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

W. E. Han

EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, U.K.

Following earlier publication of a model of crack flow and filtering based on a 2-D crack representation, the model has 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 provided evidence that the model predictions of barrier filtering capacity are likely to 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 approximation over-predict measured flow-rates by around an order of magnitude.

Keywords: flow-rate; filtering; particulates; cracks; concrete; containment

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, 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:

$$v_{\mathrm{i}} = \frac{12\eta L}{d^2 k(Re) N \rho_{\mathrm{i}}} \times \left\{ \sqrt{1 + \frac{k(Re) N d^4 G \rho_{\mathrm{i}} P_{\mathrm{o}}}{72\eta^2 L^2} \left[1 - \left(\frac{P_{\mathrm{o}}}{P_{\mathrm{i}}} \right)^{\frac{1}{G}} \right]} - 1 \right\} \quad (1)$$

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 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 $G \equiv g/(g\text{-}1)$, 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 reference [3]. Because this parameter is a function of Re, the inlet velocity must now be obtained by iteration. However, for the viscosity limited regime, we have $k \rightarrow 0$, leading to an explicit formula for v_i.

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.

author's email: winston.han@ccfe.ac.uk

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 the 4th section (section 2.4) of a theoretical modelling study which aims to combine the effects of all of these phenomena.

2.1 Flow-rate comparisons

We will 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 references [4], [6] and [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 below to the published formulae and non-SI units converted to SI where necessary.

2.1.1 CCFE equations

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

$$v_{\mathrm{o}} = v_{\mathrm{i}} \left(\frac{P_{\mathrm{i}}}{P_{\mathrm{o}}} \right)^{\frac{1}{g}} \tag{3}$$

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

$$Q = v_o wd = \frac{12\eta L w}{dk(Re)N\rho_{\mathrm{i}}} \left(\frac{P_{\mathrm{i}}}{P_{\mathrm{o}}} \right) \times \left\{ \sqrt{1 + \frac{k(Re)Nd^4 \rho_{\mathrm{i}} P_{\mathrm{o}}}{72\eta^2 L^2} \ln\left(\frac{P_{\mathrm{i}}}{P_{\mathrm{o}}} \right)} - 1 \right\} \tag{4}$$

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 $k \rightarrow 0$ for viscosity limited (plane Poiseuille) flow, and assume a small pressure drop. Equation (4) then reduces to the Nagano formula (equation (5) below). To use the CCFE model for calculating outlet flow rate, equation (1) is iterated to obtain the inlet gas velocity, and the outlet velocity then derived using equation (3). Multiplying the latter quantity by wd provides the outlet flow-rate.

2.1.2 Nagano

The Nagano formula [4] is as follows:

$$Q = wd^3 \frac{(P_i - P_{\mathrm{o}})}{12\eta L} \tag{5}$$

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:

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

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 reference [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:

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

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

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

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 equation (2) and applying to conditions at the outlet. This is given by the following relation:

$$Re = \frac{2\rho_o Q}{\eta w} \tag{9}$$

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 reference [6], requires slight rearrangement to obtain an explicit expression for the flow-rate, Q. However, the published version [6] is as follows:

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

where the parameters n and k are defined as:

$$n = \frac{9.965\times10^{-2}}{d^{0.243}}, \quad k = 1.337\times10^8 d^{1.284}$$

It should be noted that, here, the parameter k is not the same as the tortuosity head loss coefficient which appears in equations (1) and (4).

2.1.5 Suzuki

The Suzuki formula [7] is similar to Nagano apart from the inclusion of an empirically fitted COD dependent factor, as follows:

$$Q = c(d) w d^3 \frac{(P_i - P_o)}{\eta L} \tag{11}$$

where the function of COD, $c(d)$, is given by:

$$c(d) = 15.3d + 7.56\times10^{-3}$$

2.1.6 Predictions

A barrier thickness of 15 cm with a pressure drop of 0.1 bar were chosen for the comparison exercise in order to ensure similarity to the empirical conditions. Results are given in Figure 1. Flow-rates predicted with the CCFE model (given by, although not calculated with, equation (4)), as well as the 4 alternative formulae, are plotted here as a function of COD.

