Int. J. Heat Mass Transfer. Vol. 27, No. 7, pp. 1405–1408, 1985
Printed in Great Britain

0017-9310/85 $3.00 + 0.00

TECHNICAL NOTES

Mass transfer in a pulsating turbulent flow with deposition onto furrowed walls

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(*Received* 17 *September* 1984 *and in final form* 14 *January* 1985)

INTRODUCTION

BELLHOUSE *et al.* [1, 2] and Dorrington *et al.* [3] have reported improved transfer coefficients for flat channel semi-permeable membrane blood oxygenators. The walls of the device bear lateral furrows or an array of inverted dimples over which blood is pulsed in laminar flow. As fluid oscillates within the channel, so vortices form and are ejected from the hollows. The improvement of mass transfer coefficients by the use of such oscillatory flows in a channel of non-uniform cross-section is now a well-tested technique in the laminar flow regime [1–3] and the details of the velocity distribution in such a configuration have been calculated by Sobey [4]. The present series of experiments is an investigation of this method (termed 'vortex-mixing') in turbulent flows in which the poor mixing of the laminar sub-layer limits transfer fluxes, especially in fluids which foul the wall.

APPARATUS

In order to study vortex-mixing in turbulent flows a flat channel of cross-section 3 × 36 mm and 275 mm long was constructed in a 'Perspex' frame. The walls consisted of pre-machined 'Vyon filter' sheets (by Porvair) into which approximately semi-circular grooves of 0.75 mm depth and 1.25 mm separation were machined perpendicular to the flow direction. Two layers of hydrophobic polypropylene ('Celgard') membranes were laid upon this structure, thus rendering the channel walls permeable to gases but not to liquids. An oxygen gas chamber behind one wall was held at 1 bar gauge and the opposite wall was at atmospheric pressure. This difference in pressure leads to a convectively enhanced diffusive transport of dissolved oxygen between the walls at a rate which is determined by the intensity of mixing in the liquid. This arrangement is illustrated in Fig. 1 and is described in more detail and validated by Stairmand and Haworth [5].

A steady component of flow was provided by a centrifugal pump and pulsations were imposed by placing a rotating ball-valve mechanism between the pump and the channel (see Fig. 2). The mechanism consisted of two parallel branches. The main line (bore 20 mm) contained a Saunders $\frac{1}{2}$ in. ball valve which was continuously rotated so as to intermittently block the line; the second branch was a flexible tube (bore 10 mm) which could be clamped to varying degrees so as to effectively alter the stroke of the pulsations. The steady flow bulk velocity component was measured using a rotameter and the pulsation amplitudes were measured with an electromagnetic flow-meter. If we express the change in flow rate with time as

$$Q = \bar{Q} + \hat{Q}\sin(\omega t)$$

then the degree of pulsation is given by ϕ where

$$\phi = \hat{Q}/\bar{Q}.$$

The condition $\phi = 1$ could be set up by closing the bypass branch thereby ensuring that when the valve was shut the flow would be stopped. However, for the present series of experiments, the bypass arm was kept partially open. The resulting variation in ϕ with mean flow ($\bar{Q}$) is given in Table 1. Since ϕ is approx. 0.25 for all but the highest flow, it is apparent that the peak-to-peak flow pulsation is 50% of the mean flow rate.

We shall present the mass transfer data as a Sherwood number (Sh), being related to the oxygen gas flux (F) at a particular flow condition and the purely diffusive flux F_0 which is obtained when no velocities are imposed. This latter parameter may be predicted theoretically in terms of the

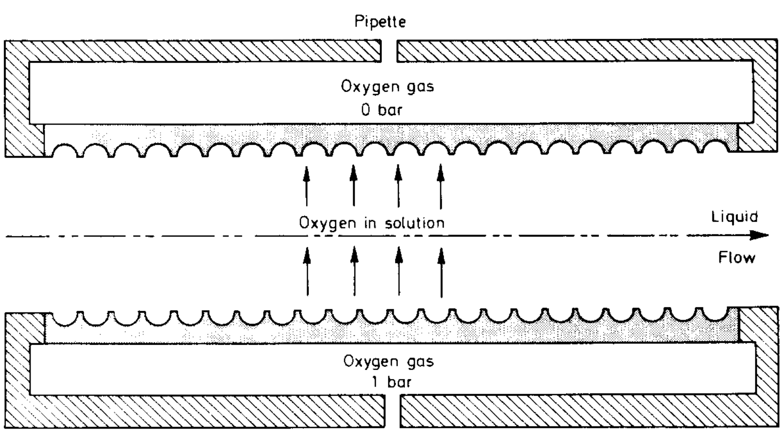

FIG. 1. Schematic illustration of device to measure mass transfer.

