Hydrodynamics of Disturbed Flow and Erosion–Corrosion: Part I — Single-phase Flow Study

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Numerical simulations of turbulent flow have been used to determine the flow structure in a sudden pipe expansion, in order to explain the effects of disturbed flow on mass transfer controlled erosion–corrosion. Previously determined rates of mass transfer through the liquid boundary layer have been directly related to the predicted levels of near-wall turbulence. When rust films are present, the turbulent fluctuations affect both the mass transfer through the boundary layer and the removal of the film. The determining resistance to mass transfer, under the conditions examined, was that of the rust film.

On a utilisé des simulations numériques d'écoulements turbulents pour déterminer la structure de l'écoulement dans une expansion abrupte du expansion, dans le but d'expliquer les effets de l'écoulement perturbé sur l'érosion et la corrosion contrôlées par le transfert de matière. Les vitesses de transfert de matière déterminées antérieurement dans la couche limite liquide ont été directement reliées aux niveaux prédits de turbulence près des parois. En présence de films de rouille, les fluctuations turbulentes influent à la fois sur le transfert de matière dans la couche limite et le retrait du film. La résistance déterminante au transfert de matière, dans les conditions examinées, était celle du film de rouille.

Keywords: erosion–corrosion, disturbed flow, two-equation turbulence model.

Erosion–corrosion can be defined as the accelerated corrosion of a metal as a result of a flowing fluid disrupting or thinning a protective film of corrosion products. Different flow parameters have been used in the past to correlate the flow and the metal loss rate, including: velocity (Copson 1960), Reynolds number (Mahato et al., 1968; Shemilt et al., 1980) and wall shear stress (Efird, 1977; Silverman, 1984). In more recent studies (Blatt and Heitz, 1990; Nešić and Postlethwaite, 1990) the local near-wall turbulence has been proposed as a key factor.

For attached flow in a simple geometry such as a straight pipe or a rotating cylinder, an increase in velocity corresponds to an increase in the Reynolds number and wall shear stress. Higher shear stress creates higher local turbulence levels close to wall and higher rates of mass transfer and corrosion. So it is acceptable, in this case, to use any of these parameters for correlation of the flow with erosion–corrosion. However problems arise when results from one simple geometry such as a rotating cylinder, which is a popular system for laboratory studies, are applied to a practical system involving pipes. Similar velocities and Reynolds numbers in the two systems do not guarantee hydrodynamic and mass transfer similarity, so the results from different studies are hardly comparable (Syrett, 1976). The use of wall shear stress overcomes this problem (Silverman, 1984). In a simple flow geometry the main source of turbulence is the wall shear stress and it is not surprising that the wall shear stress is a suitable correlating factor for the effect of flow on erosion–corrosion.

Erosion–corrosion problems encountered in industry often involve separated flow conditions at geometrical irregularities such as weld beads or fittings. Under such conditions turbulence is transported downstream from the point of separation and there is no simple relation between the bulk flow parameters and the local near-wall hydrodynamic and mass transfer conditions. In these systems there is no similarity between the wall shear stress and the turbulence profiles, so they must be measured or obtained from numerical simulation studies (Zeisel and Durst, 1990; Nešić and Postlethwaite, 1990).

Turbulent fluctuations interfere with the formation of protective films and also affect the rate of mass transfer of corrosion reactants through the liquid boundary layer. For example when the reduction of dissolved oxygen is the cathodic reaction, the process of corrosion is mass transfer controlled (Shemilt, 1980). Following Loss and Heitz (1973), we can adopt the concept of a double layer resistance to mass transfer, consisting of the resistance in the protective corrosion film on the metal surface and the resistance in the fluid boundary layer. Intensive turbulence close to the wall probably affects both, by disturbing the mass transfer boundary layer, and by disrupting the protective corrosion layer.

Hydrodynamic aspects of erosion–corrosion

Flow through a sudden pipe expansion was chosen as a generic test case, to study the relationship between the hydrodynamic parameters of the flow and mass transfer controlled erosion–corrosion in disturbed flow conditions. This geometry, extensively studied in fluid dynamics, has a high level of hydrodynamic complexity with separation, reattachment and recirculation of the flow. It is also of practical interest, as many severe problems in industry are related to situations where disturbed flow conditions are present.

