International Journal of Heat and Mass Transfer 95 (2016) 288–295

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Enhanced evaporation from an oscillating liquid in a capillary tube

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ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form 4 November 2015
Accepted 2 December 2015
Available online 21 December 2015

Keywords:
Vapour diffusion
Evaporation
Taylor's dispersion
Capillary tube
Oscillatory flow

ABSTRACT

Enhanced evaporation inside a capillary tube into which the liquid/gas meniscus oscillates is experimentally studied. It is found that the meniscus oscillation can markedly level-off the evaporation rate, while keeping an apparent diffusive behaviour. The apparent diffusive coefficient can reach a tenfold increase in the explored range of parameters. The dependence of the effect is studied by varying the capillary tube diameter, the frequency and the amplitude of the liquid oscillations. The parametric dependence of the apparent diffusive coefficient is well captured by the associated dimensionless Péclet number. A nice collapse of the experimental measurements consistent with a quadratic scaling with Péclet number is found. Such scaling is suggested by previous theoretical and experimental analysis associated with a Taylor dispersion transport mechanism. Nevertheless the prefactor of those theory is found to under-predict the observed effect by a factor three. This deviation from Taylor's dispersion driven transport predictions is discussed.

1. Introduction

In the present work, we study the evaporation of a volatile liquid contained in a vertical capillary tube, when oscillations of the liquid/gas interface meniscus are imposed. Evaporation is due to vapour diffusion through air, from the oscillating meniscus to the still ambient external air, where the mass fraction of the vapour is negligible. This problem is related to the classical Taylor's dispersion phenomenon, named after his discoverer [1]. The classical analysis of Taylor's dispersion deals with the enhanced dispersion of a tracer in a non oscillatory flow. When a fluid flows through a tube, a velocity profile develops in the transverse direction due to the no-slip boundary condition at the tube's edge. Since the resulting velocity profile is not uniform, over the cross-section of the tube the fluid move faster in the centre than near the edges. Such transverse gradient of the longitudinal velocity is the key ingredient for longitudinal dispersion to occur: a small plug of vapour in air which diffuses transversely from the centre to the edge will experience a strong longitudinal shear because a change in transverse position will translate into a change in longitudinal velocity. This mechanism explains how the apparent longitudinal diffusion of vapour along the direction of air flow is enhanced. As a phenomenon, Taylor's dispersion resembles molecular diffusion, but it actually results from the interaction between transverse diffusion and velocity shear, and is therefore a function of the flow type and the channel geometry. Other factors, like flow dynamics and chemical reactions can produce additional effects to the dispersion. In laminar flow with molecular diffusivity D, the effective longitudinal diffusion coefficient can be shown to fulfil $D_{eff} = D(1 + \gamma Pe^2)$, where $Pe \equiv \langle u \rangle d/D$ ($\langle u \rangle$ is the average velocity over the tube cross-section) is the Péclet number and the parameter γ depends on the shape of the channel cross-section and velocity profile [2]. Taylor [1] showed that for Poiseuille flow in a circular tube of diameter $d, \gamma = 1/192$.

A similar effect occurs when the flow is oscillatory, as is the case in the present work. An oscillatory tube flow is characterised by the Womersley number $\alpha = \frac{d}{2}\left(\frac{\omega}{\nu}\right)^{1/2}$, where ν is the kinematic viscosity, ω the angular-frequency, and the Reynolds number $Re_\delta = \bar{u}\delta/\nu$, where $\bar{u} = 2b\omega$ is the cross-section average of the peak velocity amplitude which depends on the oscillation amplitude b and $\delta = (2\nu/\omega)^{1/2}$ is the Stokes-layer thickness. Experiments [3] have shown that such a flow is laminar when the Reynolds number is bellow a given threshold: $Re_\delta < 500$. For $Re_\delta > 500$, the core flow remains laminar while the Stokes layer becomes unstable during the deceleration phase of fluid motion. For increasing Reynolds number the turbulence is confined to an annular region which is a few times the Stokes-layer thickness near the wall. Thus, in this

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.012
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Nomenclature

