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Theoretical modelling of gas flow and filtering of particulates in cracks in containment barriers, and comparison with other theoretical and empirical studies

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ABSTRACT

Following earlier publication of a model of crack flow and filtering based on a 2-D crack representation, the model has now been improved and submitted to validation by comparison with data from a number of other theoretical and experimental studies. This process has led to improved understanding of gas flow and filtering in real crack geometry and reinforced expectations that the model predictions of barrier filtering capacity will be conservative for realistic containment conditions. Our analysis also indicates that, because of drag effects related to the existence of reduced aperture sites, the viscosity limited flow cannot be approximated by the plane Poiseuille model. As a result, theoretical models employing this assumption over-predict measured flow rates by around an order of magnitude. The narrowing of the flow stream at these reduced aperture sites is also found to be a factor which significantly boosts the filtering of particles. As a result of these investigations, there is a strong possibility that we have now identified all essential elements required for a detailed description of aerosol transport through cracks via the laminar flow of a non-condensible carrier gas.

1. Introduction

The CCFE crack filtering model [1] employs 2-D crack geometry, following Boussa et al. [2], making use of published parameters derived from measurements of crack characteristics in concrete samples performed in the latter study. The path of the flow is represented by a series of linear segments whose orientations vary with respect to the average flow direction. It is reasonable to expect a similar level of granularity in the crack walls for variation in the direction transverse to the flow, as well as similar statistics. However, the 2-D model geometry takes no account of variation of crack characteristics in the transverse direction. An additional assumption is that the crack opening displacement (COD) is constant throughout the crack.

The CCFE model has benefited from a number of improvements. In particular, it has been extended to include diffusional particle removal, in addition to inertial particle removal (which arises when some particles, unable to precisely follow a change in the direction of the flow stream, maintain trajectories which intersect the crack wall), and also revised with an improved model of bend losses due to laminar-swirl effects. Following these and other minor revisions to the gas flow equations, a more compact form for the inlet velocity is now obtained:

$$v_i = \frac{12\eta L}{d^2 k(Re) N \rho_i} \left\{ \sqrt{1 + \frac{k(Re) N d^4 G \rho_i P_o}{72\eta^2 L^2} \left[1 - \left(\frac{P_o}{P_i} \right)^{1/G} \right]} - 1 \right\} \quad (1)$$

where Re is the Reynolds number, given by:

$$Re = \frac{2\rho v d}{\eta} \quad (2)$$

ρ and v are the gas density and average velocity, respectively, at an arbitrary position along the flow (mass conservation dictates that the product ρv, and therefore also Re, is constant at all distances along the flow path), d is the thickness of the flow stream (approximated by the COD), N is the average number of crack segments per unit length in the flow direction, ρ_i is the inlet gas density, P_i and P_o are the inlet and outlet gas pressures, respectively, η is the gas dynamic viscosity, L is the length of the flow (barrier thickness) and $G \equiv g/(g-1)$, where g is the polytropic expansion exponent. A correlation for the tortuosity head-loss coefficient, k, has been derived from results of measurements on bend losses in microchannels published in Ref. [3]. Such losses will result from laminar-swirl effects. Because k is a function of Re, the inlet velocity must now be obtained by iteration. However, for the viscosity limited regime, we have $k \to 0$, leading to an explicit formula for v_i.

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Having implemented the above revisions, validation of the model was undertaken based on comparisons with a number of other studies. These comparisons have led to an appreciation of the limitations of the 2-D modelling approach, but have also provided useful information with regard to the conservatism of the current CCFE model. The comparisons, reported in Section 2, have also led to a new understanding of gas flow and filtering in real crack geometry.

One of the aims of these investigations is to contribute to improved assessments of the consequences of hypothetical accident scenarios for fusion power plants. Therefore, as an adjunct to this study, example calculations are also performed for a bounding accident scenario for a design concept for a potential fusion power plant, and reported in Section 3. The results illustrate the capability and convenience of the current CCFE crack filtering model.

2. Comparisons

The main aim of this study is to undertake validation of the CCFE model of gas flow and filtering in cracks by comparisons with data from a range of other theoretical and empirical studies. The project has been divided into 3 separate areas:

a. gas flow rate comparison,
b. inertial filtering comparison,
c. diffusional filtering comparison.

Each of these areas is discussed in the following 3 sections, and this is followed by a brief discussion in Section 2.4 of a theoretical modelling study which attempts a convenient simulation of the combined effects of a number of selected phenomena by careful fitting of associated established formulae.

