Reproducible Direct Exposure Environmental Testing of Metal-Based Magnetic Media

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Abstract

A flow geometry and flow rate for mixed flowing gas testing is proposed. Use of an impinging jet of humid polluted air can provide a uniform and reproducible exposure of coupons of metal-based magnetic media. Numerical analysis of the fluid flow and mass transfer in such as system has shown that samples confined within a distance equal to the nozzle radius on the surface of impingement are uniformly accessible to pollutants in the impinging gas phase. The critical factor is the nozzle height above the surface of impingement. In particular, the uniformity of exposure is less than ± 2% for a volumetric flow rate of 1600 cm^3/minute total flow with the following specifications: For a one inch nozzle, the height of the nozzle opening above the stage should be 0.177 inches; for a 2 inch nozzle - 0.390 inches; for a 3 inch nozzle - 0.600 inches. The tolerance on these specifications is 0.010 inches. Not only is the distribution uniform, but one can calculate the maximum delivery rate of pollutants to the samples for comparison with the observed deterioration.

Introduction

Recording density and archivability are important characteristics of any data storage medium. Metal-based tapes such as metal particle (MP) and metal evaporated (ME) media perform well in recording but might, however, be vulnerable to corrosion.

Direct exposure to humid polluted air is a basic test of the archivability of a medium. For example, accelerated testing of MP media several years ago indicated some susceptibility to corrosion [1]. Although a tape cartridge or cassette must be considered as a "system" that affords protection of the tape by virtue of the spooling and incorporation into a package, the most basic line of defense against deterioration is the corrosion resistance of the media itself.

We have developed a corrosion test protocol based on the Battelle [2] flowing gas specifications but enhanced by the additional specification of a well-defined flow geometry, known as the "impinging jet", and flow rate. [3] We used it to expose coupons of MP [3] and ME [4] tape to variations of a Battelle Class II environment and found that some commercial MP media is very corrosion resistant while commercial ME media is vulnerable to corrosion on direct exposure. Numerical modeling of the flow has shown that, under certain circumstances to be discussed herein, the system possesses the useful property of uniform accessibility of the pollutants to the surface. In this paper, we report on the results of this modeling and discuss the standardization of direct exposure testing to eliminate the lab-to-lab variations that have been reported in the literature.

The fluid dynamics of the impinging jet

The impinging jet configuration, a variation of the stagnation point flow geometry, appears in Fig. 1. The incoming gas stream flows through a nozzle oriented perpendicularly to a nearby surface. The velocity profile of the jet changes from fully developed parabolic flow to free jet flow in the potential core, beyond which the centerline velocity of the jet decreases at a rate inversely proportional to the distance from the nozzle. The axial fluid velocity approaches zero in the region near the stagnation point. The flow in the body of the jet is axisymmetric, inviscid, irrotational, and the thickness of the boundary layer is insensitive to radial position. The flow is inviscid in the body of the jet because the vorticity is of the order of the inlet velocity divided by the radius of the jet, which is large with respect to the vorticity of the fluid in the boundary layer that grows from the stagnation point outward near the surface of impingement.

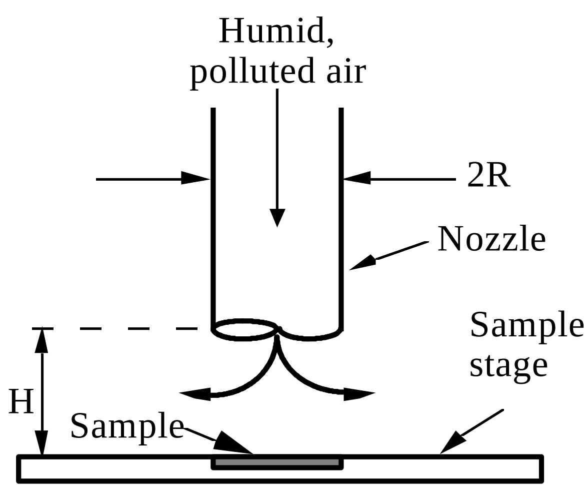

Figure 1. A schematic diagram of the impinging jet

Previous investigators have modeled the transport in the impinging jet reactor and experimented with it. The theoretical investigations can be divided into those that assume a uniform inlet flow and those that assume a well-developed parabolic flow. Homann [5] solved the one dimensional equations under the assumption of uniform accessibility. Chin and Tsang [6] surveyed the literature on the impinging jet and developed a semiempirical solution of an isothermal convective diffusion model in the form of an asymptotic series to give an estimate of the mass transfer rate for Schmidt number (Sc) >