$A \equiv (2D\rho_v/\rho_l)$	parameter quantifying the evaporation kinetic
$A_{eff} \equiv (2D_{eff}\rho_v/\rho_l)$	parameter quantifying the evaporation kinetic, in the oscillatory case
$\frac{d}{2}\left(\frac{\omega}{nu}\right)$	Womersley number
b	amplitude of the imposed oscillation of the meniscus
$\beta \equiv \delta_f/d$	dimensionless liquid film thickness
D	diffusivity of vapour (2-propanol) in air
d	tube diameter
D_{eff}	effective diffusivity of vapour (2-propanol) in air
$\delta \equiv (2\nu/\omega)^{1/2}$	Stokes layer thickness
δ_f	liquid film thickness
D_l	self-diffusivity of (2-propanol) in liquid phase
$f \equiv 2\pi/\omega$	frequency of the imposed oscillation of the meniscus
ω	angular-frequency of the forcing stroke
M	molecular weight of 2-propanol
μ	dynamic viscosity of the air
ν	kinematic viscosity of the air
P_a	ambient air pressure
$Pe \equiv \langle u\rangle d/D$	Péclet number
R	ideal gas constant
r	radial cylindrical coordinate associated with the tube
$Re \equiv \langle u\rangle d/\nu$	Reynolds number of the flow
Re_δ	Reynolds number of the flow based on δ
ρ_l	mass density of the liquid 2-propanol
ρ_v	mass density of 2-propanol vapour
$S \equiv \pi d^2/4$	tube cross-section area
$\sigma \equiv \nu/D$	schmidt number
T	2-propanol imposed temperature
t	time
T_a	ambient air temperature
u	fluid longitudinal velocity
$\langle u\rangle \equiv \frac{2\pi}{\pi d^2}\int_0^{d/2} u(r)rdr$	averaged longitudinal fluid velocity
$\bar{u} \equiv 2b\omega$	cross section average of the peak velocity amplitude
V_β	fluid (2-propanol) volumetric thermal expansion coefficient
x_e	thermodynamical equilibrium mass fraction of 2-propanol-2 in air
z	longitudinal coordinate along the cylinder direction
z_0	initial meniscus location
γ	Taylor dispersion parameter

limit, the axial transport of a passive contaminant is compounded by the interaction of the inviscid core with the turbulent boundary layer. The convective and diffusive mechanisms in laminar oscillatory flows are the same as in steady flow but a wider variety of results are found. Shear-augmented axial dispersion in oscillatory flows has been studied in [4–10] among others. For low α, the coefficient γ is predicted to be $1/192$ [6] which is in agreement with the steady-flow result [2]. However, the experimental data in this range of α are rather scarce [11,8,12].

In this paper, we specifically report the results of an experimental study of vapour enhanced-diffusion in laminar oscillatory flow of air inside a capillary tube at $\alpha \simeq 1$. The focus of the study is to measure the effective diffusion coefficient as a function of the amplitude and frequency of the oscillations and of the tube diameter.

Pulsed flow in pipes can indeed be found in various applied context such as Stirling engines and pulse tube cryocoolers for space applications, where heat transfer improvement has been reported [13]. In more academic contexts, using forced oscillations to enhance heat transfer has been demonstrated to be useful either in straight tubes [14,15,13,16] or constricted ones [17]. Two reviews have emphasised the interest of oscillating flows for enhanced heat transfer in pipes and tubes [18,19]. A recent study has experimentally measured the temperature profile along longitudinal direction in a gas flow between two parallel plates, and confirm the interest of oscillation to enhanced transfert [20]. Nevertheless, even though such elementary pump system has been studied in the context of single phase flows, the interest of oscillating meniscus for heat transfer evaporation has not been quantitatively and precisely studied yet in simple configurations. The aim of this paper is to fill this gap in the litterature, with an emphasis on providing relevant dimensionless parameter to the transfer rate. In this paper we thus experimentally investigate how oscillating transfer can be interesting for enhanced evaporation inside a tube.

The paper is organized as follows, Section 2 is devoted the presentation of the experimental set-up. Section 3 presents the obtained results within a critical and synthetic manner. In Section 4, we discuss the results in the light of theoretical predictions found in the litterature, as well as comparisons with previous experimental results.

2. Experimental setup and protocol

2.1. Experimental setup

The experimental setup is shown in Fig. 1. It consists of a syringe filled with fluid and connected to a long borosilicate glass capillary tube (Fig. 1a). The tube diameter, d, varies from 0.70 to 2.05 mm. The syringe is placed inside a bronze cavity to manage the temperature of the working fluid (see below). In the experiments, we use three-component syringes with rubber gasket. The flexible gasket plays the role of a membrane to generate the fluid oscillations. The membrane is driven by a rod attached to the centre of an acoustic louder. The handling of the acoustic louder is carried out by a digital generator PGSF-052 and an amplifier Digisynthetic DP3200. The electrical signal of the generator is transmitted to the amplifier and then to the acoustic louder. The intensity of the signal is controlled by both the generator and the amplifier. The amplitude and frequency of the imposed fluid oscillations vary in the ranges $f = 5$–20 Hz and $b = 0$–7 mm, respectively. The experiments are conducted using 2-propanol.

The motion of the oscillating meniscus in the capillary tube was first studied by a high-speed camera Basler A402k equipped with a Helios-44 M-4 lens. Depending on the experimental conditions, the frame rate was varied from 140 to 200 fps (resolution is 800×400 pixels). Consequently, up to forty images of the meniscus could be acquired in the course of one period of oscillation. Typical data showing the meniscus location z as a function of time are displayed in Fig. 2. At small and moderate amplitudes of oscillations of the acoustic louder, the liquid meniscus oscillates sinusoidally (Fig. 2a). Deviations from this