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ON COUPLING CO_2 CORROSION AND MULTIPHASE FLOW MODELS

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ABSTRACT

Corrosion prediction in multiphase flow has been a challenging task in oil and gas industry for many years. Strictly speaking, the existing mechanistic CO_2 corrosion models can only be used in single-phase flow. To add the capability of predicting corrosion in multiphase flow, the mass transfer and the turbulent diffusivity correlations in the models have to be modified to properly calculate the mass flux of corrosion species. An approach for establishing these correlations in different flow regimes is presented. The implementation of the method for stratified flow proves the feasibility of this proposal.

Keywords: mass transfer, multiphase flow, corrosion model, turbulent diffusivity, correlation

INTRODUCTION

For oil and gas pipeline applications, a useful CO_2 corrosion model needs to predict corrosion rates not only in single-phase flow conditions but, more importantly, in multiphase flow conditions. It is well known that the flow variations along pipelines, such as flow regime, water wetting and liquid flow velocity, have significant effects on the corrosion process in multiphase flow conditions[1]. However, all of the current corrosion models have no virtually capability to compute the effects of multiphase flow. In order to evaluate corrosion in pipelines, corrosion models need to be adapted and coupled with multiphase flow simulators to compute the effects of multiphase flow.

Little research has been performed in the past on coupling CO_2 corrosion and multiphase flow models. Nyborg et al[2] implemented CO_2 corrosion models into a three-phase fluid flow model (OLGA). Three empirical and semi-empirical corrosion models, de Waard 93[3] and 95[4] model, and NORSOK M-506 model[5], have been embedded as a modules in OLGA. There are no studies on coupling a more mechanistic corrosion model with a comprehensive multiphase fluid flow model.

Mass transfer prediction is of great importance in computing corrosion rates, particularly for the transport based models, and is also the key for implementing the coupling of CO_2 corrosion and multiphase flow models. In the following, two mass transfer prediction methods are briefly reviewed.

Conventional tools for mass transfer predictions in fully developed single-phase pipe flow have a dimensionless number form:

$$Sh = a \times \mathrm{Re}^{b} \times Sc^{c} \tag{1}$$

where *a*, *b* and *c* are the constants determined by experiments, *Sh* is the Sherwood number *kd/D*, *Re* is Reynolds number *Ud/v*, and *Sc* is Schmidt number *v/D*. A number of empirical mass transfer correlations have been developed in the past for single-phase flow starting with the well-known Colburn[6] (1934) correlation:

$$Sh = 0.023\,\mathrm{Re}^{0.8}\, Sc^{0.33} \tag{2}$$

The most recent and widely used correlation proposed by Berger and Hau[7] in 1977 for mass transfer in smooth pipes is given as:

$$Sh = 0.0165 \times \mathrm{Re}^{0.86} \times Sc^{0.33} \tag{3}$$

However, there are no studies on mass transfer correlations valid in multiphase flow. Langsholt et al[8] and Wang[9] measured wall stress and mass transfer coefficients in a two-phase gas/liquid flow and the former results will be used below to develop mass transfer correlations for multiphase flow, which could be used with more confidence in mass transport based corrosion models, such as Dayalan et al[10]'s.

In the recent published mechanistic CO_2 corrosion models[11, 12], the mass transport of species in the diffusion boundary layer is described locally by using a much more detailed method. There the mass flux, N_i, of species *i* throughout the boundary layer can be expressed as:

$$N_i = -(D_i + D_t)\frac{\partial c_i}{\partial y} \tag{4}$$

where D_i is the molecular diffusion coefficient of species *i*, D_t is the turbulent diffusion coefficient, c_i is the concentration of species *i*, y is the distance from the wall. In the model, D_t is obtained from Davies[13]'s correlation, which is based on a semi-empirical turbulent mass transfer theory.