What is apparent from Figure 1 is the fact that the three theoretical predictions coincide for the viscosity limited regime, while the two empirical correlations predict much lower flow rates but agree well with each other over the range of the empirical measurements, defined approximately by the region of intersection of the two curves. Furthermore, we may also infer from the information they have supplied that the flow-rate measurements of Wang and Hutchinson are in good agreement with these two formulae in the same region. The latter study does not reveal the specific flow-rate details as a function of COD, but their curves showing the relative magnitudes of their measurements versus predictions (Figure 10 in reference [8]) are evidence of this agreement. Thus we may conclude that the results of these 6 separate studies indicate consistent over-prediction of flow-rates by theoretical models. Similar results were obtained for a further calculation for a higher pressure drop (ΔP = 1.07 bar). However, there were visible (although still small) divergences due to the Nagano and Suzuki formulae being less accurate for larger pressure drop.

On investigation, the reason for the theoretical over-prediction of flow-rate was found to be due to a common approach to the simplification of the flow model. This is the assumption that the flow in the viscosity limited regime can be approximated by plane Poiseuille flow, taking the thickness of the flow stream to be constant and equal to the COD. Clearly this is an approximation because, even assuming a constant COD, the effective width of the flow stream varies from point to point as a result of the varying orientations of individual segments of the crack walls. But, although somewhat larger, it remains the case that the COD will be of a similar magnitude to the spatially averaged flow thickness. This was the motivation for employing the COD as an approximate measure of the stream thickness. However, assuming Poiseuille flow, characterised by an average flow thickness, overlooks the full significance of sites of reduced flow aperture, created by the most extreme orientations. Much of the flow actually bypasses these reduced aperture sites, implying significant drag forces on the bypass flow. These reduced aperture sites can therefore make a significant contribution to the impedance to the flow, which is not accounted for with the plane Poiseuille assumption.

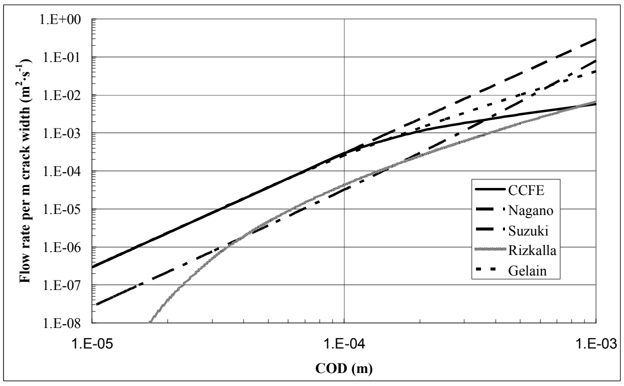

Figure 1. Five calculations of volumetric flow-rate as a function of COD for a single crack in a 15 cm barrier with 0.1 bar pressure-drop. A sixth study [8] (empirical) was also found to agree well with Rizkalla and Suzuki.

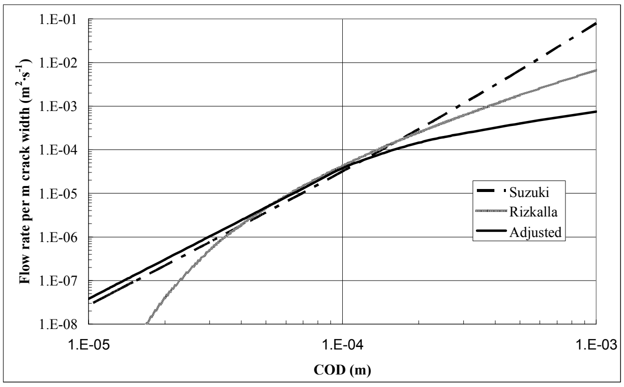

Figure 2. Flow-rate calculations for the low pressure-drop case showing Rizkalla, Suzuki, and the adjusted theoretical prediction using f_Q = 0.13.

