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Steady-state mass transport between a thin liquid layer separating a fixed (stationary) and a rotating disk in laminar flow

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Abstract

This work deals with experimental steady-state mass transport at the electrodes of thin cells employing a fixed disk and a disk rotating at low angular velocities. Theoretical solutions in the literature for mass transport to fixed disks under such laminar Bödewadt flow conditions are reviewed. In the experiments, four pairs of disks (1–3 cm dia) were used, with gap thickness H between the disks varying from 0.5 to 3 mm. The rotational Reynolds number based on H varied from 0.5 to 100. Mass transport rates to the rotating disk are higher than to the fixed disk in agreement with previous results and they extend the range of hitherto known measurements. The relationship for a uniformly rotating liquid overestimates the results with respect to theoretical ones for a fixed disk, and an additional relationship (not yet verified theoretically) shows a satisfactory agreement with experimental findings at low values of the Reynolds number. A general empirical correlation is established for each disk. Mass transport to the fixed disk is theoretically analyzed by assuming that the inviscid liquid core near the disk rotates nearly 30% slower than the rotating disk.

List of symbols

a,b	regression parameters
D	molecular diffusion coefficient ($m^2\ s^{-1}$)
H	distance between the disks (m)
I_L	limiting diffusion current (A)
$k_d(r)$	local mass transfer coefficient at radial position r ($m\ s^{-1}$)
$\overline{k_d}$	mean mass transfer coefficient ($m\ s^{-1}$)
N	speed of rotation (r.p.m.)
R	disk radius (m)
R_c	cell (chamber) radius (m)
Re_H	Reynolds number based on H, ($\omega H^2/\nu$)
Re_R	Reynolds number based on R, ($\omega R^2/\nu$)
r	radial coordinate (m)
r^*	correlation coefficient
Sc	Schmidt number, (ν/D)
$\overline{Sh_H}$	mean Sherwood number based on H, ($\overline{k_d}\, H/D$)
$\overline{Sh_R}$	mean Sherwood number based on R, ($\overline{k_d}\, R/D$)

Greek letters

γ	adjustable parameter for the angular velocity
ρ	density ($kg\ m^{-3}$)
ν	kinematic viscosity ($m^2\ s^{-1}$)
ω	angular velocity (s^{-1})

1. Introduction

A large number of studies related to the dynamics of heat and mass transport between rotating and fixed circular disks have been carried out [1]. They are generally concerned with divergent forced flow between the disks. Depending on hydrodynamic conditions created by rotation and forced flow, non-steady circulating cells can be present [2] indicating a complex flow structure existing between the disks. The Pump Cell, developed by Jansson and Ashworth [3], combines rotation and forced flow.

Cavalcanti and Cœuret [1, 4, 5] studied mass transport between a liquid and parallel fixed/rotating disks, with or without forced axial flow, leading to several empirical correlations. In the absence of axial flow, and when a rotating circular disk was facing the flat bottom of a circular cylinder [1], mass transport coefficients were determined electrochemically, similar to the investigations by Lehmkuhl and Hudson [6]. The method used in [6], based on cinnamic acid dissolution for the determination of mass transport coefficients, is less precise than the electrochemical method, particularly in the case of well-established laminar flows where mass transport rates are modest.

In later studies, Fahidy and Cœuret [7–9] focused on the specific case of liquid-to-disk mass transport in the presence of radial divergent flow between closely spaced equidistant fixed disks, extending the theoretical study of Kreith [10] with cell scale-up in mind [9].

The work presented here was motivated by the lack of data under the conditions applied in [1, 6], but at small rotation speeds, and at very small separation distances between the rotating and fixed disk. Strong deviations between the findings in [1] and [6] established the purpose of the current work, i.e. to study electrochemical mass transport quantitatively between an aqueous electrolyte solution and two circular disks (one fixed, the other rotating) in the laminar flow regime.

2. Previous efforts

As indicated above, flow between a rotating and a fixed disk, both of finite radius R_c facing each other, and located inside a cylindrical cavity (or chamber), is complex, as amply demonstrated by Soo [11], Daily and Nece [12], and Tomlan and Hudson [13].

