Numerical investigation of mass transfer in a 90° bend

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Abstract

Fluid flow and mass transfer in a 90° bend was investigated numerically. The RNG version of *k*–ε model was used for turbulence prediction. Maximum mass transfer rate was predicted at a distance one diameter downstream of the elbow. Numerical analysis results are in good agreement with experimental results obtained from literature.

Keywords : CFD simulation, mass transfer coefficient, bend, turbulent flow.

Introduction

Due to the strong influence of local mass transfer coefficients on corrosion rate predictions, several investigators conducted experiments for single-phase flows to determine the maximum mass transfer coefficients in 90° elbows and 180° bends. Poulson and Robinson [1] experimentally studied mass transfer in two 180° bends with *r*/*D* ratios of 1.25 and 2.72. An expression for the ratio of the maximum mass transfer coefficient or the Sherwood number for an elbow to the mass transfer coefficient for fully developed pipe flow (Sh/Sh_p) was also proposed by Poulson and Robinson based on the experimental data in the r/D=1.25, 180^0 bend. The proposed expression contains only the Reynolds number and it was concluded that the Sh/Sh_p decreases as the flow Reynolds number increases.

Coney [2] experimentally investigated the mass transfer in bends and developed an equation for the Sh/Sh_p:

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$$\frac{Sh}{Sh_p} = 1 + 2.2(\frac{R}{r})^{1.2}(\frac{L}{D})^{0.75} \qquad (1)$$

where $Sh = hD/D_f$ is the Sherwood number, h the mass transfer coefficient, D_f the fluid diffusivity, D the inside pipe diameter, R the radius of the pipe ($R=D/2$), r the mean radius of the elbow, and L is the length along the center line of the curved section of the elbow. For a 90° elbow, $L=\pi r/2$, and Eq. (1) becomes:

$$\frac{Sh}{Sh_p} = 1 + 1.343(\frac{r}{D})^{-0.45} \qquad (2)$$

Eq. (2) is a function of the ratio of the elbow radius to the pipe diameter. This correlation suggests that the Reynolds number does not have an influence on the Sh/Sh_p. (It should be noted that the Reynolds number does influence the mass transfer coefficient in elbows.)

Sprague et al. [3] measured local mass transfer coefficients in 45° and 180° bends with an $r/D=2.72$. Based on the experimental data, Sprague et al. [3] concluded that the Sh/Sh_p in 45° and 180° bends decreases as the flow Reynolds number increases.

In the present investigation flow and mass transfer coefficients in a 90° elbow was investigated numerically. Predicted mass transfer coefficients from the pipe wall to the fluid or from the fluid to the pipe wall are compared with available experimental data in the literature to verify the model.

Description of computational models

Governing equations of fluid motion (Navier–Stokes equations)

The governing equations of flow employed in CFD are discussed in this section. The continuity and momentum equations are given in Eqs. (3) and (4), respectively [4]:

$$\frac{\partial r}{\partial t} + \nabla\,(r\vec{U}) = 0 \qquad (3)$$

$$\frac{\partial (r\vec{U})}{\partial t} + \nabla\,(r\vec{U} \otimes \vec{U}) = \vec{B} + \nabla\,(-r\overline{u' \otimes u'} + s) \qquad (4)$$

where ρ is the fluid density, $\vec{U}$ is the instantaneous velocity vector, $\vec{B}$ is the body force, u' is the fluctuating velocity due to turbulence (i.e. $\vec{U} = u + u'$, where u is the mean velocity component), $r\overline{u' \otimes u'}$ is the Reynolds stress; and the stress tensor, s, is given by

$$s = -\frac{P}{r} I + \frac{m}{r}[\nabla\vec{U} + (\nabla\vec{U})^T] \tag{5}$$

where P and m are the local pressure and viscosity of the fluid, and I is the identity matrix. There are several turbulence models available in the CFD code. Among them, the RNG version of k–ε turbulence model was used to predict turbulent flow and mass transfer in elbow.

Mass transfer equation:

$$\frac{\partial r_A}{\partial t} + r_A(\nabla \cdot v) + (v \cdot \nabla r_A) = D_{AB}\nabla^2 r_A \tag{6}$$

Where r_A is the concentration of diffusive component, v is the fluid velocity and D_{AB} is diffusion coefficient.