It is important to have a good knowledge of the relevant flow parameters in order to understand the effect of turbulent disturbed flow on erosion–corrosion. Flow through a sudden expansion has been modelled in a number of hydrodynamic and heat transfer studies. Gosman et al. (1979) presented predictions for seven different two-dimensional elliptic flows, by using a two-equation, kinetic energy of turbulence — turbulence dissipation rate ($\mathbf{k} - \epsilon$) model. For flow through an axisymmetric sudden expansion, they compared their results with the experimental findings of Back and Roschke (1972), and reported good agreement for the reattachment length. Ha Minh and Chassaing (1979) presented an experimental study of air flow through a sudden expansion (both confined and unconfined — jet flow). They also made predictions using an Eddy Viscosity Model (EVM) and a Reynolds Stress Transport Model (RSTM), and

TABLE 1
Important Geometric, Hydrodynamic and Numerical Parameters

	Test case 1	Test case 2	Test case 3
Inlet diameter (mm)	26	20	21
Outlet diameter (mm)	40	40	42
Length (mm)	420	420	500
Inlet velocity (m/s)	1.14	6.74	13.2
Outlet velocity (m/s)	0.48	1.68	3.3
Inlet Reynolds number	37000	168000	340000
Outlet Reynolds number	24000	84000	170000
Number of x grid points	48	48	58
Number of y grid points	12	13	14
Number of iterations	252	376	429
Total error of prediction (%)	0.1	0.1	0.1
VAX 6320 CPU time (s)	136	207	313

reported that both models performed reasonably well, compared to their measurements made with the hot-wire anemometers. Recently Gould et al. (1990) showed results of simultaneous two-component laser Doppler (LDA) measurements in the incompressible turbulent air flowfield following an axisymmetrical expansion. The experimental measurements were compared with predictions generated by a code employing a **k** − ϵ model of turbulence. They found good agreement for mean axial velocities, turbulent kinetic energy, and turbulent shear stresses, but poor agreement for normal turbulent stresses.

In the present study, flow through a sudden expansion was modelled by a well established Eulerian based control volume method. The turbulence model is based on a standard single phase **k** − ϵ model described by Launder and Spalding (1973). The conservation equations for mass, axial and radial momentum, kinetic energy of turbulence and its dissipation are solved numerically by using the SIMPLE algorithm of Patankar and Spalding (1972). All conservation equations for the fluid phase have a general form:

$$\underbrace{\partial(\rho U_i \Phi)/\partial x_i}_{\text{convection}} = \underbrace{\partial(\Gamma_\Phi \partial\Phi/\partial x_j)/\partial x_i}_{\text{diffusion}} + \underbrace{S_\Phi}_{\text{source}} \quad \ldots\ldots (1)$$

where $\Phi = U, V, k, \epsilon, \ldots$

Full equations have been given elsewhere (Nešić and Postlethwaite, 1990).

BOUNDARY CONDITIONS

Since the set of partial differential flow Equations (1) is elliptical, it is necessary to define boundary conditions for all variables on all boundaries of the flow domain: inlet, exit, walls and symmetry axis. At the inlet, mean velocity and turbulence intensity can be taken from measurements, while zero gradients can be set at the axis and the outlet. Near the wall three basic approaches are possible: wall functions (simplest and most popular method), Low Reynolds Number (LRN) models (e.g. Jones and Launder, 1973) and Parabolic Sublayer (PSL) treatment (Iacovides and Launder, 1984).

In this study wall functions described previously by Nešić and Postlethwaite (1990) were used. Velocity in the computational node closest to the wall was computed from the universal logarithmic velocity profile, while wall shear stress, kinetic energy of turbulence **k** and its dissipation ϵ are obtained by assuming local equilibrium (production of turbulence = dissipation).

Simulation results and discussion

As the aim of this study was to reveal the relationship between the hydrodynamics of complex flows and erosion–corrosion, the test cases selected had to include both aspects of the problem. Parameters for all three test cases, relevant for this study, are given in Table 1. Some of the more important parameters of the numerical method used, like grid configuration, number of nodes, solution criteria, are also included.