A theoretical analysis is difficult even in the laminar flow regime. Heat and mass transport rates depend not only on the principal geometrical parameters H/R and R_c/R, but also on the fact that the angular velocity of the inviscid core near the fixed disk, may be smaller than the angular velocity of the rotating disk, ω. In the literature, the angular velocity of the fluid near the fixed disk is given as γω, where γ is an adjustable parameter ($0<\gamma<1$) which quantifies the ratio of the fluid angular velocity near the fixed disk to that of the rotating object (e.g., disk, impeller). The value of γ also depends on H/R and R_c/R. Theoretical values of γ were obtained e.g. in [6, 12]. The theoretical value of $\gamma=0.44$ cited by Colton and Smith [14] for a radial confinement close to unity ($R_c/R\approx1$), and the value of $\gamma=0.3$, by Lehmkuhl and Hudson [6] for an infinite disk rotating in parallel to a fixed disk, are representative examples. Experimental velocity profiles obtained in [6] yield γ values always lower than 0.4, and mostly lower than 0.3.

In the sequel, discussion is limited to fluid-to-disk mass transport.

2.1. *Theoretical analyses under laminar flow conditions*

2.1.1. *Transport to/from the fixed disk*

In a theoretical study of hydrodynamic voltammetry, Matsuda [15] recommends the following analytical expression for the local mass transport coefficient, $k_d(r)$, at radial position r on the surface of a circular fixed disk of radius R located in an infinite liquid rotating at uniform angular velocity, ω:

$$k_d(r) = 0.761 D^{2/3}\nu^{-1/6}\frac{r}{(R^3-r^3)^{1/3}}\omega^{1/2} \quad (1)$$

Integration along R leads to the mean mass transport coefficient:

$$\overline{k_d} = 0.761 D^{2/3}\nu^{-1/6}\omega^{1/2} \quad (2)$$

If R is chosen as the characteristic dimension, Equation (2) yields the dimensionless mass transport relationship:

$$\overline{Sh_R} = 0.761 Re_R^{1/2} Sc^{1/3} \quad (3)$$

where $\overline{Sh_R} = \overline{k_d}R/D$; $Re = \omega R^2/\nu$ and $Sc = \nu/D$.

For this mass transport problem in a Bödewadt flow and for high Sc numbers, Smith and Colton [16] obtained, at the same time as Matsuda [15], the relationship:

$$\overline{Sh_R} = 0.768\gamma^{1/2} Re_R^{1/2} Sc^{1/3} \quad (4)$$

The only difference between Equations (3) and (4) is that in the latter a liquid core rotating velocity γω near the fixed disk is considered, thus justifying the supplementary multiplying factor $\gamma^{1/2}$. Equation (3) was also obtained by Homsy and Newman [17] for mass transport to a fixed plane situated below a rotating disk.

Based on the analytical velocity distribution obtained by Grohne [18] for a very slow liquid flow between a rotating and a fixed disk, the analysis by Arvía and Marchiano [19, 20] deals with mass transport to a fixed disk of radius R facing, at a very small distance H, a rotating disk of radius R. A detailed analytical development leading to this expression for strongly laminar flow can also be found in the Appendix of [21]. The inherent hypothesis that the fixed disk is a uniformly accessible electrode is questionable, inasmuch as mass transport has been shown [1] to decrease near the centre of the fixed disk. In terms of the mean mass transport coefficient, $\overline{k_d}$, the theoretical relationship for very small H values:

$$\frac{1}{\overline{k_d}} = 0.222\frac{H}{D} + 2.28\frac{\nu^{-1/4}}{\omega^{1/2}D^{3/4}} \quad (5)$$

possesses, in principle, the advantage [19, 20] of a simultaneous determination of D and ν, hence Sc, from experimental $1/\overline{k_d}$ vs. $\omega^{-1/2}$ plots. For such a purpose, not only would Equation (5) have to be valid in the considered angular velocity range of interest, but the term 0.222 H/D would also have to be non-negligible. To the authors' knowledge, the validity of Equation (5) has not been experimentally verified. Taking R as the characteristic dimension, the dimensionless form of Equation (5) is:

$$\overline{Sh_R} = \left\{0.222\frac{H}{R} + 2.28 Re_R^{-1/2} Sc^{-1/4}\right\}^{-1} \quad (6)$$

which predicts, in the case of H/R tending to zero, the relationship:

$$\overline{Sh_R} = 0.439 Re_R^{1/2} Sc^{1/4} \quad (7)$$

Table 1. Theoretical correlations for dimensionless mass transport rates to a fixed circular disk in laminar flow (characteristic dimension: H)

