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Experiments on the mass transfer of gas bubbles in mineral oil

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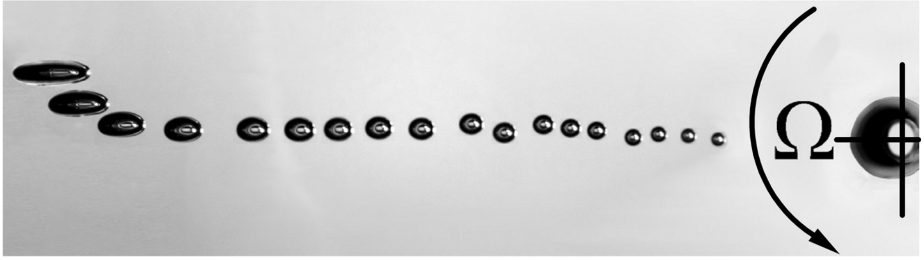
GRAPHICAL ABSTRACT



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ABSTRACT

The present experimental work uses the rotary chamber technique to observe bubbles rising in oil in a levitated position. Sizes from 0.3 mm to 8 mm are covered. Main bubble gases are oxygen, nitrogen and argon. The oil is white oil. The focus of the investigation is on the mass transfer rate of the bubble gas into the undersaturated oil. Constituent quantities are the rise velocity and the bubble shape. While velocity and shape show a low-key behavior the transfer rates are unusual. The normalized mass transfer in terms of the Sherwood number exhibits three zones. Both, the large bubble and the small bubble zone obey $Sh \propto Ar^{1/3}$. However, they are substantially shifted with respect to each other and connected by a transition zone. From arguments concerning the bubble drag we conclude that large bubbles have a mobile interface which develops into an immobile one for the smaller bubbles. Thus the state of the interface affects the mass transfer rate heavily.

1. Introduction

The main issues studied in context with rising bubbles are the rise velocity, the shape and the mass transfer between bubble and liquid. Each issue spreads into a number of sub issues. For example the velocity of single bubbles in water depends on the state of the interface which again may depend on the bubble release mechanism [1,2]. Bubbles in water have been of predominant interest over decades [3] because they are ubiquitous and readily made. Furthermore the bubble-water interface is special due to the high surface tension and the high attraction to surfactants. However, there are other important systems and applications. In process engineering and lubrication technology bubbles play an important role because oil dissolves a lot of gas (much more than water) which appears in terms of bubbles caused by pressure changes. The associated processes can be severe and damaging which locates them, among others, in cavitation studies. Early on G.I. Taylor [4] found that slide bearings produce bubbles and foam due to the circumferential pressure cycle. These bubbles are not due to real vapor cavitation since the vapor pressure of oil is technically speaking zero. The obvious explanation is degassing. Initially air-saturated oil becomes supersaturated when the pressure drops entailing the release of air. Diffusion plays a substantial role in these mass transfer process. This has been widely overlooked mainly because diffusion is labelled too slow to play a role in cavitation. Peters and Honza [5] as well as Groß and Pelz [6] have conducted seminal experiments to rethink the problem.

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Nomenclature

Ar	Archimedes number [–]
C	Constant according Eq. (10) [–]
c_D	Drag coefficient [–]
c_L	Lift coefficient [–]
D	Diffusion coefficient of gas in white oil [m^2/s]
d_e	Equivalent diameter of bubble [m]
$d_{e,syringe}$	Predetermined bubble size (diameter) [m]
F_b	Buoyancy force [N]
F_D	Drag force [N]
F_L	Lift force [N]
F_{rot}	Centripetal force [N]
g	Gravitational acceleration [m]
H	Bubble height [m]
H	Henry coefficient [(kg/m^3)/Pa]
L	Ostwald coefficient [–]
$\dot{m}$	Mass flux [kg/s]
n_{D20}	Refractive index (at 20 °C for 589 nm) [–]
p	Pressure [Pa]
R	Equivalent radius of bubble (2R = de) [m]
Re	Reynolds number [–]
$\lvert dR/dt \rvert$	Slopes of de(t)-function [m/s]
r	Radial bubble coordinate (referred to chamber center) [m]
Sh	Sherwood number [–]
T	Temperature [°C]
t	Time [s]
U	Bubble rise velocity [m/s]
V	Bubble volume [m^3]
V_g	Volume of dissolved gas [m^3]
V_l	Liquid volume [m^3]
W	Bubble width [m]
W/H	Bubble deformation [–]

