# Friction force effects on vertical manipulation of nanoparticles

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**Abstract** In humid environment, a particles can be picked up from the substrate by the capillary force, such as in the colloidal probe of atomic force microscopy technique. In this paper, a model of the capillary bridge between spherical particles is used to study effect of the friction force in nanoparticles manipulation. Based on the Young-Laplace equation, Newtonian equation and adopted the constant volume boundary condition to calculate the particle motion, the friction force effects on nanoparticles manipulation are analyzed. The results show that the friction force has little effect on the particle motion, and the particle velocity decreases slightly in presence of the friction force. The friction force is opposed to the motion of the nanoparticle. As the tip velocity increases, there is a critical velocity beyond that the particle cannot be picked up from the substrate, and the critical velocity decreases in presence of the friction force. These provide a better understanding of the nanoparticle mechanical properties in humid environment.

**Key words** Friction force, Capillary force, Critical velocity, Liquid bridge

## 1 Introduction

In wet granulation, physical interaction between surfaces at nanoscales is vital for understanding the dynamic behavior of particulate systems. It has great theoretical and practical importance in interfacial dynamics[1], granular materials science[2], and nanotechnology[3]. The physical interfacial force includes van der Waals force, electrostatic force, chemical bonding force and capillary force[4,5], which attracted many researchers to work on the complex dynamics for clarify mechanisms and contribution of the forces at nanoscales.

The capillary force, which originates from condensation of water vapor from the ambient atmosphere between two solid surfaces[6-10], is as an important component of the interfacial forces, and can be utilized as the major force to pick or release nanoscopic object in nanoparticle manipulation. This arose increased attention in the past years[11,12] because it may be found in a number of practical situations, such as lithography[13], colloidal crystallization[14], microcantilevers[15], etc.

On the other hand, as the nanoparticle moves, influence of the friction force should be taken into account. There has been widespread interest in the friction force and its effects at the atomic- scale in the lateral contact[16-18]. Mo Y F, *et al*.[16] used the large-scale molecular dynamics simulations to establish friction laws in dry nanoscale contacts. Tambe N S, *et al*.[17] proposed a lateral manipulation of a nanoparticle to explain the friction behavior at nanoscales over a wide range of sliding velocities. Palacio M, *et al*.[18] carried out an atomic force microscopy (AFM) manipulation to investigate the variations of friction force with different particle areas and humidities. Krim J, *et al*.[19] found that the friction force in microscopic scales differed from that of the macroscopic sacle. However, in vertical nanoparticle manipulation, studies are needed for better understanding of the frictional effects on a moving particle.

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In this paper, we study the fiction force acting on nanoparticles in their vertical manipulation. It is shown that the particle velocity decreases in presence of friction force, which has resistance effects on the particle motion and weakens the interactions between the particles. The increasing of the tip velocity leads to a smaller pickup time, namely, the particle can be picked up from the substrate quickly. However, if the tip velocity is beyond a critical velocity, the nanoparticle cannot be picked up from the substrate. The critical velocity decreases in presence of the friction force.

## 2 Theory

Let us consider a tip-particle-substrate system[20]. The particles are partially wetted by the concave capillary liquid bridge, as sketched in Fig.1. Here, axisymmetric liquid bridge with respect to the $y$-axis[21], and hydrophilic surface and concave shaped liquid bridges, are considered.

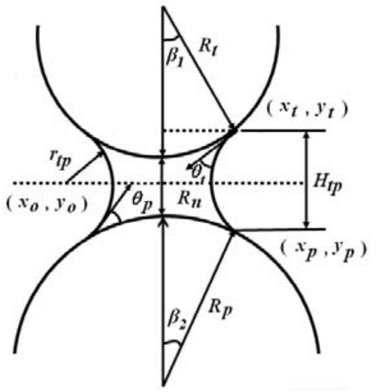


**Fig.1** Schematic diagram of a capillary bridge between tip and nanoparticle. $R_t$ and $R_p$ are the radii of the tip and nanoparticle, respectively. $H_{tp}$ is the interparticle distance from the tip to the particle. $\beta_1$ and $\beta_2$ are the half-filling angles of the tip and particle, respectively. The liquid bridge form contact angles $\theta_t$ at the tip, $\theta_p$ at the particle. rtp and rn are the azimuthal radius and meridional radius, respectively. ($x_t$, $y_t$) and ($x_p$, $y_p$) are the coordinates of the solid-liquid-vapor contact lines with solid surfaces, ($x_o$, $y_o$) denotes the center of the meniscus profile.

