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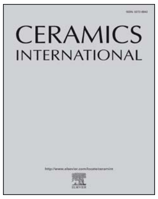

Intrinsic permeability of refractories from gas permeability measurements: Comparison of results

Emmanuel de Bilbao[a,*], Lise Loison[b], Yassine Hbiriq[a], Cédric Orgeur[a], Séverine Brassamin[a], Thorsten Tonnesen[b], Jacques Poirier[a]

[a] *CNRS, CEMHTI UPR3079, 1D, Avenue de la Recherche Scientifique CS90055, 45071 Orléans Cedex 2, France*
[b] *RWTH Aachen University, Institute of Mineral Engineering, Mauerstrasse 5, D-52064 Aachen, Germany*

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ABSTRACT

The gas permeability of porous materials largely depends on pressure, with the intrinsic permeability typically being determined using Klinkenberg's model, which is valid when the gas flows under viscous conditions. However, measurements performed on refractories with the outlet at atmospheric pressure often reveal inertial effects. Therefore, gas permeability is assumed to be flow-rate dependent; an alternative approach is proposed to determine the intrinsic properties using the Forchheimer number. A gas permeameter has been developed to improve measurement accuracy. It allows for the conduction of a test in viscous flow conditions or with inertial effects. The improved gas permeameter was used to compare the different approaches to the evaluation of the intrinsic permeability of four refractory materials with permeabilities ranging from 0.03 to 6 darcies. Combining a modified pressure drop method with Klinkenberg's model proved to be a reliable method for consistently evaluating refractory material permeability.

1. Introduction

Permeability is a very important property of refractory materials. Some examples include, the key role of permeability to gases in the dewatering of refractory castables [1–3]; in oxygen pick-up using a submerged nozzle during the continuous casting of steel [4]; and in the corrosion of refractory linings by gases (Na_2O, K_2O,…) or slag [5,6]. Corrosion could be described as a reactive transport mechanism. The slag penetrates the porous matrix and reacts with the solid phase due to thermodynamic disequilibrium between the slag and the refractory material (Fig. 1). The slag and refractory compositions then change, modifying the penetration of the slag as different chemical reactions occur [7,8]. Capillary suction, sometimes enhanced by metallo-static pressure, is the driving force. The slag impregnation into the porous space occurs under unsaturated conditions where the slag progressively replaces the gas that had previously occupied the pores [9,10]. Assuming gas flows freely through the porous space without an increase in its pressure, the slag flow rate is limited by the refractory permeability to the slag according to Darcy's law [11]:

$$\vec{v} = -\frac{k}{\mu}\overrightarrow{\mathrm{grad}}(P) \tag{1}$$

where $\vec{v}$ is the velocity of the fluid, P is the pressure, μ is the dynamic viscosity, and k is the intrinsic (or liquid) permeability since only the slag flow is considered. As a result, intrinsic permeability is a very important property of refractory materials as it plays a key role in the resistance to corrosive fluid penetration.

Permeability could be measured under steady state or unsteady state conditions using a gas or a liquid. In practice, the steady-state permeability measurement method is well suited for characterising refractories, even for materials with very low permeability. It is time-consuming, however, it yields results with better accuracy than unsteady-state techniques [12,13]. The steady-state technique primarily consists of measurements of the velocity of the fluid, v, flowing through a sample, as well as inlet and outlet pressures, P_i and P_o, respectively (Fig. 2). When the fluid is a liquid, providing a laminar flow, it is possible to directly determine the liquid permeability from a single triplet of measures applying the integrated form of Darcy's law:

$$\frac{P_i - P_o}{L} = \frac{\mu}{k}v \tag{2}$$

where L is the sample length.

In the refractory field, permeability tests are usually performed with a gas as proposed in the industry standards [14,15]. When gas is used for the measurements, its compressibility must be considered and the integrated form of Darcy's law becomes:

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[*] Corresponding author.
E-mail address: emmanuel.debilbao@univ-orleans.fr (E. de Bilbao).