The significance of the reduced aperture sites is now evident. As already observed, these sites are formed by segments of the crack walls having extreme orientations with respect to the average flow direction (alternatively, orientations nearly parallel to the direction of displacement of the crack walls). Therefore the frequency of these sites is theoretically determined by the tails of the angular distribution function for the segment orientations (see section 1). The study of Boussa et al. [2] concluded that the data for angular orientations could be represented by a normal distribution curve. Therefore the CCFE model has incorporated this information in the form of the standard deviation for the angular distribution function based on the published figures (although this model does not take account of the consequent variation in the flow aperture). However, there is now cause to re-examine the issue of the distribution.

Following the discovery of the importance of reduced aperture, a computational analysis was undertaken, taking account of the variation of flow aperture for the first time, to establish a theoretical lower bound on flow rate, based on the statistical parameters published in reference [2]. The unexpected result that this lower bound was greater than the empirical flow rate implied some error with the data. However, if the measurements in reference [2] are correctly analysed and applicable to the samples used in the flow rate studies, and the derived standard deviations are accurate, it implies that one remaining assumption must be incorrect. This is the assumption of a normal distribution. The result we have obtained therefore suggests that the tails of the angular distribution function characterising crack morphology are significantly heavier than those associated with a normal distribution. (It is also worth noting that geometrical constraints imply the angular distribution function must fall to zero at ±90º; this is another departure from the normal distribution.) Having reached this conclusion, the data provided in reference [2] were revisited to check, and found to support this hypothesis. Figure 5 of that reference shows a typical angular distribution function which clearly deviates from the normal form by virtue of the existence of very heavy tails, just as anticipated. Thus, the authors' suggestion that the normal distribution is a reasonable approximation would appear to be based on statistical considerations which are not particularly sensitive to the shaping of the tails. In fact, their data, along with the above theoretical considerations, actually support the existence of heavy tails relative to those expected for a normal distribution. This is an important finding if there is to be accurate theoretical modelling of the flow stream in the future.

We shall account for the effect on the flow of the reduced aperture sites by applying a flow adjustment factor, $f_Q < 1$, to the theoretically predicted Q. Using this modification to the flow rate, it is found that $f_Q = 0.13$ provides the best correspondence between theory and the empirical correlations (for both $\Delta P = 0.1$ and $\Delta P = 1.07$ bar). This can be seen in Figure 2 showing the result of applying this adjustment to the CCFE prediction for the conditions assumed in Figure 1. Since the predictions for the other theoretical models are coincident with those of the CCFE model in the viscosity limited regime, corresponding adjusted curves are not plotted for these cases. The adjustment to the CCFE curve is designed to achieve good agreement with the correlations in the region which has been explored empirically, defined approximately by the region of intersection of the Rizkalla and Suzuki curves.

2.2 Inertial filtering comparisons

Besides flow rate measurements, the study of Gelain and Vendel [5] also included measurements of particle filtering by the cracks, and would appear to provide the best available filtering data in the current literature. Using this information, the authors have produced an empirical correlation (adapted from a formulation intended for estimation of inertial particle removal at the entrance to a slot) to predict the filtering at different flow rates as a function of COD. The resulting correlation depends only on the Stokes number (*Stk*), defined as follows:

$$Stk = \frac{\rho_p d_p v}{18 \mu d} \qquad (12)$$

Unfortunately, as we have seen above, the validity of plane Poiseuille flow is assumed by the authors in order to infer the crack parameters, including the COD. Making use of our finding that an adjustment to the Poiseuille model of $f_Q = 0.13$ is required for accurate flow rate prediction, we have therefore applied corrections to their analysis, inferring a COD of 89.1 μm for their crack system as opposed to the two values of 49.2 and 67.2 μm derived from two different sets of assumptions in their study. Using our revised assumptions, the empirical correlation was modified for variable barrier thickness, assuming a constant fractional removal rate of aerosol particles (per m of the barrier thickness) which is a function of the pressure gradient. It was then also adjusted for a slightly different set of conditions from those used for the measurements by a rescaling based on the Stokes number dependence, but also allowing for the possibility of a Reynolds number dependence (for reasons which are outlined below). This rescaling is partly motivated by the fact that we are changing the aerosol material specification to that of potassium chloride (KCl), because it is widely used in aerosol studies and its physical characteristics are well known. Thus, the new values of d_p, ρ_p, COD (0.877 µm, 1984 kg.m^{-3}, 100 µm, respectively) preserve both *Re* and *Stk* for given filtering capacity. For these new conditions, calculations were performed with the CCFE model to predict inertial filtering performance (i.e., diffusional filtering turned off) for a range of barrier thickness and pressure drop. Predictions for the same conditions were also made with the modified empirical correlation and results are shown in Figure 3. Assuming the modified correlation to be substantially correct, it is clear that as barrier thickness increases the CCFE predictions become more and more conservative. At 1m or more barrier thickness, the CCFE model is either correct or conservative at all pressure gradients.