References	Theoretical correlation
Matsuda [15], Homsy and Newman [17]	$\overline{Sh_H} = 0.761 Re_H^{1/2} Sc^{1/3}$
Smith and Colton [16]	$\overline{Sh_H} = (0.768\gamma^{1/2}) Re_H^{1/2} Sc^{1/3}$
Arvía and Marchiano [19, 20]	$\overline{Sh_H} = \left\{0.222 + 2.28 Re_H^{-1/2} Sc^{-1/4}\right\}^{-1}$ for H small i.e. $\overline{Sh_R} = 0.439 Re_R^{1/2} Sc^{1/4}$ for Re_H very small

In both equations the exponent of Sc is 1/4 i.e. as in free convective mass transport equations, rather than 1/3 as in the case of bounday layer flow. This follows from the fact that the hydrodynamic flow regime described in [18] is very weak. As shown in Table 1, Equations (3), (4) and (7) remain unchanged if H is taken as the characteristic dimension, the new dimensionless numbers being: $\overline{Sh_H} = \overline{k_d} H/D; Re_H = \omega H^2/\nu$ and $Sc = \nu/D$.

2.1.2. *Transport to/from the rotating disk*

No specific theoretical treatment has apparently been reported for mass transport at a rotating disk placed very close to a fixed planar surface, although some hydrodynamic aspects have been discussed by Soo [11]. By means of a few experiments, Kreith et al. [2] observed the effect of a fixed surface near a rotating disk in laminar flow, the formation of circulating cells, and estimated at least a 20% reduction in the mass transport coefficient with respect to values that would be measured if the disk were rotating in an infinite medium. The latter may be estimated by the well-known Levich equation for laminar flow [22]:

$$\overline{Sh_R} = 0.621 Re_R^{1/2} Sc^{1/3} \tag{8}$$

The theoretical analysis by Lehmkuhl and Hudson [6] of mass transport to a rotating disk provides a rather complex expression for $\overline{Sh_R}/(Re_R^{1/2} Sc^{1/3})$ as a function of γ and Sc, but it does not consider the effect of a fixed disk in its proximity.

2.2. *Experimental analyses*

To the authors' knowledge, no agreement of Equation (3) with experimental data is indicated in the literature. In general, the literature contains very few experimental studies dealing with this case of laminar flow. Colton and Smith [14] determined local and mean mass transport coefficients by dissolving 0.4 cm and 3 cm dia benzoic acid disks in water. Each disk was inserted into the flat bottom of a cylindrical cavity, situated below a 6 cm dia paddle impeller. The cavity diameter was slightly larger, hence the radial flow confinement was approximately equal to one. Their empirical correlation:

$$\overline{Sh_R} = 0.285 Re_R^{0.567} Sc^{1/3}; \quad H = 0.318\,\text{cm} \tag{9}$$

is valid for $8000 \le Re_R \le 32000$, i.e. $90 \le Re_H \le 6600$ [14]. For the laminar region, $\gamma = 0.49$ (recommended as the experimental value, reasonably close to the theoretical value of 0.44 for the given geometry), and the Colton–Smith relationship is:

$$\overline{Sh_R} = 0.538 Re_R^{1/2} Sc^{1/3} \tag{10}$$

The influence of H can be neglected provided that it is very small.

