is ζ_{bed} = (Re)$^{-0,5}$.

4. Result and Discussion

Let's check reliability of heat transfer factor calculation in the pellet bed by inserting the obtained ζ_{bed} values into equation (7), at that we shall consider that heat transfer in the bed is developed in channels formed by a laminar boundary layer with periodic eddy motion and flow core [4]. To compare the obtained calculated heat transfer values α_F with the practical ones, a number of experiments has been carried out on the pellet bed heating at a unit provided in **Figure 1.** Gasses getting into the bed were heated to 800°C with a burner device, the gas temperature was maintained constant. The bed height comprised 0.3 m, gas filtration rate w = 0.8 m/sec (at normal conditions), average pellet diameter = 14.15 mm. The experiment results and data were calculated based on procedure [1], for which αp was determined by equation (7), as shown in **Figure 3**, from which it is seen that the experimental and calculated material temperatures in the heating period practically do not differ, the error comprises ± 11.4°C, that is, the hypothesis about the channel gas flow in the pellet bed at Re = 100 – 1400 is confirmed.

Therefore, use of the heat transfer factor calculation method based on the flow dynamics equations of the bed allowed ensuring high coincidence of calculated and experimental data for the pellet bed heating.

5. Summary

Research works with the use of Reynolds analogy between heat transfer and flow dynamics of dense bed allowed adjustment of heat transfer factor between the gas flow and the pellets in the course of heating. Use of filtration gas flow theory [6–9] and review of obtained data enabled detecting of steady channel flow in the pellet bed at Re = 100 – 1400 with the pattern determined by the gas dynamic resistance factor and the flow rate. However, when changing to real pellet firing conditions on conveyor machines additional factors, influencing the gas heat transfer—pellet shrinkage, gas

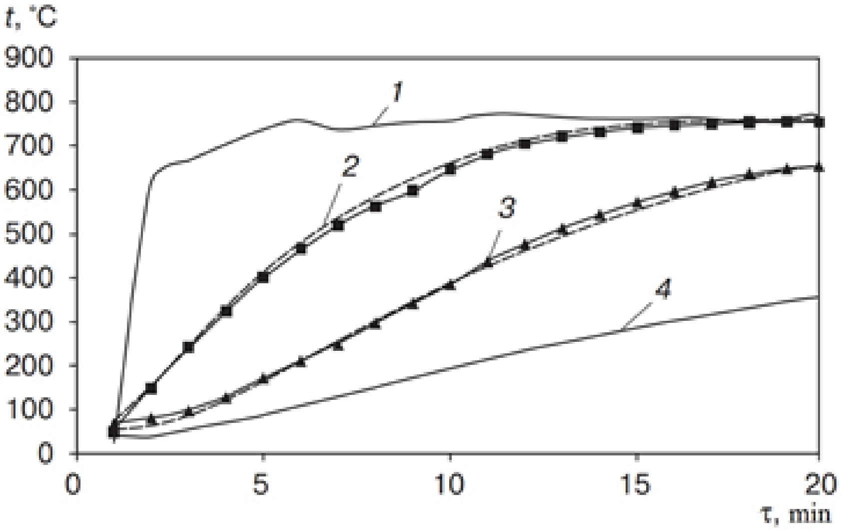

Figure 3: Change of temperature of gases and pellets during heating up to 800°C. Note: 1 = t_{gas} at the inlet; 2 = t_{pel} at a distance of 0.1 m from the surface; 3 = t_{pel} at a distance of 0.2 m from the surface; 4 = t_{gas} at the exit from the layer (—— = experimental data; - - - - = calculated data).

and pellet heat capacity change, nonuniformity of filtration rate field throughout the machine width, etc.—shall be considered.

References

[1] Sabanero, M. and Arndt, C. R. (September 1999). Production of high-quality DR grade pellets at IMEXSA, in *International Conference on Alternative Routes of Iron and Steelmaking (ICARISM)*, pp. 29–34. Perth.

[2] Huang, Z., Yang, D., and Yi, L. (2012). Effect of thermal charging of iron ore pellets on the reduction rate and compressive strength in gas-based reduction process, in *2nd International Conference on Materials Science and Information Technology*, pp. 262–266.

[3] Iguchi, M. and Ilegbusi, O. J. (2014). *Basic Transport Phenomena in Materials Engineering*. Japan: Springer.

[4] Ettrich, J. (2014). *Fluid Flow and Heat Transfer in Cellular Solids*. Karlsruhe: Karlsruher Institut fur Technologie (KIT).

[5] Alptekin, E., Ezan, M. A., and Kayansayan, N. (2014). Flow and heat transfer characteristics of an empty refrigerated container, in D. Ibrahim, M. Adnan, and K. Haydar (eds.) *Progress in Exergy, Energy, and the Environment*, pp. 641–652. Springer International Publishing.

[6] Duroudier, J. P. (2016). *Divided Solids Mechanics*. New York: Elsevier Inc.

[7] Nield, D. A. and Bejan, A. (2012). *Convection in Porous Media* (4th edition). New York: Springer.

[8] Ghiaasiaan, S. M. (2011). *Convective Heat and Mass Transfer*. Cambridge: Cambridge University Press.

[9] Tiaab, D. and Donaldson, E. C. (2015). *Petrophysics: Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties* (4th edition). New York: Elsevier Inc.