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Reduction of liquid pumping power by nanoscale surface coating

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ABSTRACT

The objective of the present study is to reduce the liquid pumping power by controlling the contact angle of the riser surface with the nanoscale surface treatment. The efficiency of a bubble pump is examined depending on the size of the riser, submersion ratio, gas inlet flow rate, and contact angle variations by nanoscale surface coating between 23.7° and 153.8°. By the nanoscale surface coating, the efficiency is improved by 22.5%, 25%, and 18%, respectively, for the 11 mm, 8 mm, and 5 mm risers compared to the uncoated surface. However, the superhydrophobic surface with a contact angle of 153.8° shows a lower efficiency compared to other surfaces due to the reversed liquid vibration flow. The highest efficiency of the liquid pumping power is obtained at the contact angle of 90.3°. An experimental correlation for the dimensionless volumetric liquid flow rate is developed with an error band of ±20%.

Réduction de l'énergie de pompage de liquide par revêtement de surface nanométrique

Mots clés : Pompe à bulle ; Angle de contact ; Énergie de pompage de liquide ; Revêtement de surface nanométrique ; Écoulement inversé de vibration de liquide ; Mouillabilité

1. Introduction

Bubble pump is a device that raises the liquid through a vertical pipe by lowering the average specific gravity of the liquid using a compressed gas after part of the riser is submerged in the liquid or the mixture of liquid and solid. Advantages of this bubble pump include simple structure and fewer troubles, as well as the possibility of using liquids that are difficult to be used in the conventional pumps. Furthermore, it is highly reliable and costs less for maintenance because it has no driving and wearing parts which need to be lubricated. Therefore, bubble pumps are being used in petrochemicals, toxic fluids, wastewater treatment, and extraction of deep sea minerals (De Salve et al., 2015; Kassab et al., 2007; Yoshinaga and Sato, 1996). However, one disadvantage of the bubble pumps is a lower efficiency compared to the conventional pumps. Thus, many theoretical and experimental studies on the performance and

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Nomenclature

A	cross section area [m^2]
B_ε	systematic uncertainty [%]
D	diameter [m]
F	force [N]
g	gravitational acceleration $[\mathrm{m\ s^{-2}}]$
h	height of meniscus [m]
$\dot{m}$	mass flow rate $[\mathrm{g\ s^{-1}}]$
N	number of measurements
Q	volumetric flow rate $[\mathrm{m^3\ s^{-1}}]$
Q'	dimensionless volumetric flow rate
R	aspect ratio $(Z D^{-1})$
r	radius of meniscus [m]
S_ε	random uncertainty [%]
U_ε	overall uncertainty [%]
Z	length of the riser [m]

Greek letters

α	submersion ratio
η	efficiency
θ	contact angle [degree]
κ	standard deviation $[\mathrm{g\ s^{-1}}]$
ρ	density $[\mathrm{kg\ m^{-3}}]$
Σ	surface tension number $\sigma \rho^{-1} g^{-1} D^{-2}$
σ	surface tension $[\mathrm{N\ m^{-1}}]$

Subscripts

ad	adhesion
corr	correlation
G	gas
L	liquid
l	lift
s	submerged
t	total

two phase flow in the bubble pumps have been conducted to solve this drawback. Nicklin (1962) proposed an empirical formula for the rising speed of bubbles with two phase flow in a vertical pipe. Clark and Dabolt (1986) suggested a design correlation of bubble pump including the friction loss in a slug flow area. Jeelani et al. (1979) reported that a theory for small diameters of the bubble pump was required. Based on the findings of Nicklin (1962) and Clark and Dabolt (1986), Reinemann et al. (1990) studied the effects of surface tension on the bubble speed for 20 mm or smaller diameters of bubble pump. For a study related to bubbles, Apazidis (1985) investigated the bubble expansion according to the rising bubbles in a bubble pump. For a study on the bubble pump nozzle, Cho et al. (2009) examined the nozzle size and the submersion ratio. Fan et al. (2013) studied the capacity and efficiency of bubble pumps by changing the nozzle design parameters. For a study on the riser, Stenning and Martin (1968) presented quantitative data about the operation characteristics of a one-dimensional bubble pump considering the friction and slip between gas and fluid when part of the bubble pump riser is submerged in water. However, no study has been conducted to improve the efficiency by improving the wettability or friction among the bubble, liquid, and riser which has the solid surface.

The surface wettability is determined by the contact angle between water drop and surface. If this angle is smaller than 90°, the surface is called "hydrophilic"; otherwise, it is "hydrophobic". Furthermore, the surface is called "superhydrophobic" if the contact angle is greater than 150° and Zhang and Lv (2015) reviewed the recent advances in superhydrophobic surfaces and emerging energy-related applications. The superhydrophobic surface is being applied to various areas such as anti-icing (Carton et al., 2012; Farhadi et al., 2011; Liao et al., 2014; Mohseni and Amirfazli, 2013; Peng et al., 2012; Yang and Li, 2013) and anti-fouling (Meng et al., 2014) due to very small wettability. It has particularly small wettability for fluids such as water. Hence, studies were conducted to move fluids with a micro volume after superhydrophobic coating was applied to the inside of the pipe (Gogte et al., 2005; Ou et al., 2004). Kim et al. (2013) studied on the Lindenfrost mechanism on hydrophilic and hydrophobic surfaces.

In this study, the contact angle of the risers of the bubble pump with hydrophilic, hydrophobic, and superhydrophobic surfaces is controlled to improve the liquid pumping efficiency. The optimum conditions of bubble pumps are proposed for the efficiency enhancement according to the wettability of the bubble pump riser surface, and the flow patterns for different contact angles of the riser surface are examined using a high-speed camera. Furthermore, an experimental correlation for the dimensionless volumetric liquid flow rate is developed for bubble pump application.

2. Bubble pump theory

In this study, the theory of Reinemann et al. (1990) is used to determine the efficiency and characteristics of the bubble pump. Fig. 1 shows the schematic of the bubble pump riser. The submersion ratio (α), which is a critical factor of the bubble pump, is represented by the ratio of the submerged length of the bubble pump riser (Z_s) to the total length (Z_t).

$$\alpha = \frac{Z_s}{Z_t} \tag{1}$$

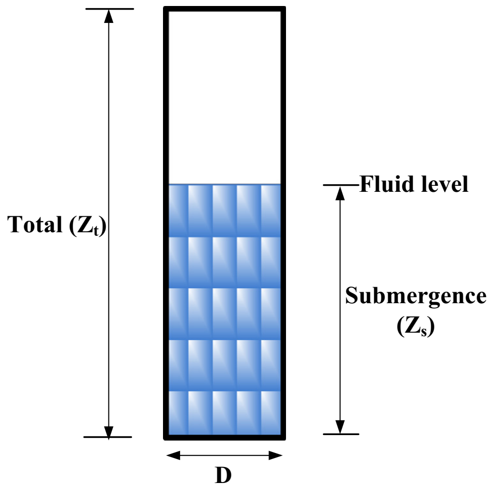

Fig. 1 – Schematic of the bubble pump riser.