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Mode selection between sliding and rolling for droplet on inclined surface: Effect of surface wettability

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ABSTRACT

Onset of droplet motion is important for various applications, including dropwise condensation and water management in fuel cells. In order to determine critical conditions for onset of motion and specific motion mode, a general problem having a droplet sheared by a gas stream on inclined surface is investigated. Two criterion equations are theoretically established for onset of droplet sliding and rolling independently, including dimensionless parameters of Bond number (Bn), Ohnesorge number (Oh) and Weber number (We), inclination angle parameter and wettability parameters. The criterion equations predict critical gas velocity, maximum droplet radius, and "sliding angle" or "rolling angle". Droplet sliding predictions agree well with experimental data in the literature. Criterion surfaces of sliding or rolling are constructed to verify if sliding or rolling can be initiated, influenced by both equilibrium contact angle and contact angle hysteresis. By coupling the criterion equations of sliding and rolling, we develop a mode selection criterion equation, which is only dependent on equilibrium contact angle θ_e. Three regions are clarified: (1) for $126.3° < \theta_e < 147.0°$, a droplet rolls if $Bn < Bn_t$ and slides if $Bn > Bn_t$, where Bn_t is the transition Bond number; (2) for $\theta_e < 126.3°$, a droplet only slides; (3) for $\theta_e > 147.0°$, a droplet only rolls. The theoretically determined 147.0° contact angle is newly recommended as the contact angle boundary between hydrophobicity and super-hydrophobicity. One of the applications of this work is to provide a general guideline for droplet detachment or retention in fuel cells and condensers.

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1. Introduction

The determination of critical condition for droplet detachment on inclined surface is important for many natural phenomena and engineering applications. In arid and semiarid environments, leaf hydrophobicity of plant species is important for rain droplet detachment to increase water availability for soil [1]. On the other hand, tank-mix adjuvants are used to improve the efficiency of foliage applied pesticide formulations, especially if they are used at reduced dose rates. In this context, liquid retention on leaf surfaces is the desired outcome [2–4].

Water management is important in polymer electrolyte fuel cells (PEFCs) and proton exchange membrane fuel cells (PEMFCs): appropriate humidification is critical to achieve high ionic conductivity of membrane but excessive water causes flooding and consequently reduces cell performance [5,6]. Water droplets occur on hydrophobic gas diffusion layer (GDL) surfaces and hinder the transport of oxygen and hydrogen towards respective catalyst layers where the electrochemical reactions occur. Droplets should be removed in a suitable gas shearing flow.

Dropwise condensation on hydrophobic surface improves condenser performance. Droplet nucleation, growth and detachment are key to affect condensation heat transfer. Two droplet sizes should be included in condensation heat transfer model [7,8]: minimum drop radius at which a drop initiates nucleating (r_{min}), which is beyond the scope of this paper, and maximum droplet radius at which a droplet initiate moving, r_{max}, which is the scope of this paper.

Considering a droplet sheared by a gas stream on inclined surface, there are four possible detachment modes: sliding mode in which the relative position between any two liquid particles is not changed (see Fig. 1a), rolling mode for a droplet rotating (see Fig. 1b), lifting mode to float a droplet (see Fig. 1c), and dripping mode to make a droplet falling down (see Fig. 1d). Physically, the critical condition at which a droplet begins to move depends on the deformed droplet induced surface tension force competed by gravity force and/or shear force for sliding, lifting and dripping modes. Alternatively, the critical rolling condition depends on the competition of various forces induced torques.