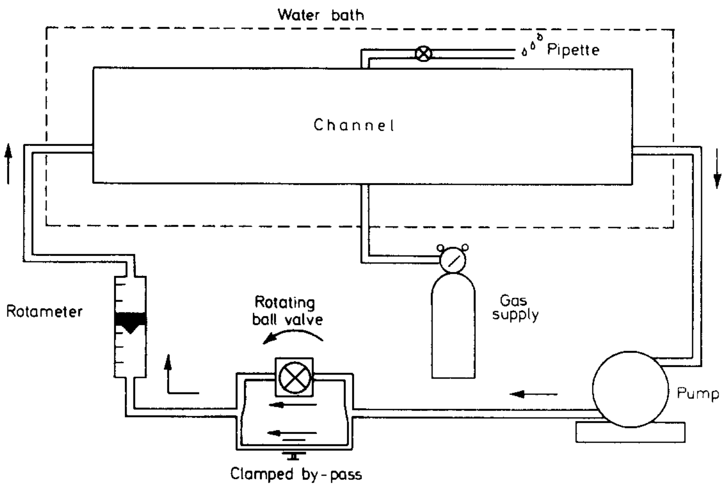

FIG. 2. Flow circuit for mass transfer device.

pressure difference between the two gas chambers (ΔP), the solubility of oxygen in water (S), the diffusion coefficient (κ) and the channel dimensions as

$$F_0 = bl\kappa S\Delta P/h,$$

where h is the channel gap (3 mm), b is the channel breadth (36 mm) and l is the channel length (275 mm). A comparison of the theoretical and experimental values of F_0 was made by Stairmand and Haworth [5] who obtained agreement to within 10%. When fluid velocities are applied down the channel the gas flux F determines the Sherwood number as:

$$Sh = Fh/(bl\kappa S\Delta P)$$
$$= F/F_0.$$

We observe that this group is related to the standard mass transfer Nusselt number (Nu) by

$$Sh = \tfrac{1}{4}Nu.$$

Note that we here define both the Nusselt and the Reynolds numbers in terms of the hydraulic diameter of the channel, i.e. twice the channel gap. Thus

$$Re = \frac{2hU}{\nu} \quad \text{and} \quad Nu = \frac{2hK}{\kappa},$$

where ν is the kinematic viscosity, K is the bulk mass transfer coefficient and U is the bulk flow velocity.

RESULTS

Readings for the oxygen flux were taken using distilled water or milk as the working fluid. Measurements were made at 10-min intervals over the course of at least 1 h until readings for the oxygen flux across the channel were steady. The results of this study are shown in Fig. 3 as a plot of Sherwood number (Sh) vs Reynolds number (Re) with and without 8-Hz pulsations. The data indicate that application of pulsations to the water-filled channel increased the Sherwood number by about 20%. When milk was used as the working fluid, the membrane was rapidly fouled leading to a reduction in the measured oxygen flux. Such effects prevented increase in the Reynolds number of the uninterupted flow from significantly increasing the Sherwood number above a value of about 40 (see Fig. 3). However, this phenomenon could be in part reversed by the application of pulsations. For the larger flows, the Sherwood number could be enhanced by a factor of about 2 after imposition of pulsations. A similar effect was observed when the working fluid was an agitated saline solution of waxy lipidic ester (concentration c = 1 part in 7500–15,000). For these experiments the time response of the apparatus to changes in the flow condition was monitored by taking readings at 5-min intervals. In Fig. 4 we show the effect of alternately imposing and removing pulsations for various Reynolds numbers. Application of flow pulsations leads to an enhancement in mass transfer which is gradually lost once the pulsations have been removed. Although the change in flux is largely complete by 5 min, there is still some measurable variation after 15 min. We attribute these improvements in mass transfer to the gradual stripping and subsequent reforming of a fouling layer.

Table 1. The variation in flow pulsatility (ϕ) with mean flow rate ($\bar{Q}$)

$l\bar{Q}$ (min^{-1})	ϕ
8	0.294
10	0.267
12	0.257
14	0.429

SUMMARY AND DISCUSSION

Measurements of mass transfer have been made in turbulent flows at Reynolds numbers of up to 14,000. Grooved walls were used and 8-Hz pulsations were imposed onto the flow. In fouling liquids this arrangement improved mass transfer fluxes by as much as a factor of 2. A study which is similar to the present one was carried out by Sparrow and Tao [6]. These authors measured transfer coefficients and pressure drops in corrugated channels carrying steady turbulent flows, and obtained up to 90% improvements in Nusselt number over the flat wall case at the cost of significantly increasing the pressure drop. The present studies differ in that pulsatile flows were imposed and fouling liquids were used. Clearly the nature and concentration of the foulant which is present in a system determines the extent to which membrane deposition impedes transfer through the walls. However, in the present study of two different fouling systems in turbulent flow, it is evident that