$$D_t = 0.18\left(\frac{y}{\delta}\right)^3 \frac{\mu}{\rho} \tag{5}$$

where δ is the thickness of the laminar boundary layer, ρ is the density, and μ is the dynamic viscosity. The coefficient 0.18 was derived on the basis of several assumptions. For pipe flow, δ can be expressed as a function of Reynolds number

$$\delta = 25\,\mathrm{Re}^{-7/8}\, d \tag{6}$$

where *d* is the pipe diameter. Lin et al[14] presented a similar correlation:

$$D_t = 0.041(\frac{y}{\delta})^3 \frac{\mu}{\rho} \tag{7}$$

Yet another semi-empirical correlation was reported by Rosen and Tragardh[15], which contains a Schmidt number dependence:

$$D_t = 0.155 Sc^{-0.112}(\frac{y}{\delta})^3 \frac{\mu}{\rho} \tag{8}$$

Both methods for calculating mass transfer rates: globally by using Sherwood number or locally by using D_t must yield similar results to be considered as valid. Since all the expressions shown above were developed for single-phase pipe flow, applying them to the multiphase flow without any modification is uncertain.

In the present work, in order to obtain the mass transfer correlations that can be used to couple corrosion and multiphase flow models, an approach for establishing the correlations in different flow regimes is presented. First, a relationship between the *Sh* and the D_t has been derived. Secondly, an empirical Sherwood number correlation similar in the form to (1) is developed based on the measured mass transfer coefficients in multiphase flow regimes. Then the corresponding turbulent diffusivity correlation was obtained. The validation of the method for stratified flow is shown as an example.

THEORIES AND METHODS

Relationship of the Two Mass Transfer Prediction Methods

The global equation defining a turbulent mass transfer of species *i* is

$$N_i = -k_i(c_{i,s} - c_{i,b}) \tag{9}$$

where N_i *is flux* of species *i*, $c_{i,s}$ and $c_{i,b}$ are the concentrations of species *i* at the surface and bulk respectively. Here, *k* depends markedly on flow conditions, which are represented by a dimensionless Reynolds number (*Re*). Also, it is a complicated function of fluid properties, which is conveniently related to the dimensionless Schmidt number (*Sc*). Sherwood number, *Sh = kd/D*, which can be determined by equation such as (3), relates the turbulent mass transfer coefficient *k* to the molecular diffusion rate *D*, where *d* is to a characteristic dimension such as a pipe diameter.

In turbulent flow, the mass flux N_i of species *i* can also be expressed by equation (4), which describes in more detail the mass transport through the boundary layer and can be rewritten as:

$$\frac{N_i}{D_i + D_t} dy = -dc_i \tag{10}$$

Integrating (10) across the boundary layer, one has

$$\int_0^{\delta} \frac{N_i}{D_i + D_t} dy = c_{b,i} - c_{s,i} \tag{11}$$

Substitution of (9) into (11) yields a relationship between the mass transfer coefficient and turbulent diffusivity:

$$\int_0^{\delta} \frac{dy}{D_i + D_t} = \frac{1}{k_i} \tag{12}$$

Given a mass transfer coefficient correlation, the corresponding turbulent diffusivity correlation can be obtained, vice versa.

Numerical Verification in a Single-phase Pipe Flow

To verify the feasibility of the derived relationship between the mass transfer coefficient and turbulent diffusivity correlations, numerical tests were implemented for single-phase pipe flow in which the available mass transfer correlations have been well established. The comparisons are based on an assumption that Berger and Hau[7] correlation can be treated as a valid benchmark because of a large amount of experiments, which have confirmed its reliability in the past.

The first numerical test was carried out at a fixed Reynolds number *Re* = 151,250 for the different Schmidt numbers, which correspond to species including H^+, Fe^{2+}, Na^+, Cl^-, CO_2, H_2CO_3, HCO_3^-. With the Berger and Hau[7] empirical correlation, one can calculate directly the Sherwood number as a function of Schmidt number. Alternatively, by using the various turbulent diffusivity correlations (5), (7), and (8), the mass transfer coefficients and the Sherwood numbers were computed by integration (12). The comparison is presented in Figure 1. It demonstrates that Lin et al[14]'s and Rosen and Tragardh[15]'s correlations show better agreement with the Berger and Hau[7] correlation over a wide range of *Sc* numbers.