As Figure 3 shows, the CCFE prediction of filtering capacity (F_p) underestimates the empirically derived value (F_e) throughout most of the pressure-drop range where $0 < F_e < 1$, and F_e increases with increasing barrier thickness in line with our assumptions. Thus, for barrier thickness of order 1 m or more, we find $F_p \leq F_e$ throughout. Since the current CCFE model has been shown to overestimate the flow rate, and therefore the average stream velocity, it might seem surprising that it should underestimate inertial deposition rates. However, there are two mechanisms which can account for the existence of deposition rates greater than those predicted by the CCFE model. Firstly, local variations in flow stream thickness, velocity and direction, not accounted for by the 2-D CCFE model, will bring faster streams of gas closer to the walls, enhancing deposition rates. And, secondly, laminar-swirl effects, equivalent to low Reynolds number Dean flow in pipe bends [9], will increase further the proximity of fast flowing streams to local regions of the crack walls, boosting filtering capacity even more. The result is that particle removal is expected to begin in a small number of regions inside a real crack at much lower pressure drops than for the onset of filtering in the CCFE model. As pressure drop increases there should be a gradual increase in the number of deposition sites, and a corresponding gradual increase in the filtering capacity as more of the flow passes through them. In the case of the CCFE model, on the other hand, the deposition sites start to become effective over a very narrow range of pressure drop (for a given particle size), and there is no bypassing of these sites by any part of the flow. It is these factors which are believed to give rise to the lower pressure-drop onset of filtering in real cracks, and the slower rate of increase of filtering capacity in comparison to the results of the CCFE model. We are thus able to account qualitatively for the observed differences between empirical and theoretical results. Although an aspect of Dean flow has been included in the CCFE model, its function there is limited to increasing the flow resistance when the Reynolds number becomes sufficiently large. Particle

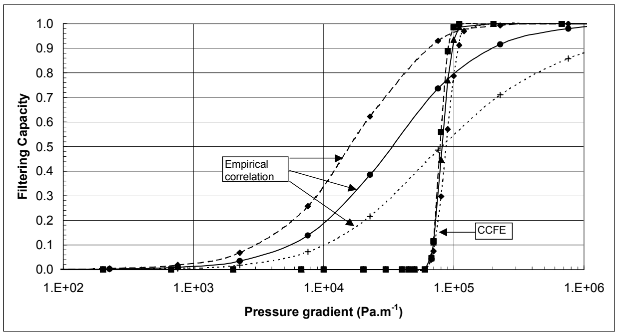

Figure 3. The inertial filtering capacity as a function of pressure gradient as given by the CCFE model and the empirical correlation. Results are given for 5 cm (dotted curves), 10 cm (solid curves) and 20 cm (dashed curves) barrier thickness. Also assumed are d_p = 0.877 µm, ρ_p = 1984 kg.m^{-3}, COD = 100 µm,

deposition rates in the model are not modified to account for the changes in flow pattern. It is the expectation of laminar-swirl effects which implies the possibility of dependence on *Re*, allowed for in our rescaling.

As already observed, assuming the modified empirical correlation to be accurate, the CCFE prediction of inertial filtering capacity appears to be conservative at all pressure gradients for barrier thickness around 1 m or more, and to such an extent that it is likely to remain so for any particle size for which inertial filtering dominates, despite possible dependence on Reynolds number. Moreover, since the CCFE model overpredicts flow rate by about a factor of 8, there is even greater conservatism for predictions of aerosol mass flow rates to the environment.