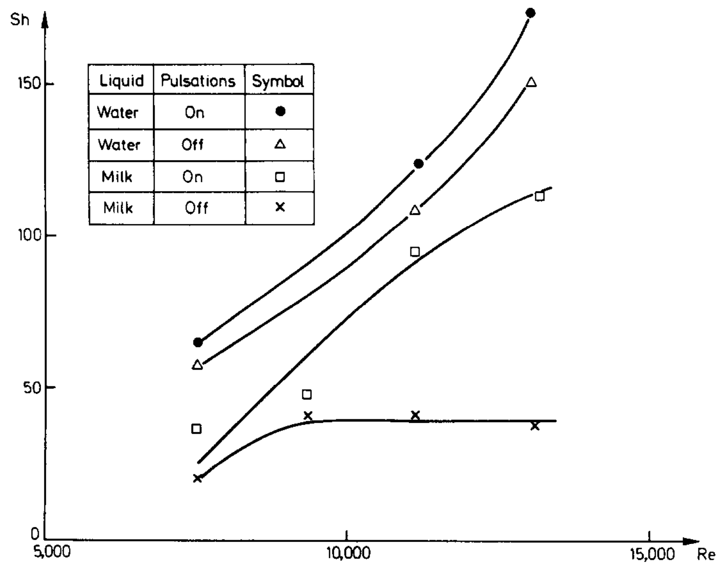

FIG. 3. Plot of Sherwood number vs Reynolds number in distilled water and in milk with and without pulsations of frequency 8 Hz. Small improvements are made when pulsations are added to the water-based system. The Sherwood numbers for the milk system without pulsations are much reduced, but this effect is largely reversed upon application of pulsations.

significant increases in mass transfer fluxes may be achieved by the imposition of flow pulsations. The channel geometry has not been optimized and it is likely that with modifications, operating regions of larger improvements could be identified. A plausible explanation for the improvements we have already measured is that vortices form within the laminar sublayer in a manner similar to that described by Sobey [4] for wholly laminar flow. Indeed such a phenomenon has recently been observed experimentally by Buckles *et al.* [7] who used a laser–Doppler velocimeter to measure velocity profiles in a steady turbulent flow over a wavy surface. The work described by Sobey was concerned with a system in which the core velocity reversed strongly; in this respect alone the present study is markedly different since the bulk fluid in the turbulent core does not reverse. Instead, the pulsations which have been applied to the steady flow impose an oscillatory component onto the pressure gradient. In an inertially-dominated flow this can lead to local velocity reversals in the slower moving wall region without reversal in the bulk. Thus, it is not necessary for a bulk reversal of the flow to occur in order to measure improvements in mass transfer. This conclusion is of importance if vortex formation techniques are to be extended to the turbulent regime for which the imposition of a fully reversing pulsatile flow would imply the use of undesirably large oscillatory velocities.

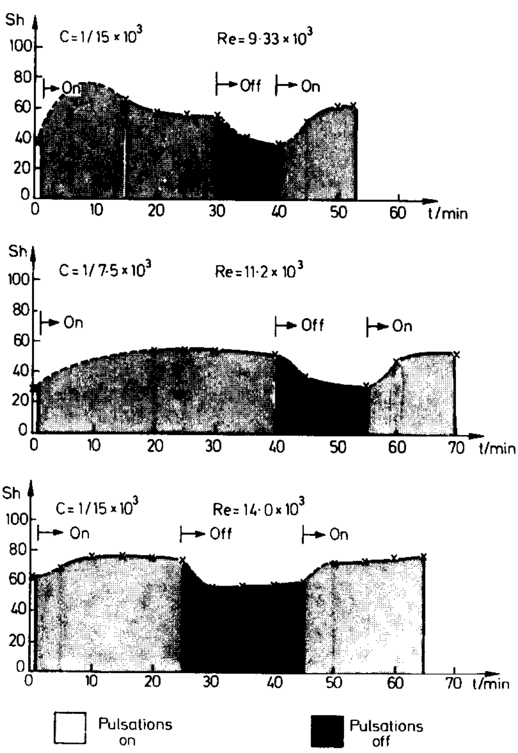

FIG. 4. Plots of Sherwood number vs time with intermittent application of pulsating flows of 8 Hz with waxy lipid ester solution as the working fluid. The application of pulsations rapdily improves the Sherwood number for all cases.

Acknowledgement—The authors acknowledge the technical assistance of Mr M. A. L. Stevenson and the helpful comments of Dr W. S. Haworth. This work has been funded by the British Petroleum venture research scheme.

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Int. J. Heat Mass Transfer. Vol. 28, No. 7, pp. 1408–1411, 1985
Printed in Great Britain

0017-9310/85 \$3.00 + 0.00
Pergamon Press Ltd.