Model description and verification

In CO_2 corrosion of oil and gas pipelines, concentrations of chemical reacting species can be dilute. Thus, their reactions with the pipe wall may not significantly change the fluid or flow behavior. Therefore, it is assumed the flow field results will not be affected by chemical reactions. This de-couples the governing flow equations from the governing equations for mass transfer. Based on this assumption, the CFD code was used to simulate flow and mass transfer in elbows. Flow in an elbow is assumed to be turbulent and turbulent flow models are needed to calculate the turbulent viscosity that is needed in the Reynolds (time-averaged Navier–Stokes) equations. There are several turbulence models available in the CFD code. Among them, the RNG version of k–ε model was used for turbulent flow and mass transfer in elbows.

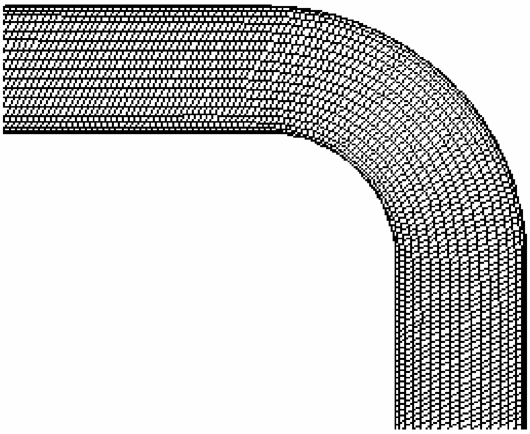
A description of the governing equations that are used to solve the flow field and mass transfer coefficient is given in Eqs. (3-6).

The experimental data of Enayet et al. [5] for turbulent flow in a 90° elbow were used to evaluate the turbulence models used in this study. Mass transfer results were compared with experimental data of Achenbach [6] to verify the models.

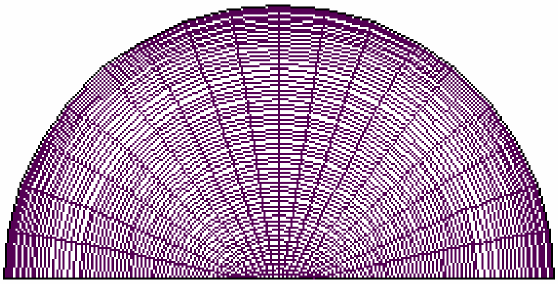
Flow model verification in a 90° elbow

The experimental data provided by Enayet et al. [5] with a Reynolds number of 43000 were numerically simulated. The simulation started at a plane 1 meters upstream of the elbow inlet (i.e., $x = -1$) assuming a uniform inlet velocity profile (Enayet et al. data did not give details of flow upstream of the elbow) and finished at a plane 1 meters downstream of the elbow outlet (i.e., $x = 1$).

For this simulation, the total number of grid points used was 389918 with 330 in the stream wise direction (Fig. 1). The total number of grid points in the half of cross-section plane is 1098 with 18 grid points in the circumferential direction (Fig. 2). A grid refinement study was performed using the RNG version of k–ε model by doubling the number of grid points in the radial direction. The solutions for the velocity profiles and the mass transfer coefficient ratios (discussed below) that were obtained by the finer radial grids were compared to the solutions presented below. The differences between the solutions for the finer grid and the results presented in this section were generally less than one or two percent.