TEST CASE 1 — HYDRODYNAMICS

The purely hydrodynamic aspects of fluid flow downstream of a sudden pipe expansion, were experimentally studied in the past decade, by employing laser Doppler anemometry (LDA). These include studies by Khezzar et al. (1985), Szczeppura (1985), Durret et al. (1988) and Stieglmeier et al. (1989). All authors experienced problems in measuring in the near-wall region, due to the refraction of the laser beams on the cylindrical surfaces of the test section. Unfortunately the flow parameters in this region are of primary interest for erosion–corrosion studies. Blatt et al. (1989) have reported both the LDA measurements in the near wall region, and erosion–corrosion measurements for flow through a sudden expansion, and their results were selected to verify the accuracy of the hydrodynamic model used.

The comparison of the simulation and the measurements for the axial velocities, at the centerline and 2 mm from the wall are shown in Figure 1a. The character of the curve for decay of the axial centerline velocity is captured by the predictions, although a discrepancy up to 10% exists in the

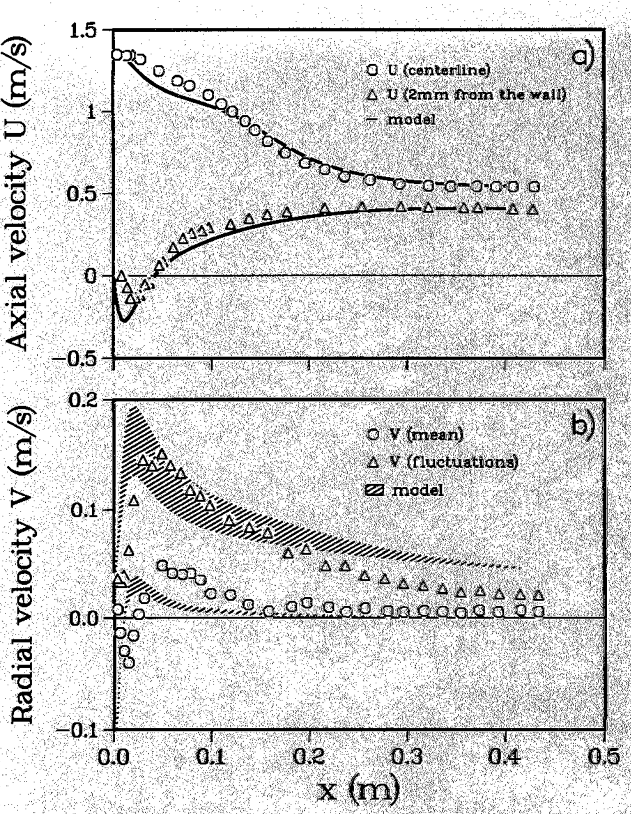

Figure 1 — (a) Predictions and measurements of the mean axial fluid velocity for flow through a sudden expansion — test case 1. (b) Predictions and measurements for the mean and fluctuating component of the radial fluid velocity, 2 mm from the wall, for flow through a sudden expansion — test case 1. Measurements taken from Blatt et al. (1989).

first part of the calculated domain. This may be due to the inaccurately defined flow parameters at the entrance of the flow domain in the original paper, and/or due to the faster spreading of the confined jet in the predictions. This problem is also found with other $\mathbf{k} - \epsilon$/ wall-function models (Yap, 1987).

The region close to the wall is of particular interest in this study, and Figure 1b shows comparisons of predictions and measurements of the radial velocity components for the same geometry 2 mm from the wall. According to calculations this point is in the buffer layer. As the typical measuring volume for LDA is of the order of 1 mm, and the gradients in the near-wall region are large, predictions are shown as the shaded area, with the limits corresponding to predictions at 1.5 mm and 2.5 mm from the wall. The predicted profile of the fluctuation velocity shows a good agreement with the measured values, taking into account that the predictions show a space-averaged value while the measurements present the radial component of the fluctuating velocity near the wall. This explains different asymptotic values for the fluctuations further downstream, given by the predictions and the experiments. Also, the predicted value is higher, as it is known that near the wall, the axial component of the fluctuating velocity is larger than the radial, so the space-averaged predicted value is expected to be larger than the measured radial component. Predictions of mean radial velocity show moderate agreement with the experiments. The maxima of both predicted curves are located somewhat before the measured values in the axial direction, which corresponds to the predicted faster spreading of the jet. In general, simulation of the hydrodynamic parameters of test case 1 have shown good agreement with the measured values, and the hydrodynamic model used can be considered reliable for predicting the flow structure in future erosion-corrosion studies.