The second numerical test was performed for a fixed Schmidt number *Sc* = 562.8 (corresponding to the Fe^{2+} ion) as a function of Reynolds number covering velocities from 1 m/s to 10 m/s in a 0.1 m ID pipe. The comparison obtained by different correlations is shown in Figure 2. Again it can be concluded that Lin et al[14]'s as well as Rosen and Tragardh[15]'s correlations are the closest to the Berger and Hau[7] correlation.

The numerical tests show that the mass transfer coefficient and turbulent diffusivity correlations can be simply compared by the derived relation (equation 12). For single-phase pipe flow, Lin et al[14]'s turbulent diffusivity correlation is recommended to compute D_t.

MASS TRANSFER COEFFICIENT CORRELATION IN MULTIPHASE FLOW

Poor Performance of the Berger and Hau[7] Correlation for Stratified Flow

Since no explicit mass transfer correlations for multiphase flow can be found in the open literature, the simplest approach is to try and use the single-phase Berger and Hau[7] correlation to predict mass transfer in multiphase flow by replacing the pipe diameter in (3) with a hydraulic diameter[12].

In order to evaluate the above proposition, the mass transfer coefficients measured by Langsholt et al[8] were compared with those calculated by Berger and Hau[7] correlation in stratified flow and are shown in Figure 3. Another nondimensional comparison of the same data is shown in Figure 4, in which the hydraulic diameter was used to compute *Sh* and *Re*. Thus, it is obvious that the Berger and Hau[7] correlation cannot be directly applied to predict mass transfer in multiphase flow. A modified mass

transfer coefficient correlation for multiphase flow regimes needs to be developed. Similarly, the use of turbulent diffusivity correlations, such as Davies[13], Lin et al[14], or Rosen and Tragardh[15]'s, for multiphase flow is also uncertain. Therefore, a modified turbulent diffusivity correlation for multiphase flow regimes is needed.

A Modified Mass Transfer Correlation for Stratified Flow

The mass transfer coefficients experimentally obtained in a fully developed two-phase gas/liquid flow by Langsholt et al[8] were used as a basis for the development of an improved mass transfer correlation for stratified flow.

It is assumed that the new correlation will retain the same form as given by (1). The exponent on the Schmidt number remains 0.33, which is based on an assumption that the eddy diffusivity near the pipe wall is proportional to $(y^+)^3$ as proposed by several researchers. Therefore, the key point is to determine a and b in (1).

After carefully analyzing the stratified flow data, a modified mass transfer correlation for stratified flow was identified:

$$Sh = 0.64\,\mathrm{Re}^{0.59}\,Sc^{0.33} \tag{13}$$

The liquid film height is used to compute Sherwood number and the pipe diameter is used to compute Reynolds number. Figure 5 shows the agreement of the new correlation with the data of Langsholt et al[8]. Another way of demonstrating the agreement is shown in Figure 6, which is a great improvement when compared to the Figure 3 and Figure 4 where Berger and Hau[7] correlation was used.

Extended Application of the New Correlation for Slug Flow

Slug flow is another important multiphase flow regime that frequently occurs in pipeline transport of oil and gas. While the hydrodynamics of slug flow is very complex, one can crudely distinguish the slug, which moves very fast (approximately at the gas superficial velocity) and the film, which moves much slower (approximately at the liquid superficial velocity). For the film, one can test the same correlations as used for stratified flow. Thus the mass transfer correlation (13) should be applicable to the film zone. Although only limited data for slug flow are available from the work by Langsholt et al[8], Figure 7 shows good agreement between the mass transfer coefficients predicted by (13) and the experiment data. The further validation of the new correlation will be done when more data become available.

TURBULENT DIFFUSIVITY CORRELATION IN STRATIFIED FLOW

Once the new mass transfer correlation (13) was established, one can derive the turbulent diffusivity correlation for stratified flow by using equation (12).