0.7. Scholtz and Trass [7], examining mass transfer in a laminar impinging jet with a parabolic velocity profile at the inlet, measured velocity, pressure distributions, and the evaporation of naphthalene in a jet of air flowing at nozzle Re in the range 375 to 1970. The results of the experiments agreed satisfactorily with their analysis of the fluid flow and mass transfer equations under the nozzle. The rate and radial distribution were insensitive to nozzle height in the range 0.25 to 6 nozzle diameters. The mass transfer was uniform to the surface from the stagnation point to one fifth of the nozzle radius. The dependence of the mass transfer on radius from the axis was a strong function of nozzle height. For nozzle heights greater than half a radius, the mass transfer rate was a maximum at the axis and decreased radially. The mass transfer rate at the nozzle radius was approximately 80% of the rate at the stagnation point for nozzle heights of greater than one half the nozzle radius. For nozzle heights less than a third of the radius, the pattern was inverted; that is, the mass transfer rate was a minimum at the axis and increased radially. Snyder et al. [8] modeled the flow numerically and confirmed this inversion of the radial dependence of the mass transfer.

We used the impinging jet design in accelerated corrosion testing of magnetic media [3,4] because of its simple construction and high mass transfer rates but were concerned about the uniformity of the exposure. The inversion of the mass transfer rate dependence on the nozzle height, noticed by Scholtz and Trass [7] and illustrated in Fig. 2, presented an opportunity to improve the uniformity of the mass transfer to the surface under the jet. We sought to determine the radial profile of the mass transfer flux for various values of H/R between 0.3 and 0.5 in order to explore what happens when the profile changes from the one having a maximum at the axis to the profile having a minimum at the axis. The results of this modeling and their relation to the uniformity and rate of mass transfer of dilute components from a flowing mixed gas to coupons in an impinging jet chamber are presented in this contribution. The objective of the modeling was to determine conditions under which the uniformity of mass transfer to coupons would be optimal.

The Numerical Model of the Impinging Jet

A diagram of the domain appears in Fig. 2. A carrier gas and a reactive minor component enter the domain with a parabolic velocity profile and the flow emanates from a nozzle six to seven radii from the inlet. The gas impinges on a surface located at various distances from the nozzle and it exits along the open end of the domain. For the purposes of this study, the concentration of the minor component vanishes at the impingement surface (i.e. mass transfer control). This specification produces the maximum rate of delivery of the reacting species to the surface. The width of the domain was two radii. Axial symmetry in the problem allowed two dimensional representation and sectioning of the domain. Equations for the convective diffusion of mass and momentum in the impinging jet geometry governed the transport in the domain [7]. The dilute solution approximation was appropriate for this case. The boundary conditions were: (1) zero flux of mass and momentum through the nozzle wall and the reactor wall connected to the nozzle; (2) zero flux of momentum through the impingement surface; (3) finite concentration of the minor component at the inlet and (4) zero concentration at the surface of impingement.

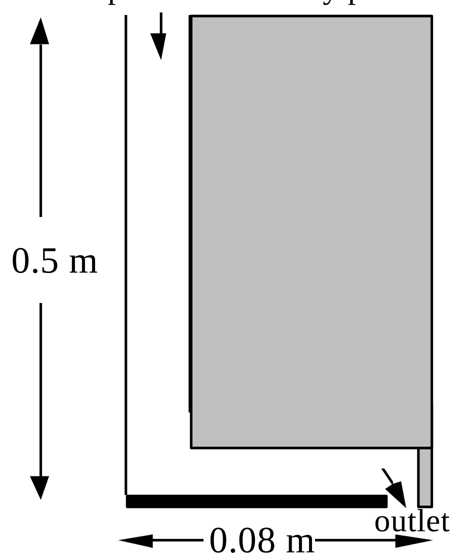

Figure 2. A schematic diagram of the domain of the numerical solution.

A diagram of the chamber used in the experiments [3,4] appears in Fig. 3.

The program for the impinging jet reactor in this study solved the governing equations subject to the boundary conditions using a finite volume method documented by Patanker [9]. The FLUENT software package was used to formulate and solve the appropriate discretization equations for the impinging jet model. Details about the grid and the solution method can be found in Snyder *et al.* [8]. The physical constants and specifications used in the simulation were the following:

Molecular diffusivity of the pollutant:	1.5E-5 m^2/s
Volumetric flow rate of humid polluted air:	2.67E-5 m^3/s
Density:	1.13 kg/m^3
Viscosity:	1.85E-5 kg/ms
Temperature:	303 K

These factors gave a Sc number of 1.09. This volumetric flow rate gave Re numbers of 82, 41, and 27 for the 1 inch, 2 inch and 3 inch tube diameters, respectively.