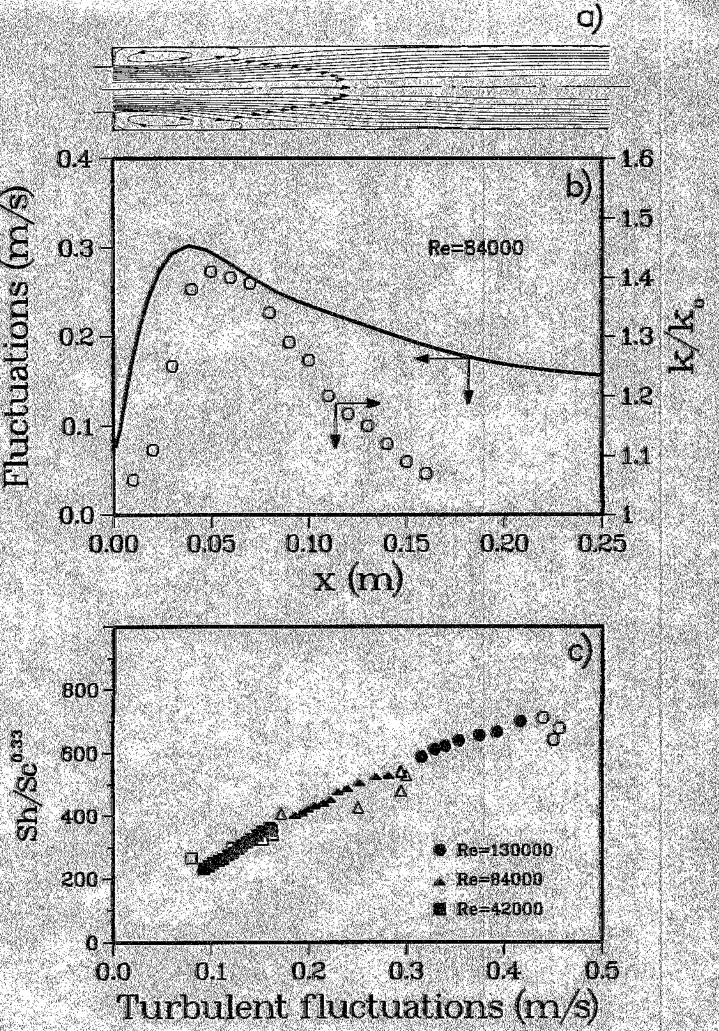

Figure 2 — (a) Predicted fluid flow streamlines — test case 2. (b) Profiles of measured increase in the mass transfer coefficient (Sydberger and Lotz, 1982) and predicted near-wall turbulence — test case 2. (c) Corrected Sherwood number vs. turbulent fluctuations in the buffer layer — test case 2.

TEST CASE 2 — MASS TRANSFER

The second test case was used to study the effect of disturbed flow on the mass transfer to the wall, as this is often a rate determining step in the corrosion process. Experimental results of Sydberger and Lotz (1982) were selected as they studied electrochemical mass transfer to clean smooth surfaces in complex flow geometries.

The flow geometry and predicted streamlines, with the recirculation region are shown in Figure 2a. Figure 2b shows the measured increase in mass transfer coefficient downstream for the expansion for $Re = 84000$. Since there were no surface films, this increase is a consequence of smaller effective thickness of the mass transfer boundary layer, caused by increased turbulent transport in this region. Predictions show that the shape of the curve and its maximum qualitatively coincide with the predicted profile of turbulence near the wall (Figure 2b). Identical conclusions were reached when flow at Reynolds numbers of 42000 and 130000 was simulated. Thus increased turbulence caused by separation and reattachment of the flow, creates turbulent eddies that reach very close to the wall, increasing the rate of wall-mass transfer.

Turbulent mass transport in the flow domain has not yet been directly modelled. Reasons are that the Schmidt numbers in liquid systems are of the order $10^2 - 10^3$ meaning that the mass transfer boundary layer is much thinner than the viscous sublayer. Application of wall functions for mass transfer is then not suitable as a much finer mesh, that goes closer to the wall than the one used for hydrodynamics, would be required.