2.3 Diffusional filtering comparisons

A simple model of diffusional filtering in cracks has been developed and incorporated into the CCFE model. Modelling cracks as straight sided channels, the diffusional filtering capacity is approximately given by:

$$F_D = 1 - e^{-4.5\theta} \tag{13}$$

where:

$$\theta = \frac{8DLw}{3Qd} \tag{14}$$

and *D* is the particle diffusion coefficient. Diffusional filtering in real cracks is expected to be greater than for straight sided channels because of increased wall surface area and the occurrence of laminar-swirl effects analogous to Dean flow in pipe bends [9].

The predictions of equation (13) have been compared with two other theoretical models [10,11] which are also functions of θ, and two empirical studies of diffusional filtering. Agreement with the other theoretical models, which also assume straight sided channels, is good, with

CCFE tending to predict slightly higher filtering capacity than the others, but by a margin no greater than 25%.

The study of Liu and Nazaroff [11] on diffusional filtering in cracks reveals good agreement between measurements for real cracks (in building bricks) and the predictions of the theoretical models which, as we have already noted, assume straight sided channels. On the other hand, the filtering which they observe for straight sided channels is slightly lower than the theoretical predictions.

The comparisons between theory and experiment performed by Gelain and Vendel [5] initially appeared to show over-prediction of the filtering capacity in real cracks by the theoretical model which assumes straight sided channels. Their response was to assume that the observed crack width is an overestimate of the total effective flow stream width, and by performing additional detailed flow measurements, assuming the Poiseuille flow model, and fitting its predictions to the measured filtering capacity, they derived a revised value for the COD and a reduced estimate of the effective flow stream width. However, since the comparison exercise of section 2.1 has demonstrated that the flow cannot be described by the plane Poiseuille model, we choose not to rely on the results of that analysis.

As discussed earlier, we believe that 89.1μm is a more accurate estimate of the crack COD characterising the measurements of reference [5], based on insights gained from the comparisons (see section 2.2.1). Figure 8 of reference [5] shows diffusional filtering measurements in comparison with predictions based on an assumed value of 49.2 μm COD. This prediction is a function of θ (equation (14)), which implies that the existing curve should be corrected by a shift along the horizontal axis towards the origin using a compression factor of 49.2/89.1 = 0.55. Inspection of Figure 8 of reference [5] readily confirms that such a transformation would bring the theoretical prediction into line with the experimental data.

It would therefore appear that the measurements of Gelain and Vendel, using real cracks, also agree well with predictions based on the assumption of straight-sided channels, thus corroborating the results of Liu and Nazaroff. This is a favourable result allowing useful predictions to be made. However, the question remains as to the reason for the observed, albeit quite small, disparity. The results of both studies appear to demonstrate that diffusional filtering in real cracks is slightly lower than might be anticipated theoretically, and the results of Liu and Nazaroff also demonstrate a similar shortfall for the case of straight sided channels. Having briefly examined this issue, we have been able to identify one mechanism which could account for such a shortfall. We now believe that a type of hydrodynamic lift force may be responsible for the reduction in diffusional filtering relative to initial expectations. This has also been referred to as the wall effect [12], in which the asymmetric wake of a particle resulting from proximity to the wall leads to a lift force away from the wall. Such a force becomes increasingly important for smaller, lower density particles.

We are now able to account qualitatively for the differences between empirical measurements of diffusional filtering and the predictions of existing theoretical models. Additionally, comparisons between a number of studies has demonstrated that models of diffusional filtering in straight sided channels provide good predictions of the filtering capacity of cracks in concrete or bricks, over the range of conditions investigated. However, we must recall that the CCFE model currently overestimates the flow rate through cracks by a factor of around 8. The impact of this on the parameter, θ, implies that diffusional filtering predictions by the full CCFE crack filtering model is conservative for all presssure drops.

