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TECHNICAL NOTES

Mass transfer in a rotating disc oxygenator

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INTRODUCTION

ROTATING disc mass transfer devices are used, among other things, for extracorporeal blood oxygenation and in fermentation studies. The work reported here was performed using a modified blood oxygenator. The conventional Kay–Cross Oxygenator, where oxygen enters through a perforated tube near the top of the cylinder was modified to put the oxygen through the central shaft so that larger diameter discs could be used for a given cylinder diameter and the amount of blood required could be reduced [1]. A comparison of the two configurations is shown in Table 1.

MASS TRANSFER

As the discs rotate, they pick up a film of blood which comes into contact with the gaseous oxygen in the cylindrical enclosure. Mass transfer of oxygen to blood occurs primarily on this film though some transfer also takes place at the free surface of the pool of blood between two consecutive discs. The studies thus far have generally assumed the film to be of uniform thickness which is in fact not the case. It was conclusively demonstrated in our studies [2, 3] that centrifugal, viscous, inertial, surface tension and gravitational forces determine the shape and thickness of the film on a vertically rotating disc. The film is thin in the inner region and increases in thickness towards the periphery with a maximum value occurring near the edge of the disc. This is shown qualitatively in Fig. 1(a) for a vertical disc just immersed, and in Fig. 1(b) for a disc half immersed in the liquid. Quantitative values are available elsewhere [2, 3]. The dimensionless relation for the film thickness is reproduced below from refs. [2, 3]:

$$T = 7.99\,Ca^{2.93}\eta^{0.15}\mathscr{R}^{5.23}\mathrm{Cas}^{3.09}\chi^{0.024}. \qquad (1)$$

THEORY

Lightfoot [4] gives a relation for time-averaged Nusselt number for mass transfer, based on a reference area dS_0 as:

$$Nu^{\circ}_{\mathrm{loc}} = -\Pi(0)\sqrt{\frac{D^2}{\mathscr{D}_{O_2m}t}}\sqrt{\frac{1}{t}\int_0^t\left(\frac{S}{S_0}\right)^2 \mathrm{d}t}. \qquad (2)$$

While applying equation (2) to the rotating disc blood oxygenator, Lightfoot [4] has neglected the effect of surface stretch, i.e. (S/S_0) within the integral sign in equation (2) has been taken to be equal to unity. However, the surface stretch is an important item and should be considered for realistic results. It can be calculated from equation (1). Using this, the average mass transfer coefficient can be written as

$$\bar{k}_{cm} = \overline{Nu}_m\mathscr{D}_{O_2m}/D$$

$$= -\frac{\Pi'(0)}{A_n}\sqrt{\mathscr{D}_{O_2m}}\int_{A_n}\frac{1}{t}\sqrt{\int_0^t\left(\frac{S'}{S}\right)^2 \mathrm{d}t}\,\mathrm{d}s, \qquad (3)$$

where A_n is the area over the disc exposed to the gas, obtained by equation (1) and is given by

$$A_n = \int_{R_0}^{R}\int_{\theta_0}^{\theta_f}\sqrt{\left(\frac{\partial H}{\partial\theta}\right)^2 + r^2}\sqrt{\left(\frac{\partial H}{\partial r}\right)^2 + 1}\,\mathrm{d}\theta\,\mathrm{d}r. \qquad (4)$$

The mass transfer occurs primarily on the discs. The mass transfer on the free surface was negligible since the free surface of blood between any two consecutive discs was very small ($6.08\times10^{-4}\ \mathrm{m}^2$) compared to the area of the film exposed on the two discs ($215\times10^{-4}\ \mathrm{m}^2$) giving the ratio of the two areas to be only 2.83%. The values of the areas can easily be calculated from Table 1.