In (12), the thickness of the laminar boundary layer δ is needed. For pipe flow, equation (6) was used to calculate δ. However, it also needs to be modified when calculating the layer thickness for stratified flow. Using trial and error, the modified turbulent diffusivity correlation for stratified flow is obtained as:

$$D_t = 0.06(\frac{y}{\delta})^3 \frac{\mu}{\rho} \tag{14}$$

and

$$\delta = 25\,\mathrm{Re}_d^{-7/8}\, h \tag{15}$$

where h is liquid film height, pipe diameter d is used to calculated Reynolds number. Figure 8 shows that the mass transfer coefficients predicted by (14) compare well with those predicted by (13) and measured by Langsholt et al[8] for stratified flow.

CONCLUSIONS

- Use of standard single-phase flow mass transfer correlations (such as Berger and Hau[7]) in multiphase flow by employing the equivalent diameter concept leads to large errors.
- A new mass transfer correlation has been derived for stratified flow that agrees well with available experiment data.
- A new turbulent diffusivity correlation was established for stratified flow which enables more accurate implementation of mass transfer effects in CO_2 corrosion in multiphase flow.

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NOMENCLATURE

c	concentration of species	[kmol/m^3]
D	diffusion coefficient	[m^2/s]
d	pipe diameter	[m]
h	liquid film height	[m]
k	mass transfer coefficient	[m/s]
N	mass flux of species	[kmol/(m^2.s)]
Re	Reynolds number(Ud/ν)	[-]
Sc	Schmidt number($=\nu/D$)	[-]
Sh	Sherwood number($=kd/D$)	[-]
U	liquid velocity	[m/s]
y	distance from the wall	[m]
y^+	dimensionless distance from the wall	[-]

Greek symbols

μ	dynamic viscosity	[Pa.s]
ν	kinetic viscosity	[m^2/s]
ρ	liquid density	[kg/m^3]
δ	thickness of the laminar boundary layer	[m]
τ	shear stress	[N/m^2]

Subscripts

b bulk
h liquid film height
i species
s surface
t turbulent

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FIGURES

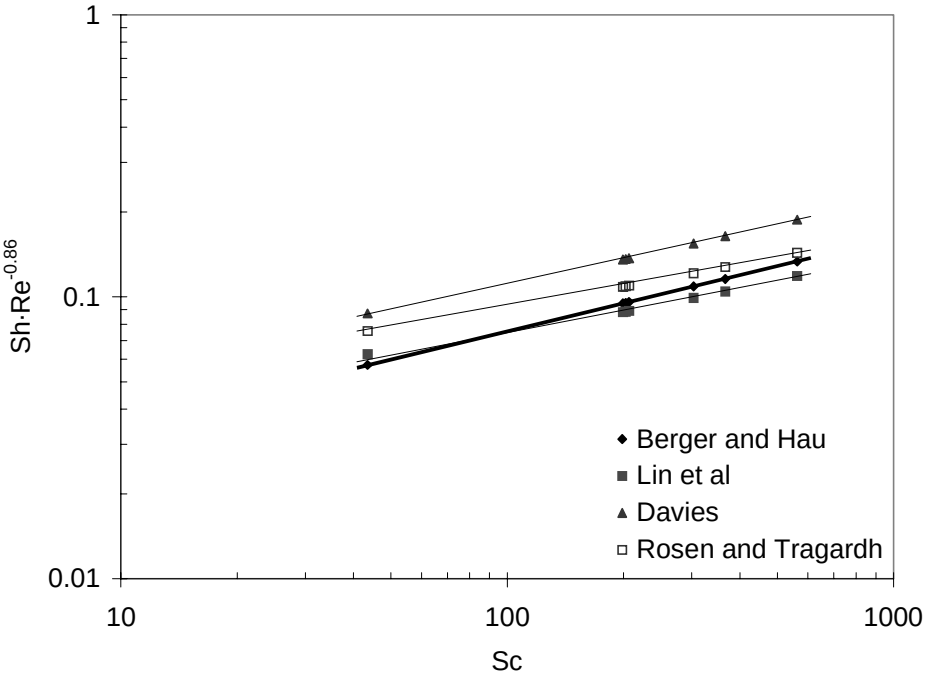

FIGURE 1 – Comparison of the various mass transfer correlations for single-phase turbulent pipe flow.

