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Water drop impacts on a single-layer of mesh screen membrane: Effect of water hammer pressure and advancing contact angles

Jinliang Xu *, Jian Xie, Xiaotian He, Yu Cheng, Qi Liu

The Beijing Key Laboratory of Multiphase Flow and Heat Transfer for Low Grade Energy Utilization, North China Electric Power University, 102206 Beijing, China

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ABSTRACT

Mesh screen membrane is a functional material for gas-water or oil-water separation. If a water drop impacts on the membrane at a sufficiently high velocity, a critical condition at which daughter droplets are generated and fall down below the membrane occurs, under which the separator is failure. The objective of this paper is to determine the critical condition. Six mesh screen membranes are used. The mesh wire diameter and mesh pore are on the same-scale (10–100 μm), involving apparent cross sectional area decrease of mesh pores in the membrane depth direction. Thus, drop impacting on the membrane yields significant liquid compression in ∼μs timescale to cause additional water hammer pressure. The analysis shows that the liquid compression is related to the number of mesh pores within drop project area (N). The water hammer pressure relative to dynamic pressure is found to be raised with N. The drop impacting process is governed by the dynamic pressure together with the additional water hammer pressure competed with the maximum capillary pressure at the throat location of the mesh pore. The modified Weber number $-We_w/\cos(\theta_A)$ was correlated with N in a single curve to predict the critical condition for droplet breakthrough, where We_w is characterized by the mesh pore width and $\cos(\theta_A)$ reflects the advancing contact angle effect. This paper is useful for membrane type gas-water or oil-water separator design.

1. Introduction

Metal mesh screen is a kind of functional material which is available from commercial market with acceptable cost. For example, pressure drops can be reduced when liquid flows on the modified mesh screen surface [1]. When liquid drops impact on mesh screen surface, the impingement process involves sufficiently high heat transfer coefficient [2]. The hydrophobic mesh screen can be used as a vapor-liquid separator [3]. When the two-phase mixture with liquid droplets entrained in vapor impacts on the mesh screen, vapor passes through mesh pores, but droplets cannot enter mesh pores, if the drop size is larger than the mesh pore size. Thus, the two-phases are separated and pure vapor is obtained. Recently, metal mesh screen is also proposed to be used for oil-water separation [4–6].

The drop impacting onto holes was performed by Lorenceau and Quéré [7]. They used single hole sieve of size ranging from 260 μm to 900 μm, smaller than the capillary length of $l_c = \sqrt{\sigma/\rho g}$ Z, where σ is the surface tension force, ρ is the liquid density and g is the gravity acceleration. The threshold for protruding liquid results in a balance between inertia force and capillary force using the Weber number defined as $We = \rho V^2 d/(2\sigma)$, built with the impacting velocity V, hole diameter d, surface tension σ and liquid density ρ.

Bordoloi and Longmire [8] studied the deformable drops falling through a circular orifice, having the Bond number in the range of 0.8–11. The orifice diameter is much smaller than the drop size. Effects of surface wettability were investigated. For the round edged case, a thin film of surrounding oil prevents the drop from contacting the orifice surface. Thus, the drop falling through the orifice is independent of surface wettability. For the sharp edged case, a contact is initiated at the orifice edge immediately after impacting. The surface wettability influences the drop outcome.

Few studies are reported on drop impacting onto multi holes. Brunet et al. [9] reported experiments of drop impacting on a hydrophobic micro-grid. Above a critical impacting velocity, liquid emerges to the other side to form micro droplets, having similar size of the grid holes. A method was proposed to produce a large quantity of micro-droplets. The critical Weber number is found to be much smaller than that predicted by the single hole theory [7]. The collective effect was believed to generate an additional pressure to cause easy liquid penetration. The additional pressure

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* Corresponding author.
E-mail address: xjl@ncepu.edu.cn (J. Xu).