Results of the Numerical Modeling

The local mass transfer coefficient to the samples below the nozzle, in dimensionless form, appears in Figures 4, 5, and 6 as a function of radial position for nozzle diameters of 1 inch, 2 inches, and 3 inches, respectively. The ordinate, expressed in physical properties, is

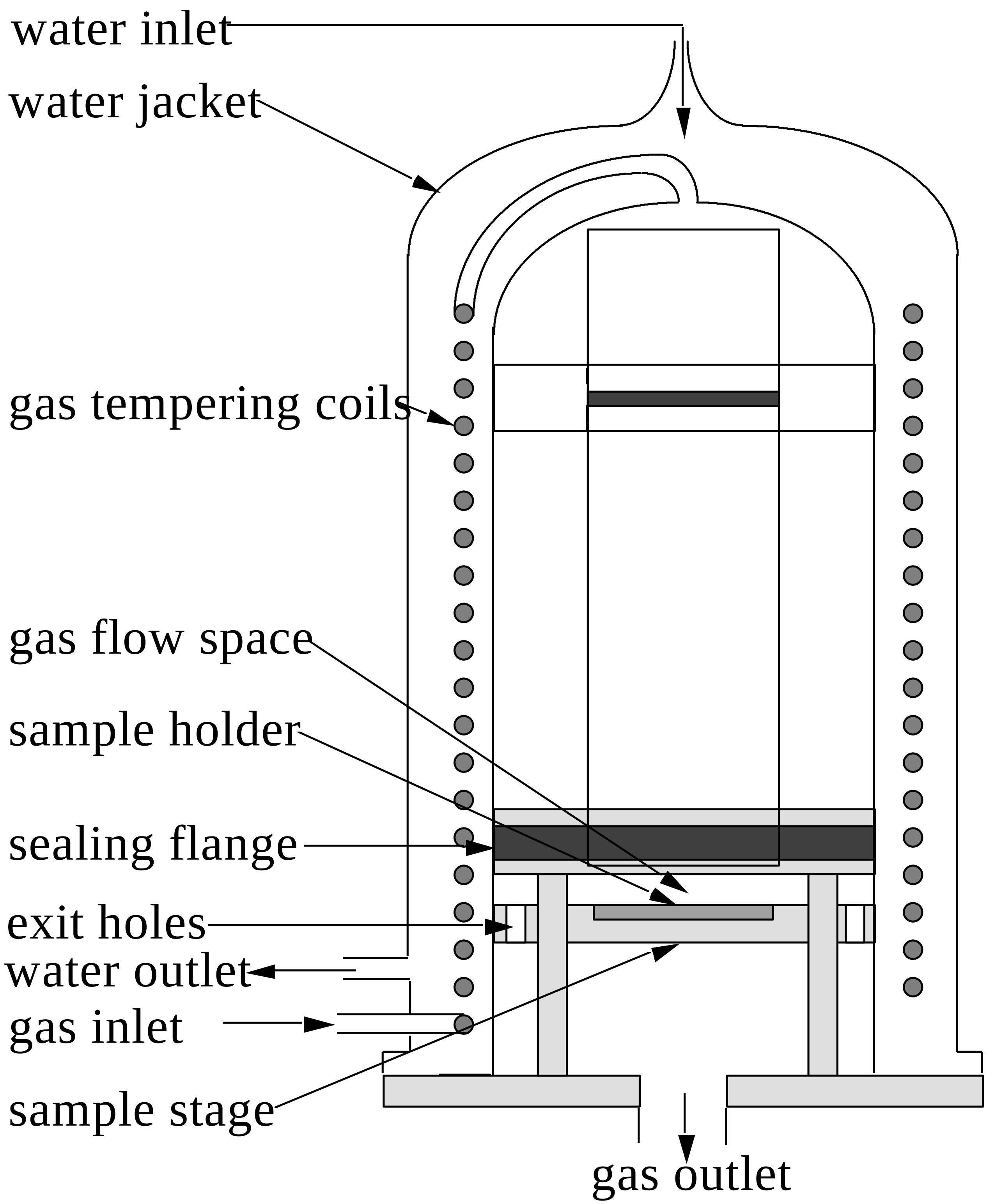

Figure 3. Detailed schematic of the impinging jet chamber

$$\frac{Sh}{Re^{1/2}} \equiv \frac{k}{D}\left(\frac{\rho R}{2\mu < v >}\right)^{1/2} \qquad (1)$$