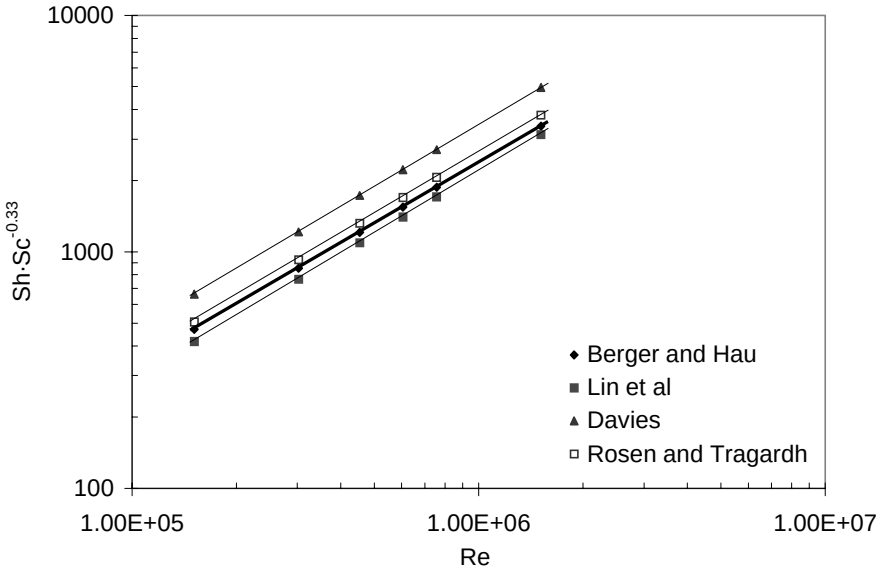

FIGURE 2 – Comparison of the various mass transfer correlations for single-phase turbulent pipe flow.

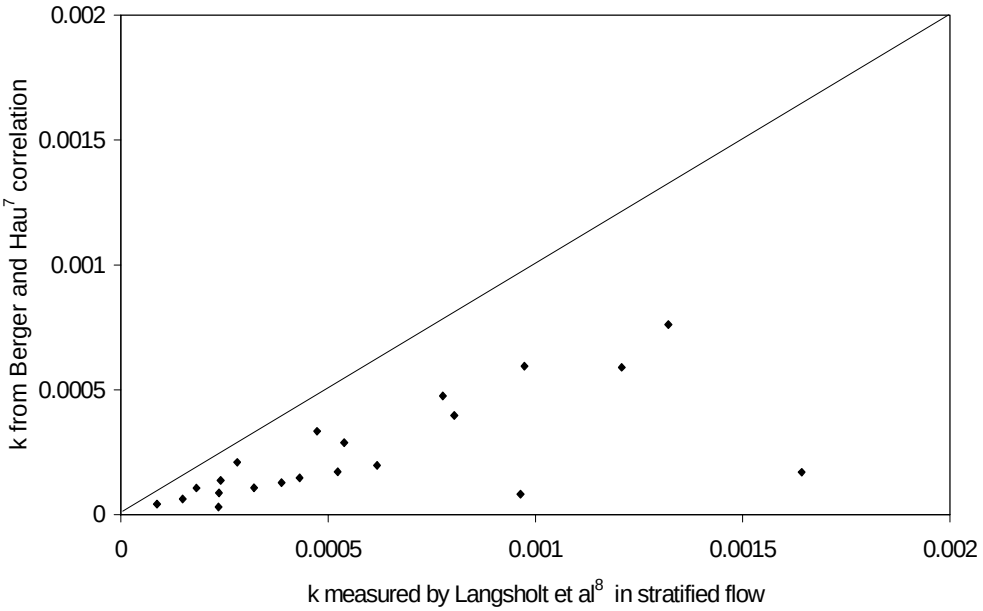

FIGURE 3 – Comparison of the mass transfer coefficients *k* calculated by Berger and Hau[7] with *k* measured by Langsholt et al[8] in stratified flow