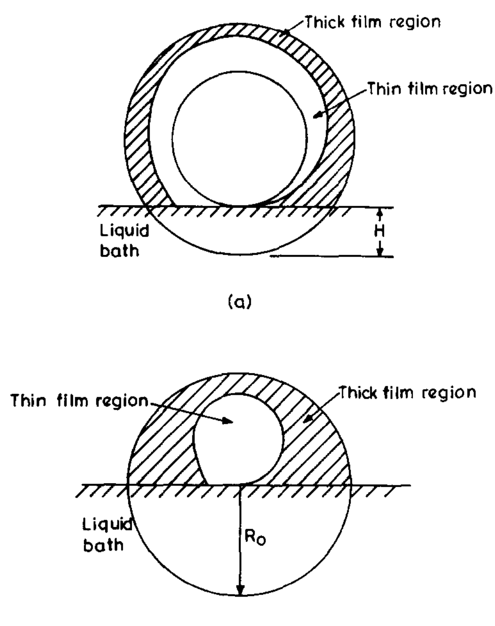

FIG. 1. Liquid distribution over the disc: (a) less than half immersed; (b) half immersed.

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NOMENCLATURE

A_n area over the disc exposed to the gas, equation (4) [m^2]
Ca capillary number, $\mu\Omega r/\sigma$ [dimensionless]
Cas modified capillary number, $\mu\Omega R/\sigma$ [dimensionless]
D characteristic length [m]
$\mathscr{D}_{O_2m}$ mean diffusivity of oxygen [m^2 s^{-1}]
g acceleration due to gravity, 9.8 m s^{-2}
H depth to which the discs are immersed [m]
$\bar{k}_{cm}$ time average mass transfer coefficient for the entire disc, equation (3) [m s^{-1}]
m slope of oxygen dissociation curve [dimensionless]
Nu°_{loc}, time-averaged local Nusselt number [dimensionless]
$\overline{Nu}_m$ time-averaged Nusselt number for the entire disc, [dimensionless]
r radial coordinate [m]
R_0 disc radius [m]
R radius of disc above the liquid surface, R_0-H [m]
$\mathscr{R}$ $=(R_0-R)/R_0 = H/R_0$
S surface area of film at time t [m^2]
S_0 surface area of disc [m^2]
S' surface area of film at time t' [m^2]
t time [s]
t' time [s]
T film thickness [dimensionless]
x^* position coordinate [dimensionless].

Greek symbols
η dimensionless group in equation (1) representing gravitational force $(\sigma/\rho)(g\nu^4)^{-1/3}$
θ angle with respect to horizontal and measured counter-clockwise [degrees]
θ_0 angular position of film when it leaves the pool, [degrees]
θ_f angular position of film when it enters the pool [degrees]
μ viscosity of liquid [kg m^{-1} s^{-1}]
ν kinematic viscosity of liquid [m^2 s^{-1}]
Π dissolved oxygen concentration profile, [dimensionless]
$\Pi'(0)$ $d\Pi/dx^*|_{x^*} = 0$
ρ density of liquid [kg m^{-3}]
σ surface tension of liquid [N m^{-1}]
ψ $\Omega^2 R_0/g = \sin\theta$, dimensionless group in equation (1) representing centrifugal force
Ω angular velocity [rad s^{-1}].

EXPERIMENTS

Experiments were done by using goat blood in a smaller version of the modified unit described in the Introduction. The smaller version (0.1 m long with inner cylinder radius of 0.036 m and a disc radius of 0.0275 m) required a smaller priming volume of the blood. Oxygen concentration was measured using an oxygen probe (Yellow Spring Instruments through Cole-Palmer, Oak Brook, IL). Figure 2 shows the experimental set-up.

RESULTS

Experimental and theoretical values, both with and without surface stretch, for the oxygen concentration are shown in Table 2 for different experiments. The average mass transfer coefficient terms have also been tabulated. As is evident, the concentration values obtained by considering the surface stretch are far closer to the experimental values than those which do not consider this factor.