2.1. Flow rate comparisons

We consider 5 other studies on flow rate in cracks, making use of prediction equations provided in 4 of them. These 4 have been proposed by Nagano et al. [4], Gelain and Vendel [5], Rizkalla et al. [6] and Suzuki et al. [7]. The 5th study by Wang and Hutchinson [8] reports extensive measurements of flow rate, and assesses the performance of each of the formulae from Refs. [4,6,7] in predicting their results. A summary of the five prediction methods, designated as *CCFE*, *Nagano*, *Gelain*, *Rizkalla* and *Suzuki*, respectively, is given in the following 5 sections. We have classified the first 3 methods as 'theoretical' and the last 2 as 'empirical'. Corrections have been made to and rearrangements performed on some of the published formulae given below, and non-SI units converted to SI where necessary.

2.1.1. CCFE equations

Eq. (1) defines the inlet flow velocity. However, it is usual to predict the outlet flow rate, determined by the outlet flow velocity:

$$v_o = v_i \left(\frac{P_i}{P_o}\right)^{1/g} \quad (3)$$

Also, we shall be comparing with other formulae which assume isothermal ($g = 1$) conditions. Hence we shall take the limit $g \to 1$, and Eqs. (1) and (3) then lead to the following expression for the outlet volumetric flow rate ($m^3\,s^{-1}$):

$$Q = v_o wd = \frac{12\eta L w}{dk(Re)N\rho_i}\left(\frac{P_i}{P_o}\right)\left\{\sqrt{1+\frac{k(Re)Nd^4\rho_i P_o}{72\eta^2 L^2}\ln\left(\frac{P_i}{P_o}\right)}-1\right\} \quad (4)$$

where w is the width of the crack.

This expression is not actually used to calculate the flow rate in practice, since the tortuosity head loss coefficient, k, is a function of Re, and therefore velocity dependent. However, as a consistency check, we can take the limit $k \to 0$ for viscosity limited (plane Poiseuille) flow, and assume a small pressure drop. Eq. (4) then reduces to the Nagano formula (Eq. (5) below). To use the CCFE model for calculating outlet flow rate, Eq. (1) is iterated to obtain the inlet gas velocity, and the outlet velocity is then derived using Eq. (3). Multiplying the latter quantity by wd provides the outlet flow rate.

2.1.2. Nagano

The Nagano formula [4] is as follows:

$$Q = wd^3 \frac{P_i - P_o}{12\eta L} \quad (5)$$

This formula is obtained by applying the plane Poiseuille flow model for small pressure drops to a crack, assuming correspondence between the COD and the plate separation parameter of this idealised model. Thus viscosity limited flow is an implicit condition of the Nagano model.

2.1.3. Gelain

This formulation is split into two parts to cover both the viscosity limited regime and a 'transition' region [5].

For the viscosity limited regime, the flow rate is given by:

$$Q = wd^3 \frac{P_i^2 - P_o^2}{24\rho_o \eta LRT} \quad (6)$$

where ρ_o is the outlet gas density. The validity of plane Poiseuille flow is again assumed but, here, the formula is valid for compressible flow.

For the 'transition' region, the relevant formulae have been cast in terms of a friction coefficient, λ, which is fitted to the flow rate measurement data of Ref. [5]. However, the calibration of this coefficient has been performed using the theoretical assumption of plane Poiseuille flow at low flow rate. The correlation for λ is given as:

$$\lambda = \left[\frac{2.11}{1+\log(Re^{1/2})}\right]^{6.7683} \quad (7)$$

The flow rate in the 'transition' region is then given by:

$$Q = \left[2w^2 d^3 \frac{P_i^2 - P_o^2}{\rho_o^2 \lambda LRT}\right]^{1/2} \quad (8)$$

where R and T are the gas constant and absolute temperature, respectively. We also need a new expression for Re, obtained by substituting for velocity in terms of flow rate in Eq. (2) and applying to conditions at the outlet. This is given by the following relation:

$$Re = \frac{2\rho_o Q}{\eta w} \quad (9)$$

The preceding 3 equations are used to solve for Q in the transition region, for given pressure and crack assumptions.

2.1.4. Rizkalla

The Rizkalla formula, parameterised to fit the measurement data of Ref. [6], requires slight rearrangement to obtain an explicit expression for the flow rate, Q. However, the published version [6] is as follows:

$$\frac{{P_i}^2 - {P_o}^2}{L} = \left(\frac{k^n}{2}\right)\left(\frac{\eta}{2}\right)^n \frac{(RT)^{n-1}}{d^3}\left(\frac{P_o Q}{w}\right)^{2-n} \quad (10)$$

where the parameters n and k are defined as:

$$n = \frac{9.965\times 10^{-2}}{d^{0.243}}, \quad k = 1.337\times 10^8 d^{1.284}$$