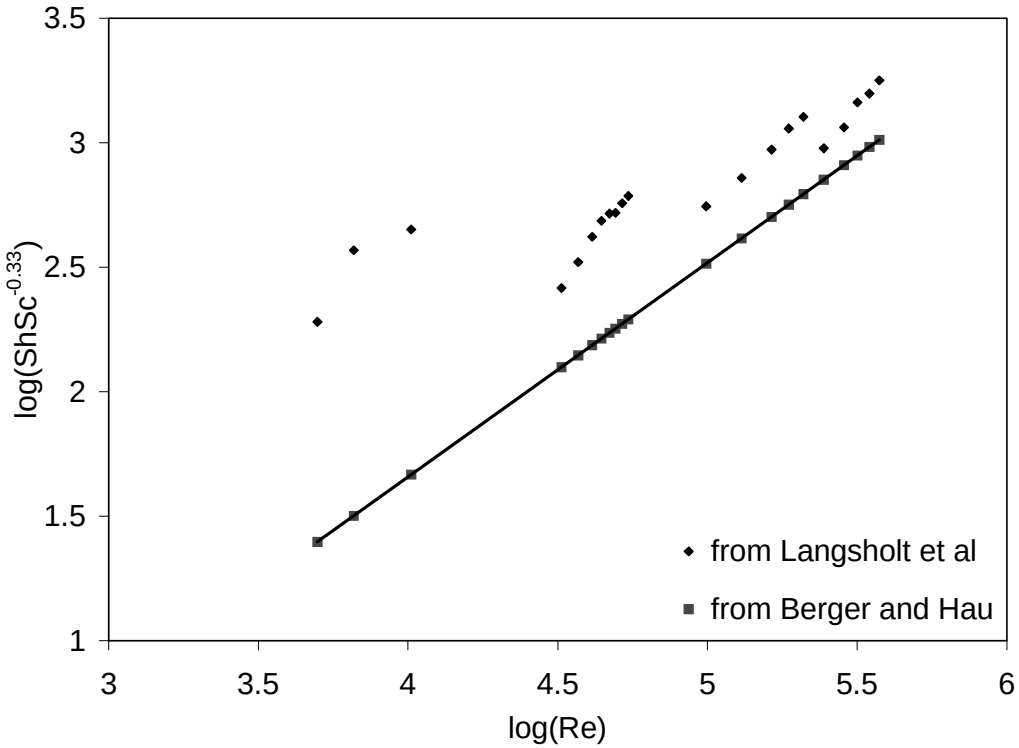

FIGURE 4 – $logShSc^{-0.33}$ vs *logRe* in a fully developed stratified flow (the hydraulic diameter is used to calculate *Sh* and *Re*).