To see if a general effect of turbulence on mass transfer can be detected over this wide range of Reynolds numbers, measured Sherwood numbers from test case 2 were plotted against predicted near-wall turbulence velocity fluctuations in Figure 2c. In this correlation the values of the velocity fluctuations at the node closest to the wall, which is in the buffer layer, were used. The Sherwood number was divided by the $Sc^{0.33}$ for generality. The very pronounced correlation obtained suggests that rates of mass transfer are directly related to the levels of turbulence near the wall, and can be predicted by using the present flow model. Open symbols that do not follow the general correlation are typical for the region before the reattachment, where the model of turbulence used is strictly not correct.

TEST CASE 3 — EROSION-CORROSION

In the presence of rust films mass transfer is not limited only by the presence of the fluid boundary layer, but also by presence of the rust and/or scale films. Thus, the third test case studied was measurement of erosion–corrosion in disturbed flow conditions in the presence of rust films, by Lotz and Postlethwaite (1990).

Predicted streamlines, the level of turbulent fluctuations in the near-wall region, the corresponding profile of the wall shear stress, and the measured values of metal loss by erosion–corrosion, are shown in Figure 3.

Comparing the profile of metal loss (Figure 3b) with the predicted curves for wall shear stress (Figure 3c), it is clear that the shear stress cannot account for increased mass transfer and corrosion due to stripping of the rust film, as shear stress is zero at the reattachment point, where metal loss rate reaches its maximum. The profile of near-wall turbulence (Figure 3b) displays a similar character as the metal loss profile with the maximum slightly moved towards the expansion. Thus, we are led to conclude that local levels of turbulence are somehow related to measured increased levels of metal loss. We know from the study of test case 2, that turbulent transport causes an increase in the local mass transfer coefficient. But when rust films are present the rate of the corrosion reaction is limited by the diffusion through the film as well as the boundary layer.

Figure 3c suggests that part of the rust formed on the surface has been removed. It can also be noticed that the amount of rust retained on the surface is nearly constant but the rate of removal is highest at the point of maximum metal loss, which corresponds to the maximum in near-wall turbulence. Thus the point of maximum rate of rust removal (erosion) coincides with the point of maximum rust production (corrosion). Both are related to the maximum in the near-wall turbulence. Where near-wall turbulence is not as high, corrosion rate and production of the rust is slower, but so is the erosion of the rust by the pounding turbulent fluctuations. This explains the rather uniform thickness of the film.

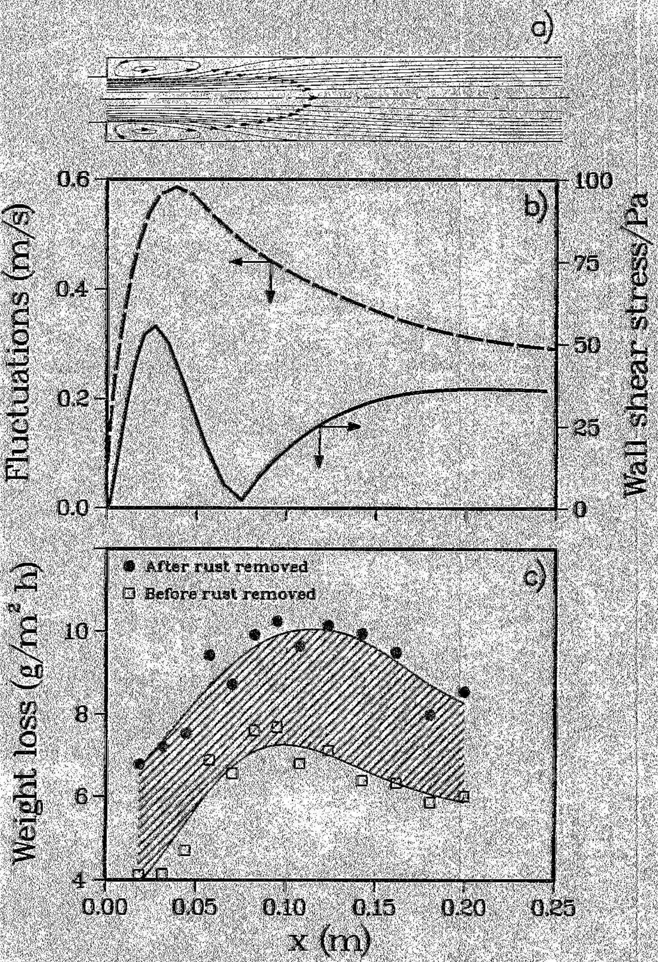

Figure 3 — (a) Predicted fluid flow streamlines — test case 3. (b) Profiles of predicted near-wall turbulence and wall shear stress — test case 3. (c) Measured rate of metal loss by erosion–corrosion after 48 h (Lotz and Postlethwaite, 1990) — test case 3.