2.4 Other theoretical modelling

The above findings are relevant to any industry employing a pressurised containment system as part of its safety strategy. There have therefore also been other attempts to theoretically model gas flow and filtering in cracks, e.g., references [13] and [14]. However, the cracks are represented by straight sided channels, and turbulent deposition mechanisms are used there to model inertial deposition in an effort to match the filtering measurements of Gelain and Vendel [5]. This of course relies on crack characteristics derived in the latter study, which we have already given reasons for disputing. Moreover, the analysis which has been partially reported above (section 2.1) suggests that the flow actually remained laminar during those measurements. Our analysis also suggests that it is in the vicinity of the reduced aperture sites (corresponding to extreme orientations of the local flow direction) where the inertial filtering is strongest, and likely to be enhanced by laminar-swirl flow patterns. These effects are not captured by straight channel models. The same sites are also believed to be responsible for suppressing the flow rate to a much lower value than that which characterises the viscosity limited flow arising in straight channels for moderate pressure drops. It remains possible that results could be fitted, for some range of conditions, by judicious scaling of turbulent models. However, if that is the case, it is important not to conclude that they necessarily describe the fundamental nature of the gas and particle dynamics.

3. APPLICATION TO FUSION

3.1 Specification of bounding accident scenario

One of the aims of these investigations is to contribute to improved assessments of the consequences of hypothetical accident scenarios. Although relevant wherever pressurised containments are employed, we are primarily concerned with fusion power plants and one of the current strands of the European fusion programme is a power plant concept known as DEMO. Thus, we shall now explore some potential DEMO relevant containment parameters, applying the CCFE crack filtering model to an example calculation.

Important guidance on the design of future fusion power plants can be found in the conclusions of the European Power Plant Conceptual Study (PPCS) [15]. Part of this study was an assessment of safety aspects of a numberof conceptual designs, including a helium cooled concept (PPCS Plant Model B) [16], on which we assume one of the DEMO concepts could be based. Data for this assessment was derived from specifications for bounding accident scenarios [17], considered to represent the worst cases in terms of consequences to the public. Our example calculations will employ parameters based on those specifications, as did the calculations of reference [16]. However, the latter study implemented a modification which will not be repeated in the current analysis. The Model B design incorporates a dedicated expansion volume (EV) which is intended to contain all material escaping from a blowdown in the event of a loss of coolant accident (LOCA). The specification is for an unlined concrete EV, with a characteristic leak rate of 75% per day at design pressure. For the assessment of reference [16] it was thought advisable to revise this specification with the addition of a steel liner to reduce the leak rate to the environment because it was not possible at that time to estimate the particle filtering capacity of cracks. However, because we are now able to put bounds on the filtering performance of concrete barriers, we shall revert to the original specification of unlined concrete.

The main parameters which have been assumed to define the containment conditions of the helium-air mixture at $t = 0$ for the bounding accident scenario are shown in Table 1. The mass median diameter (MMD) and geometric standard deviation (GSD) of the aerosol size distribution, taken to be lognormal, have been determined according to the method of reference [18] and represent the approximate long-term characteristics of the aerosol (approached after around 5 hours in this case). However, for simplicity, this specification is taken to apply from $t = 0$. We utilise the stipulated leak rate which scales with the square root of the pressure differential [17]:

$$Q = \frac{0.75V}{24 \times 3600} \sqrt{\frac{P_i - P_o}{P_m - P_o}} \qquad (15)$$

where Q is the volumetric flow rate (m3.s^{-1}) of gas (at pressure P_i) from the EV, V is the EV volume, P_i is the time dependent containment or crack inlet pressure, P_o is the outlet (atmospheric) pressure, P_m is the maximum (initial, $t = 0$) containment pressure. However, the CCFE model already calculates the gas flow rate, given the pressure differential, so it is not fully consistent to make use of an independent stipulation for this. The strategy employed was therefore to use the prescribed leakage formula to determine the time evolution of the pressure differential, while the instantaneous aerosol mass flow rate to the environment was determined by the CCFE model as a function of the pressure.