Greek symbols

ν	Kinematic viscosity [m^2/s]
ν_{ex}	Kinematic viscosity of external bubble fluid (here white oil) [m^2/s]
ρ	Density [kg/m^3]
ρ_{in}	Density of internal bubble fluid [kg/m^3]
ρ_s	Gas density in liquid (saturated) [kg/m^3]
ρ_g	External gas denisty [kg/m^3]
ρ_∞	Pre-set density of solved gas in white oil [kg/m^3]
σ	Surface tension [N/m]
τ	Shear stress [Pa]
φ	Angular bubble coordinate(see Fig. 4) [rad]
χ	Saturation degree [–]
Ω	Angular velocity of rotating chamber [rad/s]

The present work deals with a reduced, elementary experiment on bubbles in oil. We study at what rate bubbles of different gases dissolve into oil when they rise at their natural velocity. Besides the rate we determine the velocity itself, the bubble deformation and the state of the interface, whether it moves with the flow (mobile) or remains stagnant (immobile). The mass transfer results appear in dimensionless form based on the scaling parameters Sherwood number and Archimedes number. A clear view is obtained on the relation between bubble properties and mass transfer.

We use the rotary chamber technique which has been employed successfully in our group [7–11]. The key advantage of the chamber is that a bubble can be observed over its life time in a levitated position. The addressed quantities can thus be monitored.

The study involves single bubbles filled with either argon, oxygen or nitrogen. Helium and methane were only partially investigated due to a lack of fluid properties and experimental circumstances. The bubbles deform from spherical to ellipsoid with increasing volume. A natural limit is reached at about 8 mm of the volume equivalent diameter where shape and location become instable. This stability limit agrees quite well with the theoretical works of Ryskin and Leal [12] and Hua and Lou [13]. The lower size limit where mass transfer can be exploited lies around 1 mm. The mere size can be measured and calibrated down to 0.3 mm.

All experiments were carried out in mineral white oil taken from one batch (Meguin PP20 DAB10). According to the producer it is a relatively well defined mixture of iso- and n-alkanes with minute additional fractions. Physical properties were not at hand. However, they could be measured for one batch. Besides it qualifies for the experiments because it is transparent and in no way hazardous. The same properties make it a widely used primary liquid in the cosmetic and food industry.

2. Experimental

2.1. Fluid properties

Below we provide the fluid properties as far as necessary for the experiments with argon, oxygen or nitrogen. For white oil no reliable literature data could be found, especially not for the batch supplied for the experiments. Therefore all required data were measured by ourselves. No relevant data could be collected for helium and methane which means that experiments with these gases could not be fully evaluated.

2.1.1. Equilibrium gas concentration

A clear picture of the equilibrium concentration of a gas in a liquid is best illustrated by the dimensionless Ostwald coefficient L [14]

$$L = \frac{V_g}{V_l} = \frac{\rho_s}{\rho_g} \tag{1}$$

which relates the dissolved volume of gas V_g to the liquid volume V_l. This ratio is simply equivalent to the ratio of gas density ρ_s in the liquid to the external gas density ρ_g. Involving the equation of state of an ideal gas leads to Henry's law relating ρ_s to the pressure p as

$$H = \frac{\rho_s}{p} \tag{2}$$

It is understood that the Henry coefficient H is independent of pressure in the considered range. Table 1 lists L for the involved gases argon, oxygen, nitrogen at 23 °C. In brackets we show L of water for comparison [15]. As a benchmark one may say that oil takes up ten times as much gas than water. The method of measurement was based on gas volume absorption.

Table 1
Ostwald coefficient L for white oil. L for water in brackets for orientation. Diffusion coefficient D with appendant experimental spread in brackets. Corresponding Schmidt number Sc = ν/D. All values for 23 °C.

Gas –	L (–)	D (10^{-9} m^2/s)	Sc (–)
N_2	0.1147 (0.0163)	1.5 (1.2–2.0)	19380
O_2	0.2586 (0.0320)	0.6 (0.6–0.7)	48450
Ar	0.3092 (0.0350)	1.0 (0.8–1.2)	29070