

Use of hydrodynamic cavitation for volatile removal compound



Francisco J. Arias*, Salvador de las Heras

Polytechnic University of Catalonia ESEIAAT C. Colom 11, 08222 Terrassa, Spain

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ABSTRACT

Hydrodynamic cavitation and its feasibility for volatile compound removal in enclosed channels is discussed in this paper. Very high Reynolds numbers are needed to rupture liquid by decreasing its pressure below its saturated vapour pressure. Hence, a simple stratified flow, at which the two phases separate, is precluded in vertical and horizontal tubes, where turbulence stresses will be much larger than the buoyant forces. The most probable flow regime at this high turbulence regime is a bubble- or annular flow, where the volatile matter tends to concentrate in the centre of the pipe because of the lift force resulting from the unequal flow of the viscous liquid around the bubbles in the presence of the pipe wall. Therefore, boiling the volatile matter for volatile compound removal is not enough if hydrodynamic cavitation is pursued. The attainable efficiency must also be assessed. An expression for the volatile removal efficiency and the main parameters affecting this efficiency were derived by utilising a simplified geometrical and physical model. The efficiency was found to approximate a power law as a function of the volatile concentration and its strong dependence on the size of the volatile bubble reasonably well. This result implied the need of bubble growth and the limitation of the process for highly concentrate compounds to a few percent concentrations. With regard to energetic requirements, both thermal and hydrodynamic cavitations are quantitatively similar. Furthermore, the choice of one or another corresponds more to the kind of energy source available.

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1. Introduction

Volatilisation by heating methods is generally characterised by great simplicity and ease of operation, except when high temperatures or highly corrosion-resistant materials are needed. A compound can be volatilised by heating to increase its vapour pressure. Heating methods include the volatilisation of water, mercury, or arsenic trichloride to separate these substances from interfering elements. However, an alternative physical method for volatilisation that does not rely on liquid heating is possible. Indeed, volatilisation occurs when a liquid at a constant temperature is subjected to a decreasing pressure below the saturated vapour pressure. This phenomenon is called hydrodynamic cavitation.

There has been a revival in interest in hydrodynamic cavitation during the last few years on numerical (Charrire and Goncalves, 2017; Yin et al., 2016) as well as theoretical studies including the basic mechanism of pollutant degradation, modeling of pressure distribution in the cavitation reactor, and bubble dynamics models coupled with chemical reactions are evaluated (Arrojo and Benito, 2008). New results of laboratory experiments on the appli-

cation of cavitation effects to decompose selected organic compounds which hardly undergo biodegradation have been presented (Ozonek, 2012), application of hydrodynamic cavitation to wastewater treatment (Tao et al., 2016; Washio, 2014) or in microbial cell disruption (Save and Joshi, 1997), are some of the most promising fields. However, the use of hydrodynamic cavitation as a sole technique or in combination with other techniques such as ultrasound has only recently been suggested and employed (Dular et al., 2016).

Despite that hydrodynamic cavitation processes are known to lead to very effective liquid degassing (Gogate and Pandit, 2011; Iben et al., 2015), to such a degree that it can be used for removal of undesired volatile compounds and therefore boiling becomes unessential (Albanese et al., 2017). Nevertheless the volatile removal efficiency has not been addressed as far as the author knows. This study aims to analyse the theoretical efficiency of hydrodynamic cavitation as an attractive alternative method of thermal vaporisation.

By an analogy with heating volatilisation, it could be thought that boiling volatiles by decreasing the liquid pressure after increasing its velocity and relying on buoyancy forces (if horizontal pipes or channels are used) would be enough. Nevertheless, the situation is not that simple. First, in contrast with thermal volatilisation, hydrodynamic cavitation implies a very high Reynolds number depending on the degree of compound volatilisation (i.e. on

* Corresponding author at: Polytechnic University of Catalonia ESEIAAT C. Colom 11, 08222 Terrassa, Spain.

E-mail address: francisco.javier.arias@upc.edu (F.J. Arias).

Nomenclature

a	volatile bubble radius (m)
A_c	pipe area cross-section (m ²)
c	local bubble concentration (m ⁻³)
\bar{c}	average gas concentration across the cross-section (m ⁻³)
c_m	concentration at the tube centreline (m ⁻³)
c^*	$\frac{c}{c_m}$
C_{pl}	heat capacity of liquid (J kg ⁻¹ K ⁻¹)
D	pipe diameter (m)
s	$\frac{y}{R}$ dimensionless distance from the wall
f	dimensionless friction factor
L	latent heat of the volatile (J kg ⁻¹)
n	dimensionless exponent
m	dimensionless exponent
M	mass of gas to be removed (kg)
u	velocity (ms ⁻¹)
u_c	critical velocity at which cavitation occurs (ms ⁻¹)
u_l	liquid velocity in the x -direction (ms ⁻¹)
u_m	velocity of the two-phase mixture at the tube centreline (ms ⁻¹)
R	tube radius (m)
p	final pressure (Pa)
p_c	critical pressure at which cavitation occurs (Pa)
p_o	initial pressure (Pa)
p_s	saturation pressure (Pa)
p_v	vapour pressure (Pa)
Δp_c	tensile strength of the liquid (Pa)
ΔP	pressure drop (Pa)
t	pipe radius for the volatile removal or time (m)
x	volatile concentration (m ⁻³)
Z_g	total amount of gas
W_T	thermal energy for volatilisation (J)
W_W	mechanical energy for volatilisation (J)
T	initial temperature of the liquid (K)
T_c	critical temperature at which vaporisation occurs (K)
T_s	saturation temperature (K)
ΔT	temperature difference (K)