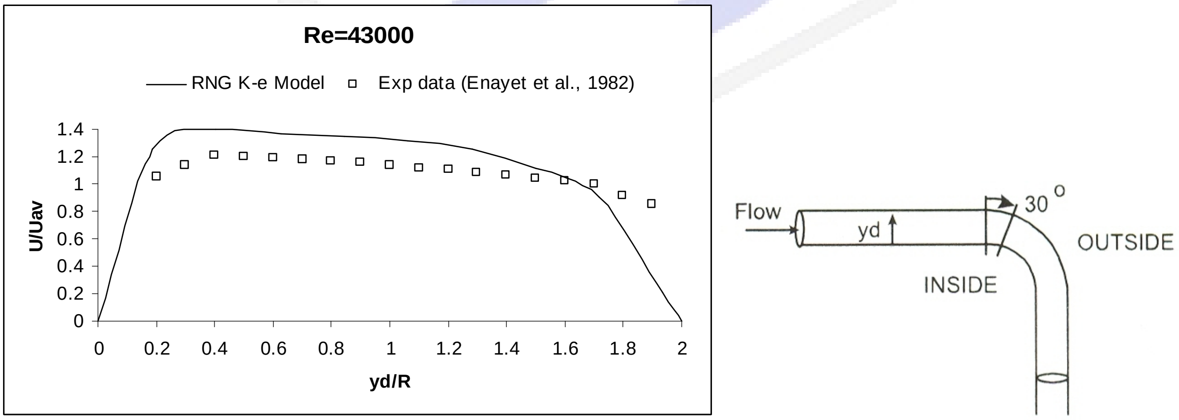


(Fig. 1) schematic scheme of grid points in the stream wise direction.



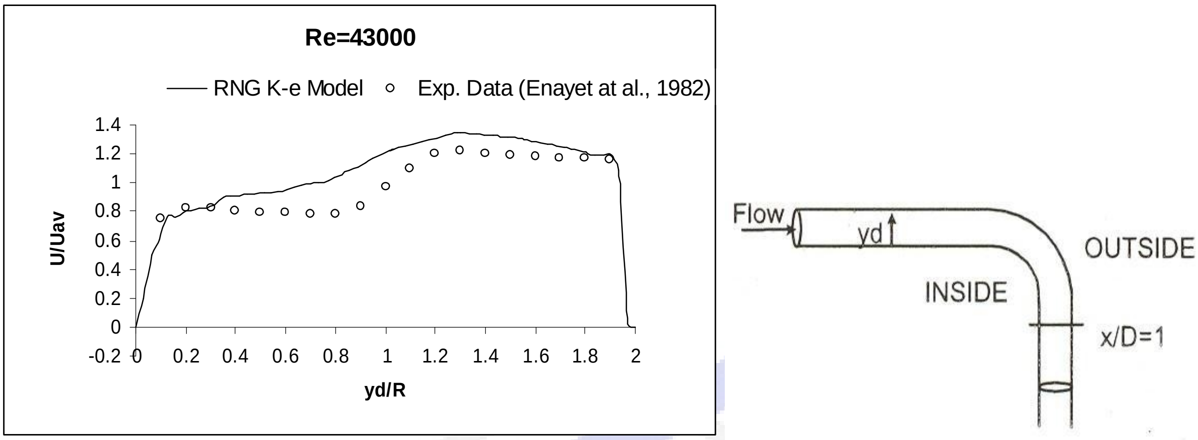
(Fig. 2) schematic scheme of grid points in the half of cross-section plan.

The predicted velocity profiles at the 30° station of the elbow are compared with the experimental data [5] and are shown in (Fig. 3). It can be seen that at the 30° station, the maximum velocity occurs near the inner wall and the RNG version of k-ε turbulence model agree well with the experimental data.



(Fig. 3) Predicted velocity profiles and experimental data [5] at the 30° station.

The flow model predictions downstream of the elbow were also carefully studied. This is because the maximum mass transfer occurs downstream of the exit of the elbows. (Fig. 4) shows the comparison of the predictions with the experimental data downstream of the elbow at *x*/*D*=1 station. From (Fig. 4), it can be seen that in the downstream region, the RNG version of *k*–ε turbulence model predictions are in better agreement with the experimental data.