where

$$Sh = \frac{kR}{D}$$

$$Re = \frac{2R \ <v> \mu}{\rho}$$

$$Sc = \frac{\mu}{\rho D}$$

and k is the mass transfer coefficient; R is the nozzle radius; D is the binary diffusivity of oxidant in the air; <v> is the average velocity in the nozzle; μ is the viscosity; and ρ is the density of the test gas. Thus the ordinate is proportional to the local mass transfer coefficient, k, and is therefore proportional to the ability of the mixed flowing gas to deliver the pollutant to a particular location.

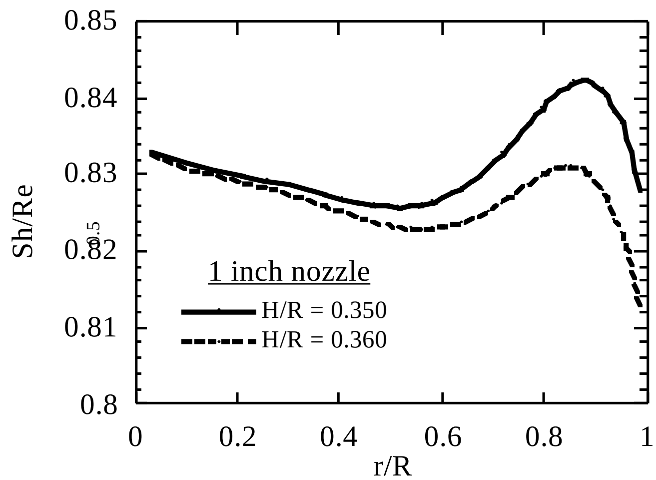

Figure 4. The dimensionless local mass transfer coefficient on the surface of impingement as a function of radius from the axis of the 1 inch nozzle. In the case of H/R = 0.35, the maximum nonuniformity is +/- 0.0085 or about 1% of the average value.

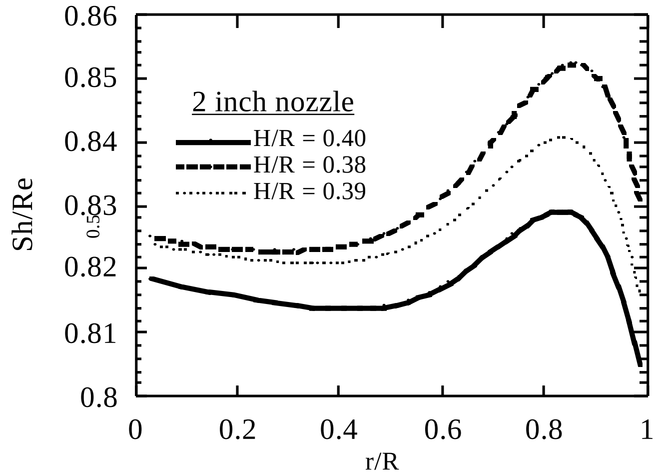

Figure 5. The dimensionless local mass transfer coefficient on the surface of impingement as a function of radius from the axis of the 2 inch nozzle. In the case of H/R = 0.39, the maximum nonuniformity is +/- 0.012 or about 1.5% of the average value.

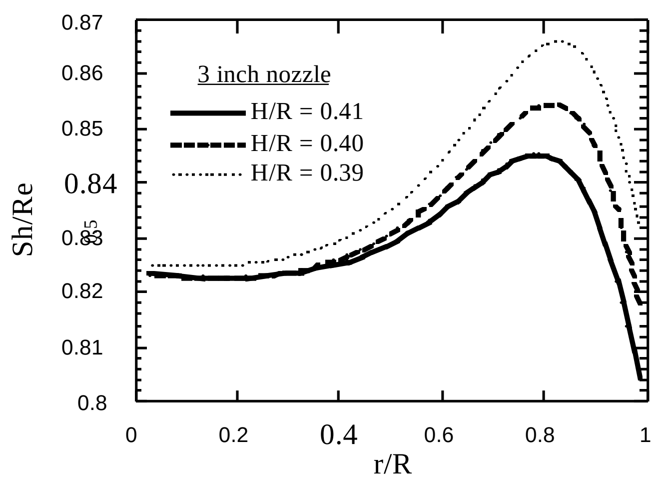

Figure 6. The dimensionless local mass transfer coefficient on the surface of impingement as a function of radius from the axis of the 3 inch nozzle. In the case of H/R = 0.40, the maximum nonuniformity is +/- 0.018 or about 2% of the average value.