Greek symbols

κ	universal constant
ρ_l	liquid density (kg m ⁻³)
ρ_g	gas density (kg m ⁻³)
ρ_v	vapour density (kg m ⁻³)
η	efficiency
ν_l	kinematic viscosity of liquid
Ψ	parameter defined by Eq. (10)
Φ	parameter defined by Eq. (11)
γ	fraction of the volatile compound in the liquid
Γ	energy cavitation-to-thermal energy ratio
Σ	thermal parameter

Subscripts

c	critical
l	liquid
g	gas
v	vapour

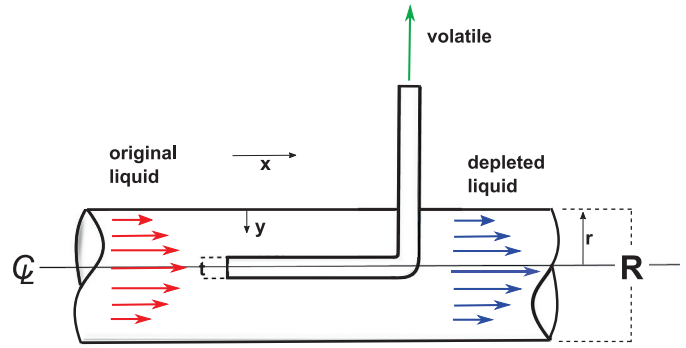


Fig. 1. Physical model for the hydrodynamic cavitation extraction of volatiles.

be necessary if a volatile compound initially dissolved into water at a room temperature of $T = 300\text{K}$, an atmospheric pressure of $p_o = 10^5$ Pa with a density $\rho_l = 10^3$ kg/m³ and a saturation pressure of $p_s = 3 \times 10^3$ Pa (i.e. higher than the saturation pressure of water at this temperature) is desired to be removed. This simple illustrative example shows that we are in a very high turbulent regime for practical pipes with diameters around a few centimetres. This turns out in precluding a simple stratified flow, at which the two phases are separated, followed by straightforward removal. The flow regime at this high turbulence regime is a bubble or an annular flow, where the volatile bubbles tend to concentrate in the centre of the pipe because of the lift force resulting from the unequal flow of the viscous liquid around the bubbles in the presence of the pipe wall. The exact profile of the radial distribution function for the bubbles at that turbulent regime is not easy to obtain, and in principle, cannot be determined by pure theoretical treatment. Nevertheless, some insights into the relevant parameters affecting the efficiency of hydrodynamic cavitation volatile removal may be obtained by a simplified analysis. The real situation can also be improved using empirical modifications.

2. Theoretical background

We first need to know the radial distribution function for the bubbles inside a pipe in the flowing liquid to calculate the efficiency of the volatile removal by hydrodynamic cavitation.

For the sake of generality, let us consider a pipe (Fig. 1), where the pressure declines to some value below the saturated vapour pressure of the volatile compound desired to be removed because of the liquid velocity. The concentration profile in a pipe could be approximated as follow as a power law distribution (Bankoff, 1960):

$$c^* = s^{\frac{1}{n}} \quad (1)$$

where $c^* = \frac{c}{c_m}$ with c_m is the maximum concentration of the gas at the centreline; $s = \frac{y}{R}$ being y is the coordinate from the wall (Fig. 1); R is the pipe radius; and n is a positive constant depending on the liquid velocity profile, $n \rightarrow \infty$ when $u_l \rightarrow 0$ and $n \rightarrow 0$ when $u_l \rightarrow \infty$ with u_l as the liquid velocity. This constant will be discussed in a later section.

The minimum velocity in the pipe should be the critical velocity, in which cavitation occurs (for the volatile compound), to produce hydrodynamic cavitation through the pipe. The velocity profile in the pipe is provided as follows by the well-known logarithmic velocity law:

$$u_l = u_m \left[1 - \frac{1}{\kappa} \sqrt{\frac{f}{2}} \ln \frac{R}{y} \right] \quad (2)$$

where u_l is the liquid velocity in the x -direction at a distance y from the wall; u_m is the velocity of the two-phase mixture at the

its saturated vapour pressure). The situation is even worse if open channels are used. For the sake of illustration, a velocity profile around $\left[\frac{2(p_o - p_s)}{\rho_l} \right]^{\frac{1}{2}} \simeq 14$ m/s and a Reynolds number of $Re \simeq 1.4 \times 10^5 D$, where D is the pipe diameter in centimetres, would

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