The experimental results of Lehmkuhl and Hudson [6] based on rotating disks of benzoic acid dissolved in water were incorporated and correlated in the study of Cavalcanti et al. [1, 21] where the electrochemical method for wall-to-liquid mass transport measurements, easier and more reliable than a dissolution method, was applied. With a radial confinement of approximately one, the diameter of the rotating disk was aproximately the same ($\approx$ 0.99) as the diameter of the cylindrical cavity, the bottom of which served as the fixed disk. In [1, 21], with $87 \le Re_R \le 9700$, i.e. $6 \le Re_H \le 7000$, the dimensionless mass transport relationships:

$$\overline{Sh_R} = 0.84 Re_R^{1/2} Sc^{1/3} \quad \text{(rotating disk)} \tag{11}$$

and

$$\overline{Sh_H} = 0.2 \left(\frac{H}{R}\right)^{-0.28} Re_H^{1/2} Sc^{1/3} \quad \text{(fixed disk)} \tag{12}$$

were obtained, the latter valid for the $0.1 \le H/R \le 1$ range. In arriving at Equation (11), the negligible influence of H, varied between 1 and 17 mm, was taken into account.

To ascertain whether the quantitative disagreement between Equation (11) and the experimental results of [6] for $2 \le Re_H \le 1000$ can be ascribed to inherent imprecision in the dissolution method used in [6], new and complementary experiments, not restricted to a radial confinement of about one, were carried out in the current study.

3. Experimental

The 6 cm internal dia cylindrical cell shown in Figure 1 was made of Altuglas, and consisted of three parts (A, B, C) assembled by bolts. The rotating disk T (of radius R) was mounted on the axis of a modified Tacussel-EDI mechanical system. The axis rotated inside the 2.4 cm dia cylindrical piece D, externally bolted in order to move it vertically through the cover C. The value of the distance H between the two disks was obtained by accurately determining the vertical movement of D (1 mm per revolution of D). Since the rotation velocity, N, was small (between 20 and 100 r.p.m.), the electrode carrier was rotated via a miniature pulley-belt system controlled by a variable speed d.c. motor. The velocity

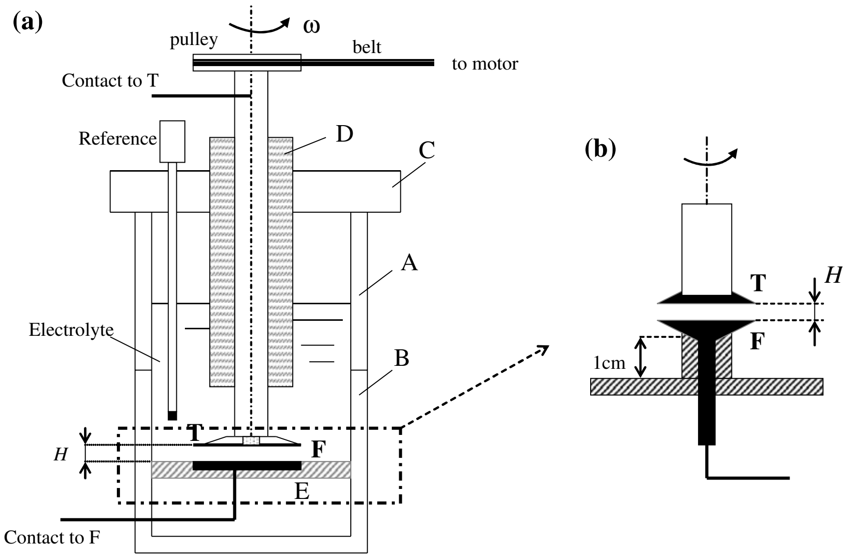

Fig. 1. Measuring cell: (a) disk F inserted in E; (b) disk F placed over a pivot.

of rotation was measured with an optical tachometer, or chronometrically at small values of N only.

The fixed disk F (also of radius R) was installed either by inserting it into the Altuglas disk E, the disk T thus facing a planar 6 cm dia surface, or by a 1 cm high P.V.C. carrying pivot, located in the axis of a P.V.C. disk (E). It was assumed a priori that, due to different conditions of the convergent radial flow over disk F, both configurations in Figure 1 would produce distinct results. The disks were made of solid nickel; only the mechanically polished facing areas πR^2 were electrochemically active, the rest of their external surfaces being electrically isolated with M-Coat D (from Vishay Micromessures). Four F and four T disks of radius 0.5, 0.75, 1, and 1.5 cm were employed with separation distance H set at 0.5, 1, 2 and 3 mm.