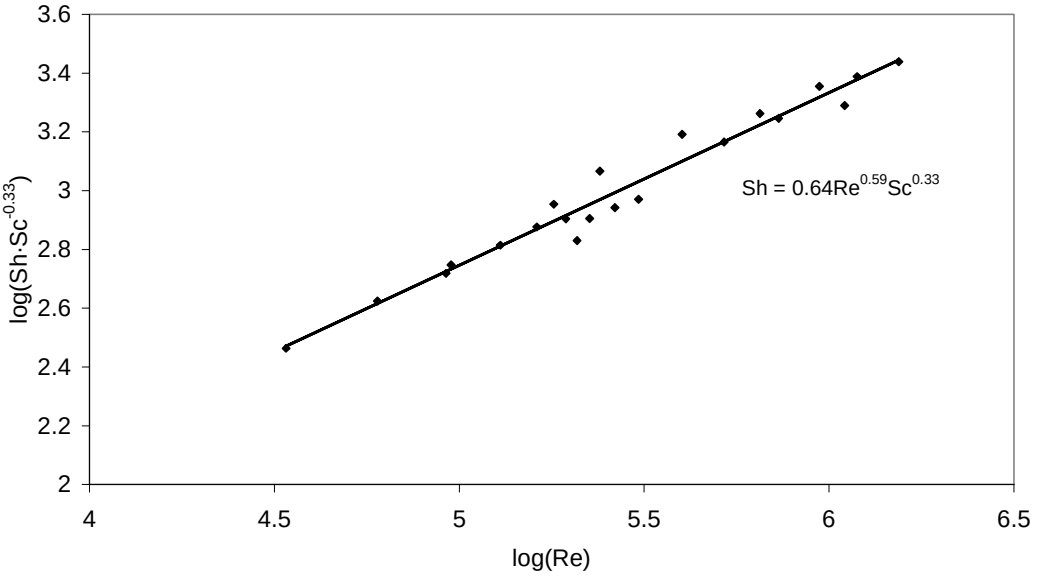

FIGURE 5 – Comparison of prediction obtained by using the newly developed correlation (13) for mass transfer in stratified flow with data of Langsholt et al[8] (the liquid film height is used to calculate *Sh*, the pipe diameter is used to calculate *Re*).

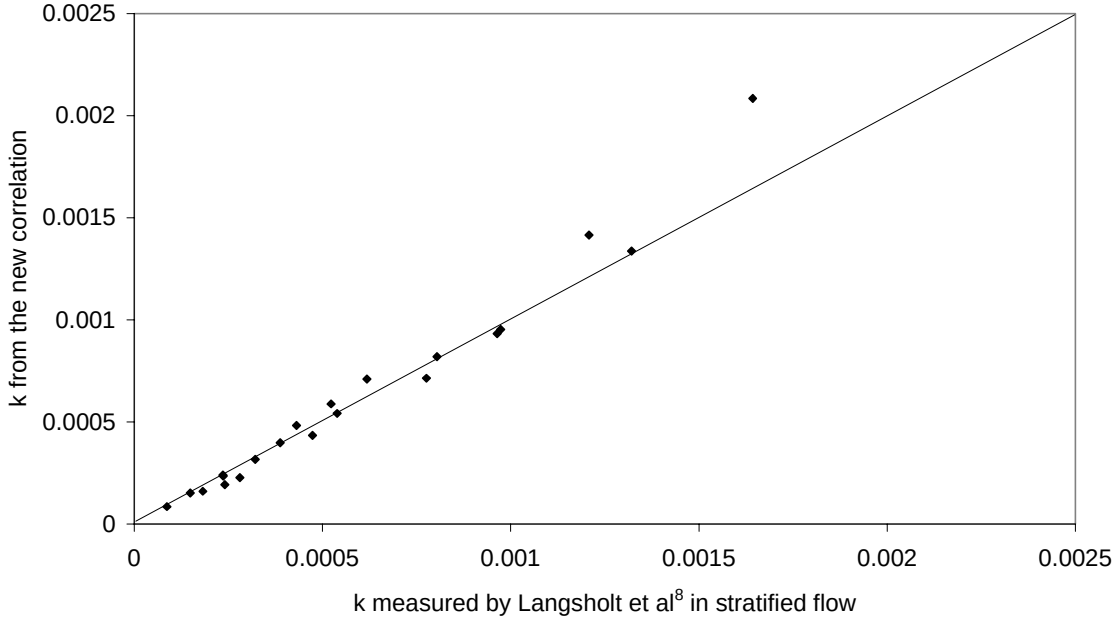

FIGURE 6 - Comparison of prediction obtained by using the newly developed correlation (13) for mass transfer in stratified flow with data of Langsholt et al[8].