Can thermal conductivity, λ, and extinction coefficient, E, be measured simultaneously?

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(*Received* 24 *October* 1984)

NOMENCLATURE

A, A_Λ	absorption coefficient at wavelength Λ [$\mathrm{m^{-1}}$]
c_P	specific heat [$\mathrm{J\,kg^{-1}\,K^{-1}}$]
D_0	total thickness of sample [m]
d	thickness of a layer in an extinction measurement [$\mathrm{m^{-1}}$]
E, E_Λ	extinction coefficient at wavelength Λ [$\mathrm{m^{-1}}$]
$\bar{E}, \bar{E}^*$	thickness-averaged value of E or E^*
E^*	effective value of the extinction coefficient (E corrected for anisotropic scattering)
I'_Λ	source function including scattered and remitted directional intensities at wavelength Λ [$\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}}$]
i'_Λ	directional intensity at wavelength Λ [$\mathrm{W\,m^{-2}\,\mu m^{-1}\,sr^{-1}}$]
K	K integral, equation (8b)
n	real part (effective value) of complex refractive index of porous medium
$p(\theta)$	scattering phase function at angle θ
$\dot{q}, \dot{q}_{sc}, \dot{q}_{rad}$	total, solid conductive and radiative heat flow [$\mathrm{W\,m^{-2}}$]
r	fiber radius [μm]
S, S_Λ	scattering coefficient at wavelength Λ [$\mathrm{m^{-1}}$]
T, T'	temperature [K]
T_1, T_2	temperatures of hot and cold wall [K]
T^{*3}	third power of radiative temperature, $(T_1^2+T_2^2)(T_1+T_2)$ [$\mathrm{K^3}$]
t	time [s].

Greek symbols

Λ	wavelength [μm]
$\lambda, \lambda_{sc}, \lambda_{rad}$	total, solid conductive and radiative conductivity [$\mathrm{W\,m^{-1}\,K^{-1}}$]
$\bar{\lambda}, \bar{\lambda}_{sc}$	thickness-averaged values of λ or λ_{sc}
μ	$\cos\theta$ of scattering angle θ
$\bar{\mu}$	weighted mean of μ with respect to scattering phase function
ρ	density [$\mathrm{kg\,m^{-3}}$]
σ	Stefan–Boltzmann constant, 5.669×10^{-8} [$\mathrm{W\,m^{-2}\,K^{-4}}$]
θ	scattering angle
$\tau, \tau_\Lambda, \tau_\Lambda^*$	optical thickness at wavelength Λ of a layer (a star denotes the integration variable)
τ_0	total optical thickness, ED_0
Ω, Ω_Λ	albedo of single scattering, at wavelength Λ
$d\omega$	solid angle element.

THIS QUESTION was the subject of an invited statement prepared for a workshop on the effect of radiation on thermal transport properties held at the 9th European Thermophysics Conference, Manchester, U.K., September 1984. Following the intentions of the workshop, this problem will be discussed primarily from an experimental point of view. Two introductory remarks on a very elementary level will be made first: total thermal conductivity, λ, is a *calorimetric*, i.e. an *integral* quantity, which can be defined, e.g. by Fourier's equation:

$$\rho\cdot c_P\cdot\frac{\partial T}{\partial t}=\nabla\cdot\lambda\nabla T. \tag{1}$$

It is obvious that equation (1) specifies λ everywhere in a solid, liquid or gas only if a gradient ∇T of the temperature $T(x)$ exists within the whole volume of interest. Let us assume that the matter occupying this volume is in part transparent. A total thermal conductivity exists only if *all* existing heat transfer modes (radiative transport by absorption/re-emission and scattering, solid or liquid or gaseous heat transfer) can be described by a specific radiative, solid, liquid or gaseous conductivity. A radiative conductivity can be defined only if the diffusion model of radiative transfer applies, i.e. for a medium of a high optical thickness, τ_0. Thus the existence of the total λ is strictly speaking, coupled to an optically thick medium.

The extinction coefficient, E_Λ, on the other hand, is an *optical, spectral* quantity and is usually defined by Beer's law for a wavelength, Λ,

$$i'_\Lambda(\tau_\Lambda)=i'_\Lambda(0)\cdot e^{-\tau_\Lambda}=i'_\Lambda(0)\cdot e^{-E_\Lambda d} \tag{2}$$

where i' denotes the intensity in a particular direction.

If we consider an experimental device for the measurement of E as schematically described in Fig. 1, care has to be taken that no scattered or absorbed/re-emitted radiation falls on the detector. Otherwise application of equation (2) for determination of E is invalid, and the solution of the complete equation of transfer including a source function I'_Λ for