The cell assembly was immersed in a reservoir containing water at the controlled temperature of 20 °C. The mass transport coefficient between the electrolyte and each disk was determined, as in the author's previous studies [7–9], by the conventional method of electrochemical reduction of ferricyanide ions dissolved in an alkaline medium [23]. One disk was polarized cathodically, the other anodically in each run. The 3-electrode set-up (T, F and a nickel wire acting as a redox reference electrode) was attached to a Tacussel PRT-20-2 potentiostatic circuit. The electrolyte was a mixture of 0.005 mol dm^{-3} $Fe(CN)_6^{3-}$ and 0.05 mol dm^{-3} $Fe(CN)_6^{4-}$ in an aqueous 0.5 mol dm^{-3} NaOH solution. Its physical properties at 20 °C [9] were: $\rho = 1033$ kg m^{-3}, $\nu = 1.07 \times 10^{-6}$ m^2 s^{-1}, $D = 5.63 \times 10^{-10}$ m^2 s^{-1}, hence $Sc = \nu/D = 1900$. Each experiment was carried out with chemically activated disks, electrolyte mixture, and the electrolyte temperature was set to 20 °C before placing it into the cell.

For each T/F set of disks of a given radius, the separation distance H was fixed and the rotation velocity was varied. The limiting current was measured at each rotation velocity and the disks were set alternatively to be the cathode and the anode, respectively.

4. Results

At $H = 0.5$ mm, i.e. the lowest separation distance, there exists a minimum value of N, between 15 and 20 r.p.m., below which I_L cannot be determined accurately for T disks because the corresponding current–potential plots do not exhibit a clearly discernible horizontal plateau. This finding is presumably due to inefficient electrolyte circulation/renewal in the vicinity of the T disk, and, in consequence, to a progressively decreasing concentration of the diffusing ferricyanide.

Figure 2 shows the experimental variation of I_L with N, for $R = 1$ cm, for both configurations of Figure 1. In Figure 2a, which corresponds to the arrangement of Figure 1a, at a fixed N and H, mass transport is more enhanced at rotating disks, and the effect of H is essentially indistinguishable. The same conclusions stand for the other disks in Figure 1a. However, the opposite is true for arrangements shown in Figure 1b, inasmuch as an H-effect is clearly demonstrable in Figure 2b for disk T, but not in Figure 3.

The values of I_L obtained at fixed disks and $H = 0.5$ mm are, by contrast, clearly distinguishable from values observed at higher disk-separation distances, and as shown in Figure 3, the data for $H = 0.5$ mm do not disagree with Equation (7), which follows from theoretical developments [19–21] for H/R tending to zero. It may cautiously be inferred that the scope of pertinent analytical efforts, the final results of which were probably first given by Arvía and Marchiano [19, 20], could be extended to the currently studied cases. However, experimental verification of Equation (7) remains difficult even with an electrochemical method when H and N values are very small.

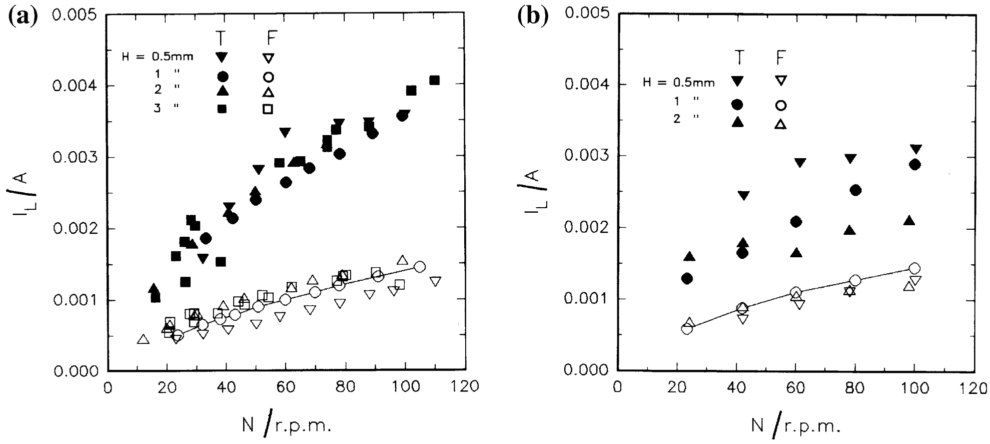

Fig. 2. The variation of limiting current with the rotation rate of T-disks. $R = 1$ cm: (a) configuration of Figure 1a; (b) configuration of Figure 1b.