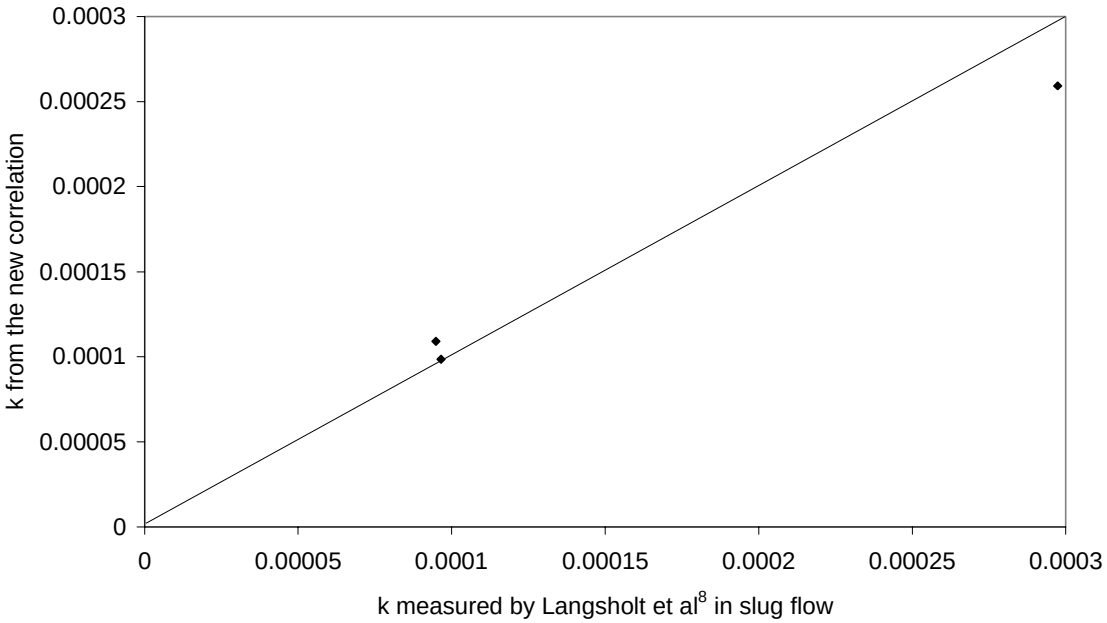

FIGURE 7 - Comparison of the mass transfer coefficients predicted by the correlation (13) with data of Langsholt et al[8] for slug flow

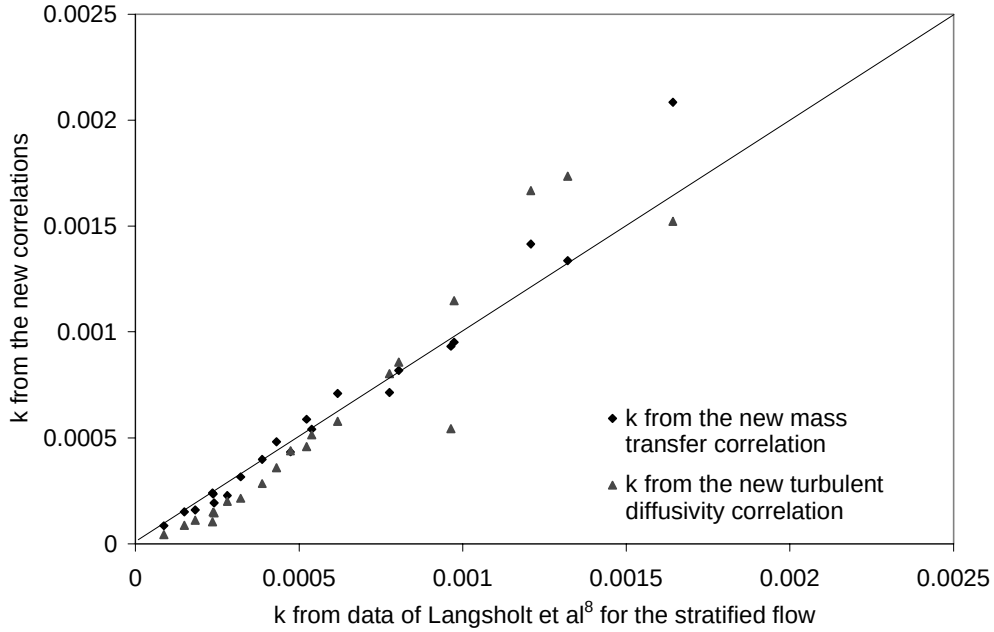

FIGURE 8 - Comparison of the mass transfer coefficients predicted by the correlation (14) with those predicted by (13) and data of Langsholt et al[8] for stratified flow