3.2 Results

Figure 4 shows the resulting time evolution of the aerosol mass flow rate to the environment. A striking feature of this plot is the fact that mass flow rate continues to increase for most of the release duration even though the pressure in the containment and gas flow rate are falling continuously. This dependency arises because it is inertial filtering which is the dominant removal mechanism under these conditions, and the inertial forces experienced by the particles in curving flow streams are proportional to the square of the gas velocity. Hence, the instantaneous release fraction (unfiltered fraction of aerosol in the flow stream) increases dramatically (about 3 orders of magnitude) over time, as can be seen in Figure 5, and only starts to decline as the end of the release duration is approached. An important lesson to learn from these observations is that it is necessary to take account of the time evolution; clearly, a knowledge of the filtering capacity at $t = 0$ only is insufficient to derive a meaningful estimate of total release to the environment.

At the end of the release duration, the net aerosol release fraction for the above scenario is 2.42 x 10^{-3}. This is comparable to previous estimates for the steel liner option [16], which were derived without assuming credit for particle removal in the cracks. This suggests the possibility that an unlined concrete expansion volume may yet be a viable proposition.

It is important, however, to be aware of the main limitations of these example calculations. For simplicity, all aerosol products were assumed to occupy the expansion volume at $t = 0$, and we adopted a form for the aerosol distribution which approximates conditions after several hours. If, on the other hand, much of the mobilised aerosol material is introduced into the EV in the form of vapour, it might escape inertial filtering until particle size has significantly increased through agglomeration. However, smaller particles are more easily captured by diffusional filtering. Thus the outcome will be dependent on assumptions about the nature and timing of the mobilisation process.

Table 1. Containment and aerosol parameters

EV Volume (m^3)	P_m	T (K)	Leak Rate	L (m)	COD (mm)	Mobilised Aerosol Mass	ρ_p (kg.m^{-3})	MMD (m)	GSD
6.80x10^4	1.6 bar	408	75% per day	1.0	0.1	1000 kg	3500	4.2x10^{-6}	1.63

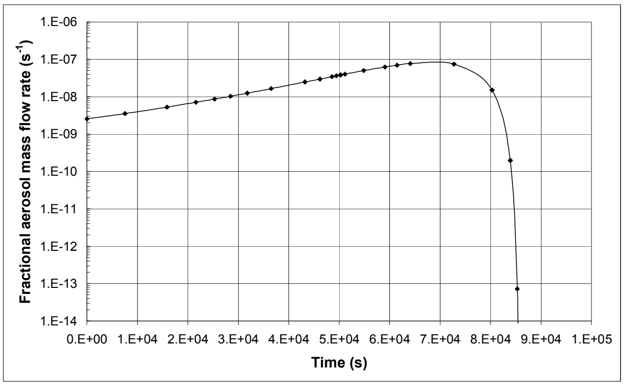

Figure 4. Fractional (relative to initial mobilised mass) aerosol mass flow rate to the environment as a function of time.

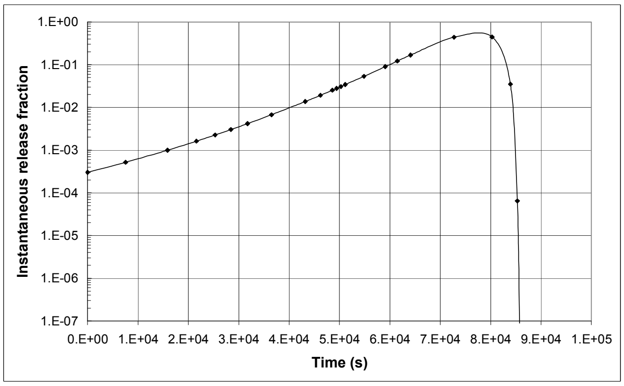

Figure 5. Instantaneous aerosol release fraction (unfiltered fraction of aerosol in the flow stream) as a function of time.

Therefore these assumptions need to be examined in more detail. Other simplifications include spherical aerosol particles, and the neglect of gravitational settling of aerosol particles in the EV. The latter effect (accounted for in reference [16]) would reduce further the calculated release of aerosol material. Gravitational settling out of the flow stream within cracks is also neglected in the CCFE model, since this is dependent on crack orientation which we do not consider.