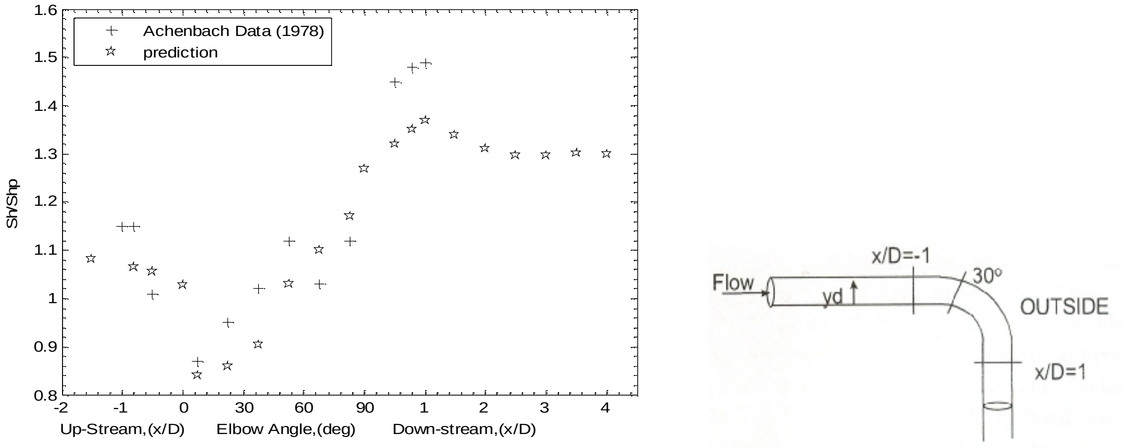


(Fig. 4) Predicted velocity profiles and experimental data [5] at x/D=1.

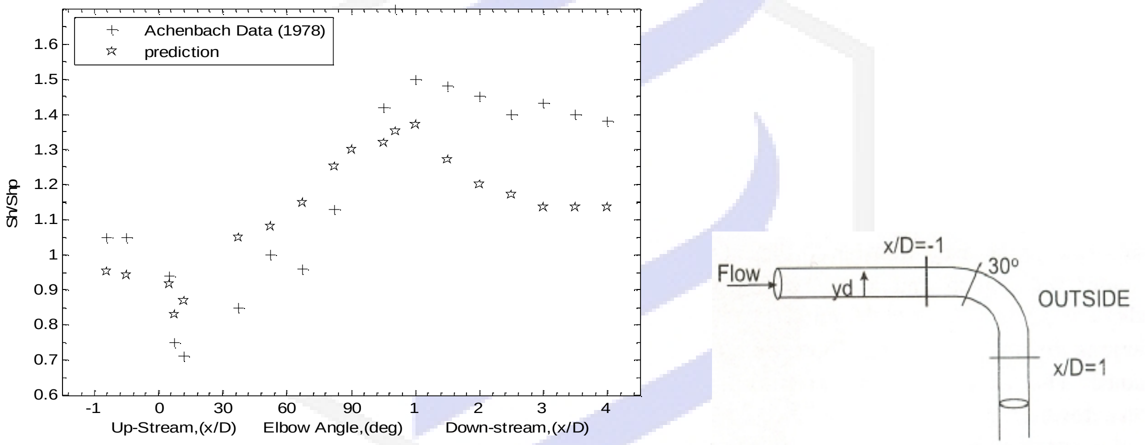
Since the maximum mass transfer occurs at the outer surface of the elbow and downstream (about one to one half diameter-downstream) of the elbow exit, where the predicted velocity profiles agree with the data, it was decided that the available flow model is good to predict the mass transfer coefficient in the outer wall of the elbow.

Mass transfer model verification

Mass transfer coefficient predictions using the CFD code were compared with the experimental data of Achenbach [6] for a naphthalene–air system. Achenbach measured mass transfer between an elbow wall and air in a 90° elbow ($r/D = 1.5$, Reynolds numbers of 9×10^4, 3.9×10^5 and a Schmidt number of 2.53). To simulate this experiment, the following boundary conditions were applied. At the inlet, it was assumed that naphthalene concentration is zero and the velocity profile is uniform. At the pipe wall, the dimensionless concentration of naphthalene is one and no-slip velocity boundary condition was applied. The predicted results of the ratio of the local mass transfer coefficient (or the Sherwood number) in an elbow to the mass transfer coefficient of fully developed flow in a pipe (Sh/Sh_p) are shown in (Fig. 5) and (Fig. 6). For both cases considered here, it was observed that the trend of the predictions agrees with the experimental data.



(Fig. 5) Predicted mass transfer coefficients in a 90° elbow vs. data of Achenbach [6] (*Re*=9×10^4, *Sc*=2.53).