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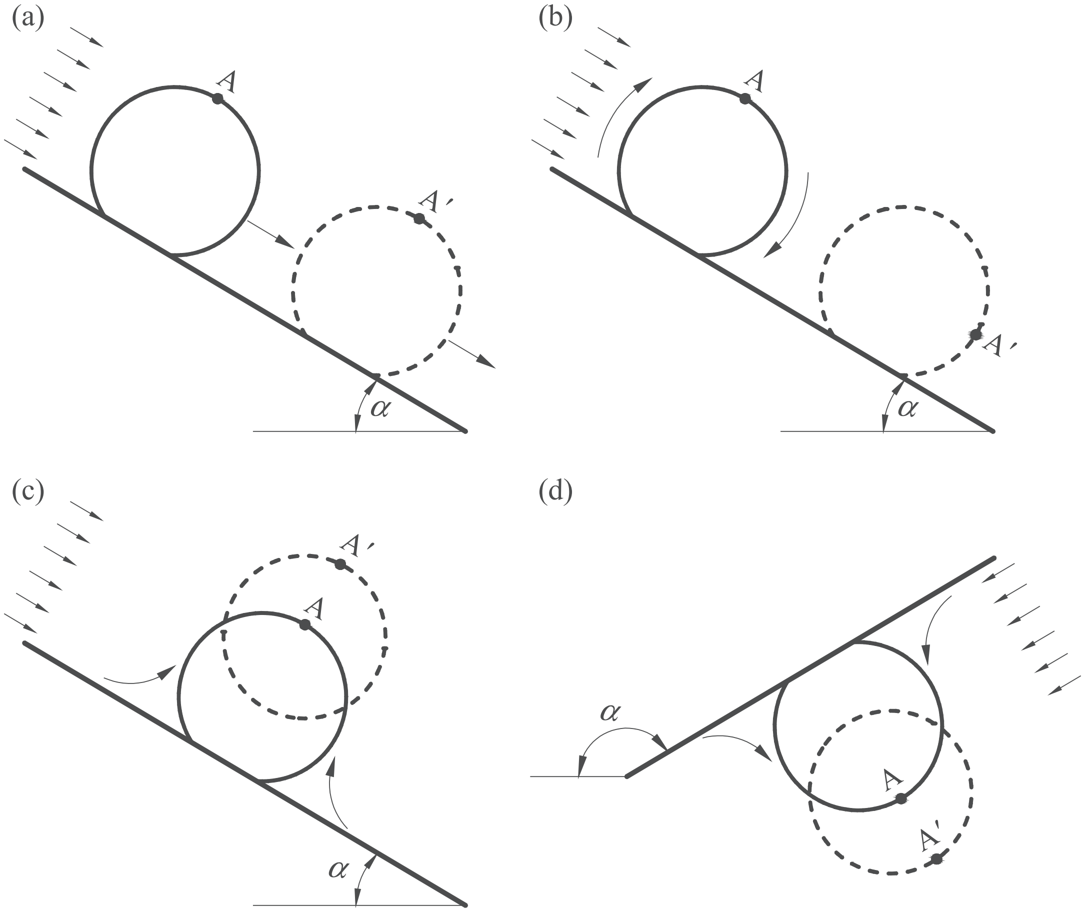

Fig. 1. The four droplet detachment modes on inclined surface (a: sliding, b: rolling, c: lifting, and d: dripping).

Table 1 summarized droplet detachment studies in the literature. Even though some sliding investigations are reported, droplet sliding under comprehensive effects of surface tension force, shear force and gravity force is not well understood. For example, Chen [9], Cho et al. [10] and Fan et al. [11] treated sliding motion under the effects of shear force and surface tension force, without considering gravity force due to the horizontal surface used. Alternatively, Dimitrakopoulos and Higdon [12] treated sliding motion with surface tension force competed only by gravity force without shear force effect.

Steady droplet rolling after its initiation has been investigated previously. Richard and Quere [13] determined the relationship between rolling velocities and droplet sizes. They found that the rolling velocity is constant for droplet radius larger than the capillary length, but is increased with the decrease of droplet radius for droplet radius smaller than the capillary length. Richard and Quere

Table 1
Literature review on droplet detachment.

Refs.	Applications	Detachment modes	Shear effect	Gravity effect	Results and comments
Chen [9]	PEMFC or PEFC	Sliding	Yes	No	Force balance analysis is used to predict critical gas velocity for drop sliding with fixed drop size in the horizontal gas diffusion layer (GDL).
Cho et al. [10]	PEFC	Sliding	Yes	No	Non-dimensional equation was obtained by forces balance in the horizontal GDL.
Fan et al. [11]	–	Sliding	Yes	No	Critical gas velocity shearing a droplet in a horizontal channel was measured, with four drop sizes, three types of surfaces and three liquids. Static, advancing and receding contact angles were given for each run, which are useful for comparison with theoretical/numerical studies.
Dimitrakopoulos and Higdon [12]	–	Sliding	No	Yes	Non-dimensional equation is obtained by forces balance parallel to the titled wall surface.
Qi et al. [18]	Dropwise condensation	Rolling	No	Yes	Critical detachment drop size for rolling was obtained by balancing moment equilibrium on vertical surface.
Ran et al. [19]	Wettability characterization	Rolling	No	Yes	Moment equilibrium analysis is used to predict critical rolling angel of titled surface for drop detachment.
Sikarwar et al. [7]	Dropwise condensation	Sliding and dripping	No	Yes	Critical sliding drop size is obtained by balancing forces parallel to titled surface. Critical dripping drop size is obtained by balancing forces perpendicular to titled surface.
Basu et al. [20]	–	Sliding and lifting	Yes	No	Critical sliding drop size is obtained by balancing forces parallel to horizontal surface. Critical lifting drop size is obtained by balancing forces perpendicular to surface. The authors show that sliding is preferred than lifting.

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