Another area of uncertainty is the characteristic size of the cracks. The assumed COD was 0.1 mm. However, as a comparison exercise, results were recalculated with a COD of 0.5 mm, which led to a net aerosol release fraction of 4.74×10^{-3}. This is less than a doubling of the original release estimate, indicating that results are relatively insensitive to uncertainty about the COD.

4. CONCLUSIONS

The CCFE crack filtering model [1] has benefited from a number of improvements. In particular, it has been extended to include diffusional particle removal and also revised with an improved model of bend losses due to laminar-swirl effects. This updated model has now been compared with a number of other theoretical and empirical studies of filtering in cracks, with results suggesting the model is conservative when applied to realistic containment systems. The comparison exercise has also revealed the limitations of 2-D modelling and led to a new understanding of gas flow and filtering in real crack geometry.

The investigation of the over-prediction of gas flow rates by the theoretical models (by around a factor of 8) revealed that the viscosity limited flow does not conform to the plane Poiseuille model, and that it appears instead to be controlled by drag forces resulting from the existence of reduced aperture sites. The characteristics of these sites are determined by the tails of the angular distribution function for the orientations of individual segments of the crack walls,and results imply that these tails must be heavier than those associated with a normal, or Gaussian distribution. Empirical support for this conclusion has also been identified. It was determined that an adjustment factor of $f_Q = 0.13$ is required to correct the plane Poiseuille model to provide accurate flow rate predictions.

The inertial filtering comparison revealed how the characteristic curve of filtering capacity versus pressure drop was shaped by the nature of the flow relative to the particle deposition sites. Because every fluid packet in the flow in the 2-D model eventually passes through each and every deposition site, the characteristic curve has a steep cliff-like nature. But because any given elemental fluid packet passes through only some of the deposition sites in the 3-D case, the curve has a more gentle slope. Additionally, laminar-swirl effects (Dean flow analogue) and other local velocity variations add further enhancements to the 3-D filtering behaviour. Despite the over-prediction of flow rate by the CCFE model, the results suggest that the prediction of inertial filtering capacity should still be conservative for barrier thickness of around 1m or more. It is important to emphasise, however, that derived inertial filtering data has been made available in only one empirical study [5] thus far.

Comparison with two other theoretical models and two empirical studies has provided corroboration for the CCFE diffusional filtering model, and demonstrated that theoretical models for straight sided channels match empirical data for real cracks very well. This fortuitous outcome is probably due to the fact that the theoretical models do not take account of hydrodynamic lift forces. The fact that the CCFE model overpredicts the flow-rate implies that its predictions of diffusional filtering capacity are conservative for all pressure drops.

The results of the current study indicate that, for realistic containment scenarios, the CCFE model underpredicts both diffusional and inertial filtering capacities of cracks, but also overpredicts the gas flow rate. All these factors taken together provide strong evidence that the model overpredicts mass flow rates of aerosol to the environment and is therefore conservative, if we can rely on the derived inertial filtering data of reference [5].

The results of an example calculation for a pressurised expansion volume in a conceptual fusion power plant design suggest that the CCFE model can throw light on the question of whether a steel liner would be necessary to mitigate aerosol leakage to the environment. The model should also provide useful guidance on parameter requirements during the process of defining accident scenario specifications.

It is proposed that an adapted empirical correlation along with the CCFE model might together provide useful tools for future accident analyses. By scaling the modified empirical correlation, which is specified in terms of the Stokes number only, and applying it to detailed accident scenarios as we have done with the CCFE model, we might obtain results which give a reasonable indication of consequences if the unknown dependence on Reynolds number can be assumed not to have an unduly large impact. Then applying the CCFE model to the same problem would, additionally, provide an upper bound to the aerosol release. These two sets of results taken together should provide a reasonable basis for a realistic appreciation of the range of possible consequences.

We have not given consideration to possible variations in the composition and microstructure of the concrete. This is partly because of the good agreement seen in the results obtained from a number of different empirical studies, despite using different concrete mixes (and, indeed, different barrier materials, e.g., brick). This may be an area which deserves further investigation but, at present, the consistency of the empirical evidence seems to suggest that any concrete variations do not have a strong impact on gas flow and filtering.

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