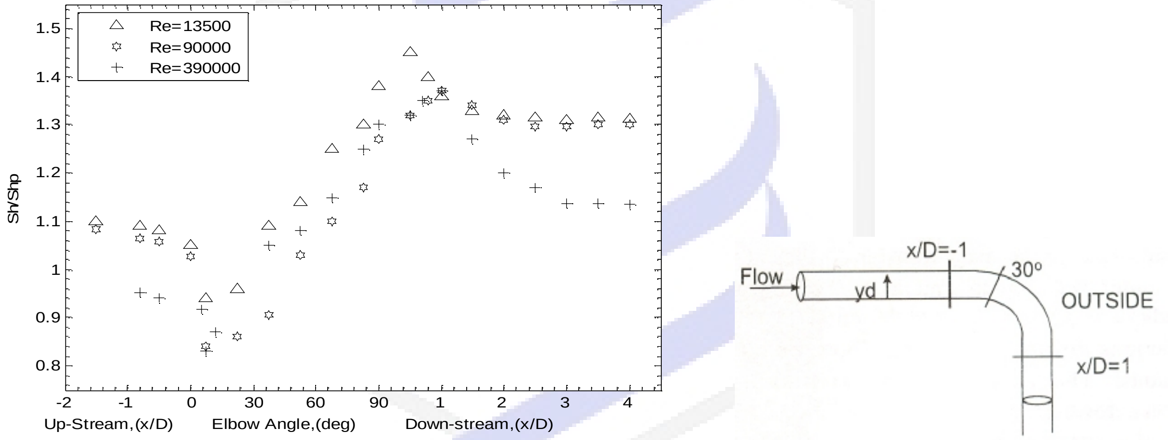
(Fig. 6) Predicted mass transfer coefficients in a 90° elbow vs. data of Achenbach [6] (*Re*=3.9×10^5, *Sc*=2.53).

From (Fig. 5) and (Fig. 6), it can be seen that the minimum mass transfer rate occurs at the bend inlet and the maximum mass transfer rate at a distance one diameter downstream of the elbow. Also, it is observed that the simulation results are in agreement with the experimental data. The predicted mass transfer profiles in the elbow identifies the right location and approximate magnitude of the maximum mass transfer rate in the elbow.

Mass transfer coefficients in elbows

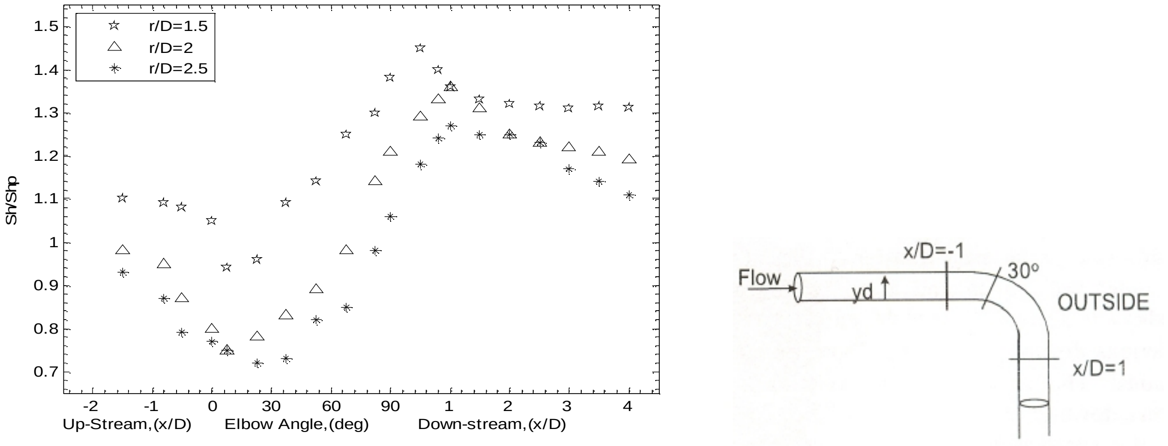
The mass transfer coefficient in an elbow varies with the flow Reynolds number (*Re*), the Schmidt number of the system (*Sc*) and the elbow radius to pipe diameter ratio (*r*/*D*). By performing CFD simulations based on different Reynolds numbers, Schmidt numbers and elbow *r*/*D*, the ratio of the local mass transfer coefficient (or the Sherwood number) in an elbow to the mass transfer coefficient of fully developed flow in a pipe (Sh/Sh_p) was obtained.