It appears clearly that the two configurations depicted in Figure 1 are not equivalent, but the authors are not aware of a systematic study of this phenomenon, although Kreith et al. [2] did find some evidence for it via preliminary experiments on mass transport by dissolution, albeit under somewhat different hydrodynamic conditions. This is the reason why only results obtained with the configuration in Figure 2a were retained for the discussion below.

5. Discussion

The specific behaviour of mass transport in the experimental range of disk-separation distance in this study represents the lower limiting case, where the influence of H on mass transport rates can be ignored within errors associated with least squares-based curve fitting. The upper limiting case corresponds to sufficiently large separation distances, where mass transport at T-disks would be the same as at a disk rotating in an infinite liquid (Levich conditions) while mass transport at F-disks would be determined by free convection. The effect of H between these two limiting conditions cannot be expressed via a single (unique) correlation, but it is worth noting that Equation (8) agrees satisfactorily with our experimental results for rotating disks.

In spite of the apparent lack of influence of the disk-separation distance at $H \leq 3$ mm, it seems more logical to prefer H to R as the characteristic dimension. Firstly, flow generated in the gap between the two disks controls mass transport at each disk by the rotation of a T-disk. Secondly, as shown in Table 1, theoretical expressions for the laminar flow regime are "isomorphic" regardless of H or R appearing in the Sherwood and the Reynolds numbers. Thirdly, for a pair of disks of radius R, Re_H varies in a wider domain than Re_R. The $\overline{Sh_H}$ vs. Re_H plots in Figure 4 corresponding to pairs of a T disk and an F-disk have been constructed in view of these arguments.

5.1. *Comparison with previous correlations*

5.1.1. *(i) Rotating disk*

Experimental limiting currents obtained at T-disks and $H = 0.5$ mm are somewhat scattered, except (Figure 4) with the configuration of Figure 1-b; in the case of Figure 4-b, it was impossible to obtain reliable I_L values.

The Levich Equation (8) with H as the characteristic dimension, shows good agreement (Figure 4a–d) with the experimental results for T-disks. The empirical Equation (11) obtained by Cavalcanti [21] for T-disks, plotted in Figure 4 and there valid only for $Re_H > 6$, agrees satisfactorily with current results. On the other hand, Equation (12) established by Cavalcanti [21] is omitted since it does not agree with Equation (11), and due to the presence of a non-negligible power of the (H/R) ratio.

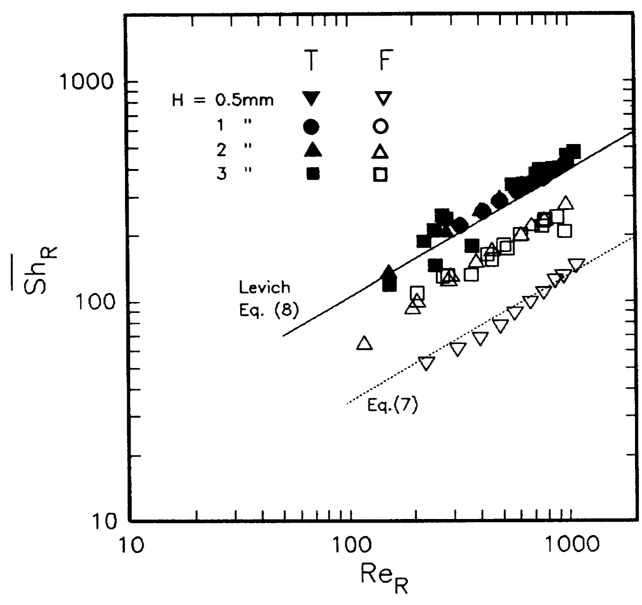

Fig. 3. The variation of dimensionless mass transport rates with Reynolds number. $R = 1$ cm; $Sc = 1900$. Configuration of Figure 1b. Characteristic dimension: disk radius R.