Note the resolution of the ordinates in Figures 4, 5, and 6. The maximum variation of the mass transfer coefficient at the surface of impingement over the radius of the nozzle is +/-1%, 1.5% and 2% , respectively, for the 1 inch, 2 inch, and 3 inch diameter nozzles.

The implication is that the delivery of pollutants to the surface of impingement is uniform to within the quoted percentages under the assumption that all of the active species in the gas phase that reach the surface are immediately and irreversibly consumed. The optimum results for the three different nozzle sizes, plotted on a scale that reveals the essential uniformity of the mass transfer coefficient over the radius of the nozzle, appear in Figure 7.

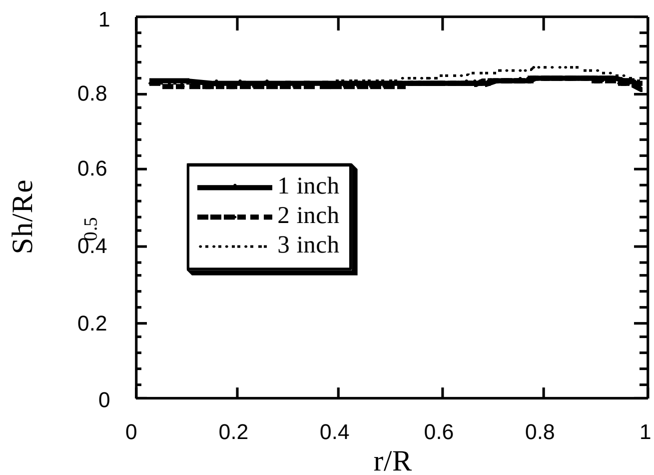

Figure 7. The uniformity of mass transfer to samples. Heights of the nozzles above the sample stage: 1 inch: 0.177"; 2 inch: 0.390"; 3 inch: 0.600". The heights should be within +/- 0.010" of the indicated values.

The domain and boundaries appearing in Figure 2 shows that the entire surface of impingement below the nozzle is active from the axis to the radius of the chamber. In practical situations, one places coupons only in the area of interest below the nozzle, but this can lead to spurious effects for the samples at the outer edge because the pollutants can diffuse upstream and increase the exposure of the outermost samples. This situation is depicted in Fig. 8. The dashed line corresponds to the case where the outer boundary of the sample region ends at the radius; the dark continuous line corresponds to the situation when the entire surface is active or when a set of buffer samples is included outside the radius of the nozzle.

Discussion

Given the above results and the work of Scholtz and Trass [7], one can express the dimensionless mass transfer rate as

$$\mathrm{Sh} = 0.82\,\mathrm{Re}^{0.5}\mathrm{Sc}^{0.36} \qquad (2)$$

Rewriting equation (2) and multiplying by the concentration of oxidant, one can calculate directly the mass transfer limited corrosion rate in μm per day.

$$\frac{d\delta}{dt} = N\left[0.82\left(\frac{\mu}{\rho}\right)^{-0.14} D^{0.64}\left(\frac{2\,\langle v\rangle}{R}\right)^{1/2}\left(\frac{Px_o}{R_{gl}T}\right)\right]\left[\frac{M_m}{\rho_m}\right] \tag{3}$$

where

$\frac{d\delta}{dt}$ = corrosion rate
$\langle v\rangle$ = average flow velocity in the nozzle
R = radius of the nozzle
P = atmospheric pressure, 1 atm
x_o = mole fraction of oxidizer in the system
R_{gl} = gas law constant
T = temperature
N = the number of media atoms corroding per molecule of oxidant
ρ_m = density of magnetic material
M_m = molecular mass of magnetic material

Equation (3) assumes that there is a primary oxidant that is transported by diffusion and convection to the sample surface where it is adsorbed and reacts with unit probability. Note that the density of the magnetic medium must be its effective density. For example, ME films contain voids, formed during the deposition process, that reduce the saturation magnetization relative to the bulk alloy [10].