On the other hand, if the thickness of the rust layer is uniform it would mean that its resistance to mass transfer is also uniform. Measured differences in metal loss rates, along the length of the expansion are then only a consequence of the differences in mass transfer through the boundary layer. So the overall shape (character) of metal loss curve is determined by the transport through the boundary layer (by the flow structure), while the magnitude of the metal loss rate is additionally influenced by the transport through the rust film which acts as a damper. Flow (near-wall turbulence) affects both. Although initially a large proportion of formed rust is removed, as time progresses experience tells us that thickness of the rust layer increases which decreases the overall metal loss rate. In addition, damping of the effect of flow must increase, to a point where it can not be distinguished.

In order to estimate the magnitude of the effects discussed, for the test case 3, we can use the correlation from test case 2 (Figure 2c) and use the model to predict levels of near-wall turbulence for the test case 3 (Figure 3b). For the maximum level of turbulent fluctuation of 0.6 m/s ($x \approx 50$ mm) the correlation in Figure 2c gives $Sh/Sc^{0.33} = 845$ and corrected for the Schmidt number for test case 3 ($Sc = 352$), $Sh = 5852$. This means that the corresponding mass transfer coefficient for the liquid boundary layer is $k_l = Sh\,D/d = 3.26 \times 10^{-4}$ m/s. The estimated effective thickness of the mass transfer boundary layer at this point is 5μm, which is at least an order of magnitude smaller than the estimated thickness of the hydrodynamic boundary layer for the same point.

From the measured maximum corrosion loss rate we can calculate the overall mass transfer coefficient to be $k_o = 2.13 \times 10^{-4}$ m/s. Here, we can keep in mind that this is an average value for the time interval measured (48 h) while the instantaneous value is smaller. If we assume the double layer resistance for mass transfer:

$$1/k_o = 1/k_\ell + 1/k_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

and an increase in the liquid mass transfer coefficient by a factor of 1.8, to account for the effect of roughness (Lotz and Postlethwaite, 1988), $k_\ell = 5.86 \times 10^{-4}$ m/s, the mass transfer coefficient for the rust layer is $k_s = 3.34 \times 10^{-4}$ m/s. Comparing the two values we can conclude that at the point of maximum turbulence and mass transfer, the limiting resistance for mass transfer is in the rust film. Had we used an instantaneous value of the overall mass transfer coefficient instead of the time average the difference would be even larger.

Conclusions

1. For disturbed flow conditions there is no simple relation between the bulk flow parameters and the near-wall hydrodynamics and mass transfer, so they must be measured or obtained from numerical simulation studies. Simulation of the hydrodynamic parameters, in this study, has shown good agreement with the measured values, and the hydrodynamic model used can be considered reliable for predicting the flow structure in future erosion–corrosion studies.
2. Rates of mass transfer through the liquid boundary layer are directly related to the levels of turbulence near the wall, and can be predicted by using a $\mathbf{k} - \epsilon$ flow model.
3. When rust films are present the overall shape (character) of metal loss curve is determined by the transport through the boundary layer (by the flow structure), while the magnitude of the metal loss rate is additionally influenced by the transport through the rust film which acts as a damper. Near-wall turbulence fluctuations affect both. Except in the early stages of corrosion the limiting resistance for mass transfer is in the rust film.

Nomenclature

d = pipe diameter, m
D = diffusion coefficient, m^2/s
k = mass transfer coefficient, m/s
$\mathbf{k}$ = kinetic energy of turbulence, m^2/s^2
Re = Reynolds number, $Re = ul/\nu$
S = general source term
Sc = Schmidt number, $Sc = \nu/D$
U, V = components of mean velocity vector, m/s
V = mean radial velocity, m/s
x = axial coordinate, m

Greek letters

Γ = general diffusion coefficient
ϵ = dissipation rate of kinetic energy of turbulence, m^2/s^3
ν = kinematic viscosity, m^2/s
ρ = fluid, density, kg/m^3

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