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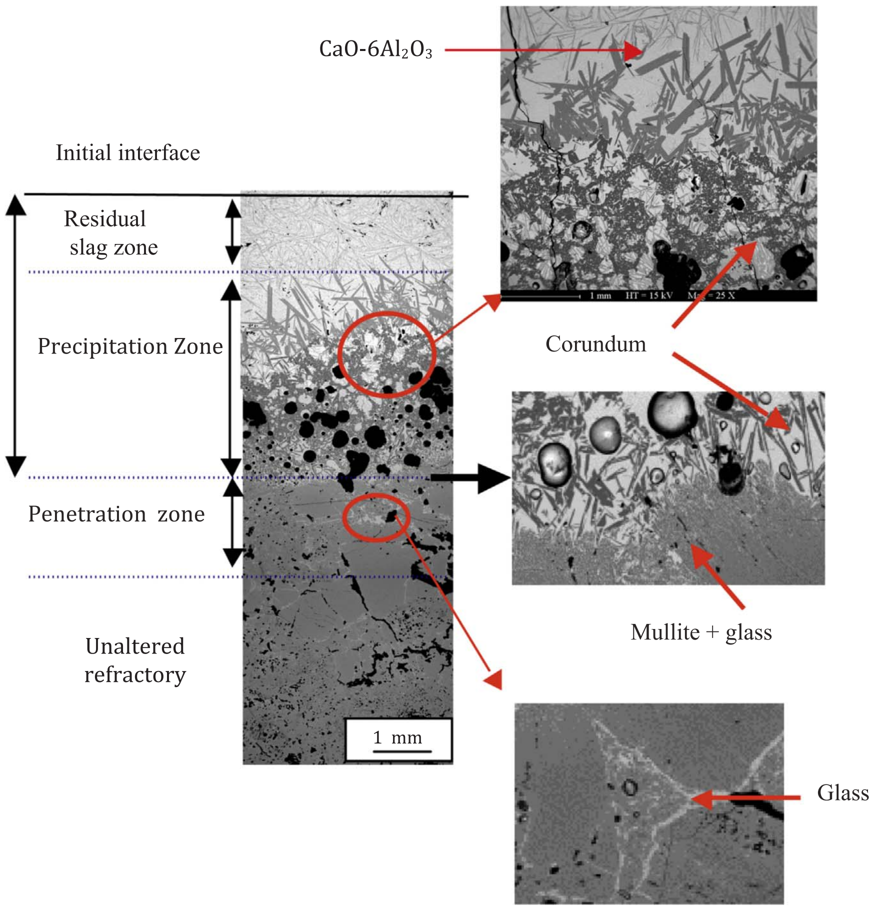

Fig. 1. Microstructure of andalusite refractory corroded by Al_2O_3-CaO slag.

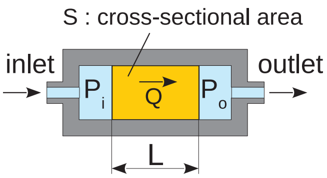

Fig. 2. Steady state measurement of permeability. The inlet and outlet pressures, P_i and P_o, and the volumetric flow rate, Q, are measured. The flow rate is derived from Q and the sample cross-sectional area, S. Permeability is calculated according to Darcy's law.

$$\frac{P_i^2 - P_o^2}{2PL} = \frac{\mu}{k_g}v \tag{3}$$

where k_g is the gas permeability and P is the absolute gas pressure for which the flow rate, v, is evaluated (P_i if v_i or P_o if v_o). Owing to the pressure gradient and gas compressibility, the flow rate is different at the entrance and exit of the sample.

There are two usual methods to conduct steady state gas permeability measurements. In the first method, the outlet is maintained at atmospheric pressure and the inlet pressure is progressively increased while the flow rate is determined from Eq. (3). The gas permeability is calculated from each triplet of measures (P_i, P_o, v). The second method consists of applying a backpressure at the outlet and increasing either the inlet pressure or the flow rate. Whatever the applied method, the gas permeability, k_g, depends on the pressure conditions; the intrinsic permeability is derived from the set of gas permeability values.

When the gas velocity increases, inertial effects may arise on a microscopic scale and the equation attributed to Forchheimer is used to consider these effects [12,16]:

$$\frac{P_i^2 - P_o^2}{2PL} = \frac{\mu}{k_1}v + \frac{\rho}{k_2}v^2 \tag{4}$$

where the factor ρ/k_2 multiplying the squared velocity accounts for inertial effects that become predominant as the flow rate increases. In this equation, k_1 is the Forchheimer viscous permeability, ρ is the pressure-dependent gas density, and k_2 is called the 'non-Darcian permeability'. The gas permeability of refractories is usually measured under steady state conditions with the outlet at atmospheric pressure; inertial effects are often observed. Different approaches have been proposed in the literature to derive the intrinsic permeability, but they may not yield the same evaluation, especially when inertial effects arise during the test.

The objective of this work is to compare the different approaches proposed in the literature to determine the intrinsic permeability from steady-state gas permeability measurements. A gas permeameter has been developed to control the flow regime. Tests and analyses were conducted on four different refractory materials using the newly developed gas permeameter.

2. Derivation of the models used to derive intrinsic permeability from gas permeability measurements

The steady-state multiple-point gas permeability measurement yields a set of triplets of measures (P_i, P_o, v). For each triplet of measures (P_i, P_o, v), the squared pressure gradient (left-hand side of Eqs. (3) and (4)) is plotted against the flow rate. This plot is called the Darcy plot in the present paper (Fig. 3).

Depending on the apparent shape of the plot, straight or parabolic, two strategies are used to derive the intrinsic permeability from the measures.