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Nomenclature

A	flow cross section area, m^2
As	shadow area of droplet on mesh screen, m^2
Au	a unit area including a mesh pore, m^2
Bn	Bond number
C	sound speed in liquid, m/s
Ca	Capillary number
d	hole diameter, m
D	droplet diameter, m
D_c	wetting diameter, m
e_A	average deviation
e_R	mean absolute deviation
g	gravity acceleration, m/s^2
H	droplet falling height, m
ΔH	falling height variation, m
k	a constant to quantify the importance of the water hammer pressure related to the dynamic pressure (see Eq. (9))
k^*	empirical coefficient
l	wetted perimeter, m
l_c	capillary length, m
m	droplet mass, kg
N	number of mesh pores within the droplet project area (see Fig. 3 and Eq. (2))
P	pressure, Pa
Re	Reynolds number
t	time, s
Δt	time variation, s
v	droplet volume, m^3
Δv	droplet volume variation, m^3
V	impact velocity, m/s
w	mesh pore width, m
We	Weber number

Greek symbols

δ	mesh wire thickness, m
θ	dynamic contact angle, °
θ_A	advancing contact angle, °
θ_c	static contact angle, °
$\theta_{c,i}$	stable contact angle after droplet impacting, °
μ	viscosity, Pa s
ρ	density, kg/m^3
$\Delta\rho$	density variation, kg/m^3
σ	surface tension, N/m
σ_n	standard deviation

Subscript

0–3	state during drop impacting process corresponding to Fig. 10
C	capillary
D	dynamic
exp	experimental value
max	maximum
pre	predicted value
w	using the mesh pore width as characteristic length
WH	water hummer

is considered as the water hammer pressure due to the shock during a sudden change of the liquid momentum. The water hammer pressure becomes important for small holes, having the same order of the dynamical pressure.

The drop impacting on textured surfaces involves several pressure balances. The dynamic pressure $P_D = 0.5\rho V^2$ is the driving force for liquid penetration into micro structures [10]. In the initial impact stage, the contact between droplet and textured surface generates a shock wave induced water hammer pressure, which is written as $P_{WH} = k^*\rho CV$, where C is the sound speed in liquid, k^* is a empirical coefficient, having scattered values in the literature. For example, Deng et al. [11] used $k^* = 0.2$ for droplet impacting on textured solid surface. Kwon et al. [12] used $k^* = 0.003$ for microdroplet impacting on micro-pillar array. The k values did not reflect physical mechanisms of drop impacting process.

Shock wave is complicated, especially for droplet impacting onto textured microstructure. The available numerical simulations on shock waves are majorly for drops impacting on plain surface [13]. The water hammer pressure is not well understood when drops impact on micro structures. Because shock wave usually happens in μs time scale, sufficiently shorter than the heat transfer process, it generally occurs under isentropic condition. On the other hand, shock wave is caused by the liquid compression. Different drop sizes and microstructure sizes yield different water hammer pressures, it is not acceptable to use a constant k^*.

Here, we investigate the drop impacting on a single layer of mesh screen membrane. The critical condition at which daughter drop begins to occur and fall down is focused on. The driving pressure is the dynamic pressure plus the water hammer pressure. The anti-pressure is the capillary pressure, reaching maximum at the throat location of the mesh pore with the advancing contact angle. The treatment of water hammer pressure is thoroughly different from that in the literature. A k factor is defined as the water hammer pressure divided by the dynamic pressure, i.e. $k = P_{WH}/P_D$. The fundamental analysis of drop impacting obstructed by mesh wires guides us to find a key parameter of N, reflecting liquid volume change induced by compression, yielding the water hammer pressure. Our experimental data successfully correlate k as a function of N in a single curve, for all the six mesh screen pieces and different surface wettabilities. Finally, the drop breakthrough criterion is written in a non-dimensional form to have a general guideline for gas-liquid or oil-water separator design.

2. Experimental section

2.1. Fabrication and characterization of the mesh screens

Six tin bronze mesh screens with 6.15–7.79 wt% tin element are used for the experiment (see Fig. 1). They are available from the commercial market. The following procedures are performed to prepare the test sections: (1) The mesh screens with planar size of 30 mm by 30 mm were first immersed in acetone solution for 1 h to remove oil contaminations. Afterwards the pieces were rinsed by de-ionized water. (2) The mesh screens were immersed in 1 M HCl aqueous solution for 5 min to remove oxidation layer and then rinsed by de-ionized water. (3) The cleaned mesh screens were suspended in a 0.5 wt% hexane solution of 1H, 1H, 2H, 2H-perfluorodecyltriethoxysilane (CAS NO: 101947-16-4, Alfa Aesar) at room temperature for 1 h. (4) The mesh screens were drying at 110 °C for 1 h in an oven at vacuum pressure.

For comparison, the static contact angles on the solid plate (same material) without holes are measured to be 45° and 112° before and after the treatment, respectively. But the static contact