The simulated results for mass transfer as a function of the Reynolds number in a 90° elbow with *r*/*D*=1.5 and *Sc*=2.53 are shown in (Fig.7). It can be observed that Sh/Sh_p decreases as the flow Reynolds number increases. The accuracy of the data is not known. But, other data for elbows [3] indicate that MTCRE decreases as the flow Reynolds number increases as indicated by the CFD code simulations.



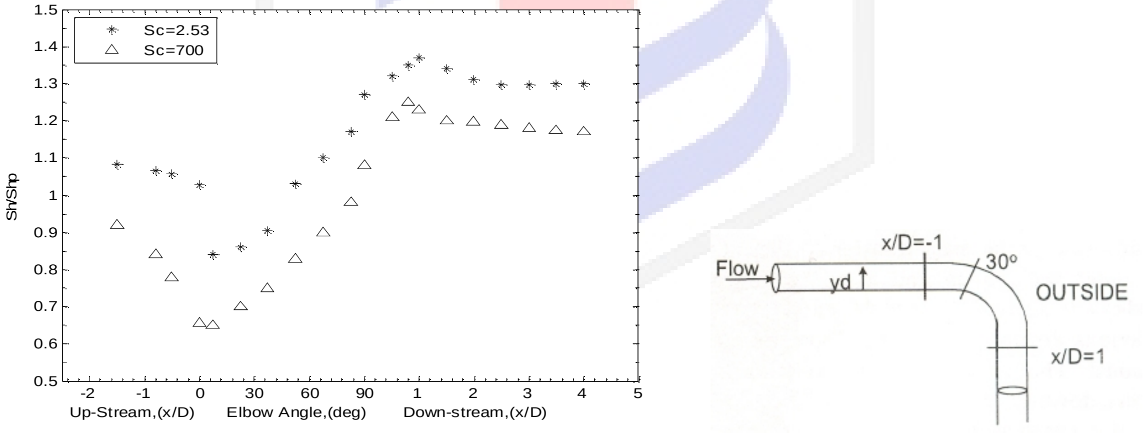
(Fig. 7) Variation of (Sh/Sh_p) with the Reynolds number (Sc = 2.53 , r/D =1.5).

The predictions from the CFD code simulations are compared for different elbow *r*/*D* values with Re=13500 and Sc=2.53. The results are shown in (Fig. 8). It can be seen that Sh/Sh_p decreases as the flow Reynolds number increases. The accuracy of the data is not known. But, Eq. (2) indicates that Sh/Sh_p decreases as the flow Reynolds number increases as indicated by the CFD code simulations.



(Fig. 8) Variation of (Sh/Sh_p) with r/D (Re = 13500 , Sc =2.53).

The predicted mass transfer coefficient ratio of an elbow (Sh/Sh_p), at a *r*/*D* of 1.5 with *Re*=$9*10^4$, as a function of the Schmidt number is shown in (Fig. 9). It can be observed that Sh/Sh_p decreases as the flow Reynolds number increases. For high *Sc* numbers, the predictions indicate that the Schmidt number does not have a significant influence on Sh/Sh_p.



(Fig. 9) Variation of (Sh/Sh_p) with the Schmit number (Re = $9*10^4$, r/D =1.5).

Conclusions

Three-dimensional computational flow modeling was applied and mass transfer predictions was developed in a 90° elbow. Mass transfer rate is a function of the flow Reynolds number, the Schmidt number and the elbow radius to diameter (*r*/*D*) ratio. The CFD code results for the maximum mass transfer coefficient in an elbow to the mass transfer coefficient in a fully developed pipe flow (Sh/Sh_p) is in good agreement with the available experimental data for flow and mass transfer in elbows. The results for Sh/Sh_p is found to decrease slightly with the flow Reynolds number, with Schmidt number, and with r/D for moderate r/D values.

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