In general, the result of experiments of this type is not either the mass transfer limited reaction rate or the reaction limited rate, but a mixed rate. The answer one wants from an experiment such as this, for comparison to other media, is not the mixed-mode rate, but the reaction-kinetics-limited rate that is obtained, in principle, when the flow velocity is infinite. One can find this rate by assuming linearity of both the transport and reaction with oxidant concentration, an assumption crucial to accelerated testing in any case, and by expressing the kinetics as a series resistance problem. Analysis of this model reveals the following relationship between the measured corrosion rate, the intrinsic reaction rate, and the radius of the nozzle., *i.e.*

$$\frac{1}{\left(\frac{d\delta}{dt}\right)} = \frac{1}{\left(\frac{d\delta}{dt}\right)_r} + C\,R^{3/2} \tag{4}$$

where $\left(\frac{d\delta}{dt}\right)_r$ is the reaction kinetics-limited rate of moment loss and C is a collection of constants related to the mass transfer part of the problem. A plot of the left side of

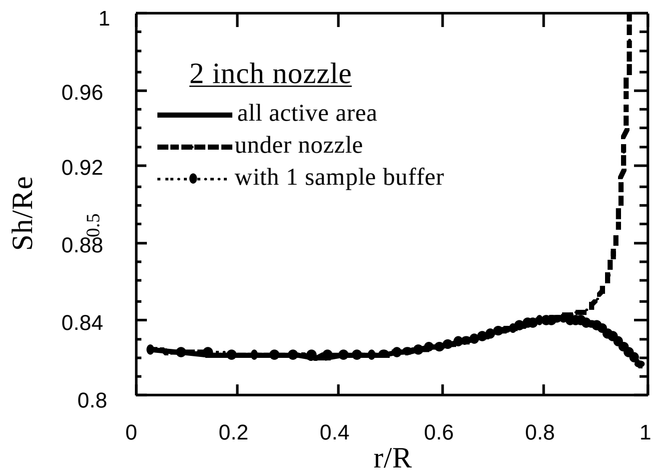

Figure 8. Dimensionless local mass transfer as a function of radial position from the axis on the surface of impingement. When the entire surface outside as well as inside the nozzle radius is active, the dependence is identical to the performance when a buffer layer one coupon wide is included is added to the samples. When no buffer layer is present, the mass transfer rate increases strongly because of the availability of species to diffuse upstream and react.

equation (4) versus the 3/2 power of the radius should be a straight line having the reciprocal of the desired quantity as the intercept at the ordinate.

Conclusion: A Proposed Flow Geometry for Direct Exposure Testing

Using the above results and analysis, we propose the following prescription as a means of assuring the reproducibility of direct exposure testing. Construct an isothermal chamber having the capacity to hold a glass nozzle 1 inch, 2 inches, or 3 inches in diameter and 30 inches long. The nozzle should face a sample stage capable of holding samples at right angles to the nozzle. The opening of the nozzle facing the samples should be flush with a plane that extends to a radius of at least 3 inches. Provide a supply of humid polluted air to the chamber at a total volumetric flow rate of 1600 sccm. All the other Battelle Class II specifications remain the same. The nozzles should be suspended above the sample stage by 0.177", 0.390", and 0.600" +/- 0.010" to assure that the delivery of pollutants to the surface does not vary from axis to nozzle radius by more than approximately 2%. The samples should be coplanar with the surface of impingement. We have found that coupons 5 mm square and attached by double stick tape to glass inserts in a plastic chip carrier matrix work very well. Coupons this size generally have sufficient magnetic moment to be measured and a number of them can be exposed at once, particularly if the 3" nozzle is used. The thickness of the glass inserts and tape can be matched to permit the sample coupons to be flush with the impingement surface.

There are two main advantages and one disadvantage of this specification. First, the proposed configuration eliminates ambiguity in the flow over the samples and therefore promotes reproducibility. Second, the laminar flow pattern can be calculated and the mass transfer coefficients deduced to determine the relation between the amount of pollutants delivered and the rate of corrosion of the samples. For example, one draws very different conclusions if the measured rate is much less than-, equal to-, or much greater than the rate of supply of pollutants to the samples. The disadvantage of the proposed approach is that the close proximity of different samples in the sample tray under the nozzle can affect the results if the samples have very different susceptibilities to corrosion. For example, if one sample is very reactive and it adjoins a relatively unreactive sample, the reactive samples will "steal" reactant from the more noble sample and the result would be that the difference between the two samples would be accentuated. If the precise corrosion rate of a particular sample is desired, the best solution is to do preliminary comparison testing of mixed sample types and then do final testing of important sample types separately. This problem could also be alleviated by a higher volumetric flow rate of gas so that the mass transfer boundary layer thickness over the samples was much less than the dimension of the samples.

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