DISCUSSION

It is evident from Table 2 that surface stretch should be taken into account in the mass transfer studies. This would also apply to situations other than blood oxygenation where rotating discs are used. Furthermore, equation (1) gives a good estimate for the film thickness from which the extent of liquid hold-up as well as the surface stretch can be calculated.

Table 1. Comparison of our modified blood oxygenator with the existing Kay–Cross design for a typical total blood film surface area of 0.7532 m^2 (7532 cm^2)

Item No.	Modified blood oxygenator	Existing type of blood oxygenator
1. Cylinder diameter	0.152 m	0.152 m
2. Disc diameter	0.14 m	0.114 m
3. Height of blood pool	0.055 m	0.0586 m
4. Width of blood film on rotating disc	0.049 m	0.0406 m
5. Film area on one disc	0.01076 m^2	0.00717 m^2
6. Number of discs to give 0.7532 m^2 area	70	105
7. Length of cylinder (discs 0.5 cm apart)	0.35 m	0.525 m
8. Total blood priming volume required	1.4×10^3 ml (1.4 dm^3)	2.36×10^3 ml (2.36 dm^3)
9. Thickness of disc	0.001 m	0.001 m

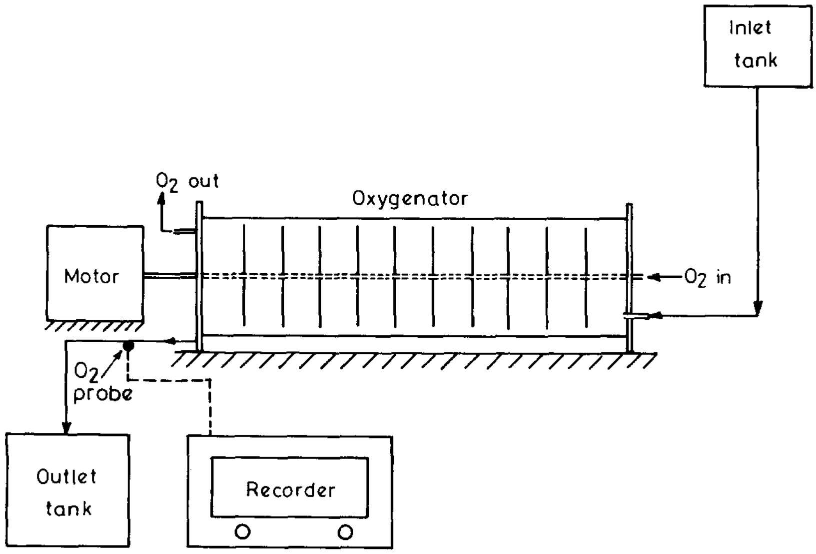

FIG. 2. Schematic diagram of the experimental set-up.

Table 2. Comparison of theoretical and experimental outlet concentrations and mass transfer coefficients

Sl. No.	Ω (rad s^{-1})	No. of disc	R (m)	H (m)	C_0 (%)	C_{out} no surface stretch	C_{out} surface stretch	C_{out} experi-mental	$\bar{k}_{cm} \times 10^{-4}$ surface stretch (m s^{-1})	$\bar{k}_{cm} \times 10^{-4}$ no surface stretch (m s^{-1})
1.	6.28	7	0.0275	0.01375	0	0.07	0.143	0.15	0.121	0.714
2.	15.71	5	0.0275	0.01375	0	0.814	0.204	0.215	0.217	1.128
3.	9.43	4	0.0275	0.01375	0	0.115	0.095	0.125	0.272	0.874
4.	4.19	5	0.0275	0.0037	0	0.005	0.0005	0	0.127	0.570
5.	10.47	6	0.0275	0.0037	0	0.020	0.0012	0.02	0.0491	0.853
6.	4.19	6	0.0275	0.0275	0	0.163	0.981	0.975	0.738	0.714
7.	11.52	7	0.0275	0.0275	0	0.40	0.935	0.925	2.328	1.185

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