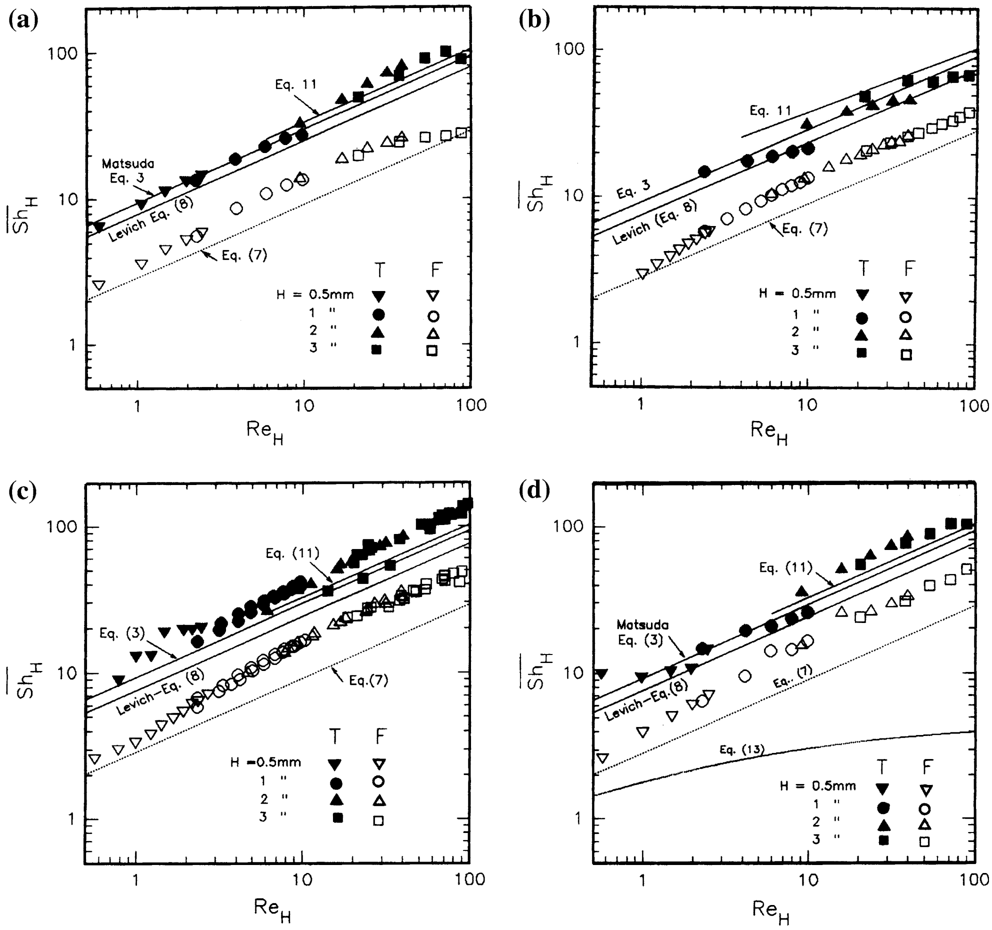

Fig. 4. The variation of dimensionless mass transport rates with Reynolds number, and comparison with previous correlations. Configuration of Figure 1a. Characteristic dimension: gap thickness H (0.5–3 mm): (a) $R=0.5$ cm; (b) $R=0.75$ cm; (c) $R=1$ cm; (d) $R=1.5$ cm.

5.1.2. *(ii) Fixed disk*

The dimensionless relationship shown in Figure 4d:

$$\overline{Sh_H} = \left\{0.222 + 2.28Re_H^{-1/2}Sc^{-1/4}\right\}^{-1} \tag{13}$$

is the equivalent of Equation (5) with H as the characteristic dimension. At low values of Re_H, the data for F-disks and $H=0.5$ mm clearly tend to the H-equivalent of Eq (7), i.e. to the limit of Equation (13). This finding supports the analysis presented in [19–21]. The validity of Equation (13) at very low Re-values may be inferred, but it would be difficult to demonstrate it experimentally. Then the possibility of a simultaneous determination of D and ν is also doubtful.

The Matsuda Equation (3), using H as characteristic dimension for mass transport to a fixed disk situated in a uniformly rotating liquid, shows strong disagreement with the results obtained at F-disks, possibly because the liquid rotates at a lower angular velocity γω near a fixed surface instead of the ''bulk'' velocity ω.

5.2. *Empirical correlations for the new results*

Dimensionless mass transport rates, shown in Figure 4, can be empirically correlated in the familiar form as $\overline{Sh_H} = aRe_H^bSc^{1/3}$ for each disk size. The examples (i) $a=0.89$; $b=0.551$; $r^*=0.986$ for $R=1$ cm T-disks ($H=0.5$ mm excluded), and (ii) $a=0.457$; $b=0.501$; $r^*=0.939$ for $R=0.75$ cm F-disks ($H=0.5$ mm included) serve for illustration. The range of the Re exponent is 0.43 to 0.65 with $r^* > 0.9$, and the inclusion/exclusion of the $H=0.5$ mm data, as indicated before, has no statistical significance.

The overall empirical correlations for the new results, and including $H=0.5$ mm data:

$$\overline{Sh_H} = 0.8Re_H^{0.56}Sc^{1/3}; \quad \text{T-disks} \tag{14-a}$$

$$\overline{Sh_H} = 0.5Re_H^{0.45}Sc^{1/3}; \quad \text{F-disks} \tag{14-b}$$

plotted in Figure 5 are valid in the $0.1 \le Re_H \le 100$ range, both with $r^* > 0.95$. As outlined for each individual scheme of Figure 4, Equation (14-a) differs slightly from Equation (11) proposed by Cavalcanti and Cœuret [1], for $Re_H \ge 6$ in the range indicated in Figure 5.

For F-disks, the Smith–Colton adjustable parameter γ varies slightly if the runs are repeated but remains about 0.3. Data used in the construction of Figure 5b yield γ = 0.27, a value only slightly different from the

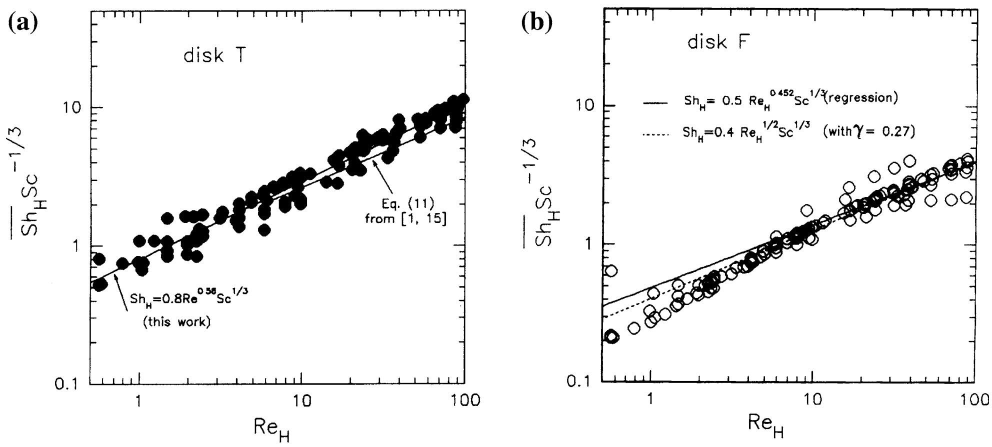

Fig. 5. Overall empirical correlations (including all values of *H*). Configuration of Figure 1a: (a) T-disks, with comparison to Equation (11); (b) F-disks.

theoretical value of $\gamma = 0.3$, corresponding to an infinite rotating disk that generates flow converging toward the centre of the fixed disk [6].

6. Conclusions

Experimental mass transport rates between closely spaced parallel circular disks and the laminar liquid flow generated by the rotation of one disk, were satisfactorily correlated. Results obtained for the rotating disk confirm previously obtained observations and extend the correlation range to smaller rotational Reynolds numbers.

Findings at fixed disks can be explained by the concept of an inviscid liquid core rotating at a smaller angular velocity than the rotating disk. The value of about 0.3, to be attributed to the reduced tangential angular velocity, is in agreement with the literature value for an infinite rotating disk.

Finally, experiments conducted at the smallest disk-separation distance employed in the current work, tend to suggest tentatively the eventual possibility of a simultaneous determination of *D* and ν from mass transport to fixed disks.

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