In nanoparticle manipulation, the total force acting on the nanoparticle is treated by a combination of capillary force and friction force:

$$F_{\text{cp\_tp}} - F_{\text{cp\_ps}} + f_{\text{friction}} = m_{\text{p}} \frac{\mathrm{d}^2 y(t)}{\mathrm{d}t^2} \tag{1}$$

where $m_p$ is the particle mass, $y(t)$ is vertical position of the particle, $\mathrm{d}^2y(t)/\mathrm{d}t^2$ is the particle acceleration, $F_{\text{cp\_tp}}$ is attractive capillary force between tip and particle, and $F_{\text{cp\_ps}}$ is attractive capillary force between particle and substrate. The capillary forces can be expressed as[22]:

$$F_{\text{capillary}} = \pi x^2 \Delta p - 2\pi x \gamma \sin(\theta+\beta) \tag{2}$$

where $\gamma$ is the surface tension, $\Delta p$ is the pressure difference between the inside and outside of the liquid bridge, $x$ is the coordinates of the solid-liquid-vapor contact lines, $\theta$ is the contact, and $\beta$ is half-filling angles (Fig.1). The pressure difference is given by Young-Laplace equation:

$$\Delta p = \gamma\left(\frac{1}{r_{\text{tp}}} - \frac{1}{r_{\text{n}}}\right) = \frac{kT \ln p / p_{\text{o}}}{V} \tag{3}$$

where $V$ is the molecular volume of the liquid, $k$ is the universal gas constant, $T$ is the temperature and $p/p_0$ is the relative humidity. The $\gamma V/(kT)$=0.54 nm was used for water at 293 K[23].

The $f_{\text{friction}}$, the friction force, acts on the interface between the air and nanoparticle. The friction force is taken to be proportional to the particle velocity, and follows the Stokes law:

$$f_{\text{friction}} = 6\pi R_{\text{p}} \eta v(t) \tag{4}$$

where $R_p$ is the radius of the nanoparticle, $v(t)$ is the velocity of the particle, $\eta$ is the air kinematic viscosity, $\eta=1.82\times10^{-5}$ Pa·s at 293 K.

Under the Toroidal approximation[24], the exact profile of the meniscus can be treated as the arc of circle. The principal radii between the tip and particle, denoted as $r_{tp}$ and $r_n$, can be described by half-filling angles and contact angles:

$$r_{\text{tp}} = \frac{H_{\text{tp}} + R_{\text{t}}(1-\cos\beta_1) + R_{\text{p}}(1-\cos\beta_2)}{\cos(\theta_{\text{t}}+\beta_1) + \cos(\theta_{\text{p}}+\beta_2)} \tag{5}$$

$$r_{\text{n}} = R_{\text{p}} \sin\beta_2 - r_{\text{tp}}[1-\sin(\beta_2+\theta_{\text{p}})] \tag{6}$$

For nonvolatile liquid in rapid separation process, the liquid bridge volume conformed the constant volume condition[25]. The volume of the tip-particle liquid bridge can be calculated by:

$$\begin{aligned} V_{\text{tp}} = {} & \pi\{(r_{\text{tp}}{}^2 + x_{\text{o}}{}^2) y_{\text{t}} - \frac{r_{\text{tp}}{}^3}{3}[\cos^3(\beta_1+\theta_{\text{t}}) + \cos^3(\beta_2+\theta_{\text{p}})] \\ & - \frac{x_{\text{o}} r_{\text{tp}}{}^2}{2}[\sin(2(\beta_1+\theta_{\text{t}})) + \sin(2(\beta_2+\theta_{\text{p}})) + 2\pi - \\ & 2(\beta_2+\theta_{\text{p}}) - 2(\beta_1+\theta_{\text{t}})]\} - \frac{1}{3}\pi R_{\text{t}}^3(2-3\cos\beta_1+\cos^3\beta_1) - \\ & \frac{1}{3}\pi R_{\text{p}}^3(2-3\cos\beta_2+\cos^3\beta_2) \end{aligned} \tag{7}$$

Due to the relative movement of tip and particle, the liquid bridge elongated continuously until its rupture distance. Our model requires the radii of the tip and particle, the contact angles, and the humidity as initial conditions, with this information and combines Eqs.(1–7), the motion of the nanoparticle at each instant in time can be obtained. An accurate calculation of the liquid bridge rupture distance and more details regarding the particle-substrate system can be found in the Ref.[26]. Let us consider a tip radius of $R_t$=50 nm and particle radius of $R_p$=20 nm, with the mass of gold being $m_p$=0.65×10$^{-18}$ kg, at $T$=293 K, and the surface tension of $\gamma$=72.75 mN/m.

## 3 Results and discussion

### 3.1 Pickup velocity

During the pickup operation, the fiction force, caused by the compression of air molecules in front of the moving nanoparticle, is closely related to the tip velocity. Thus, we first examine the tip velocity in order to identify the mechanisms of nanoparticle during the detaching process.

As can be seen in Fig.2, the pickup time decreases with increasing $v_t$ and $\theta_p$. In the success pickup operation, namely picking a particle from the substrate when the lower liquid bridge ruptured before the upper liquid bridge, the pickup time depends on particle-substrate liquid bridge rupture distance. Take the cases of $\theta_p$=5°, 45° and 85°, with $\theta_t$=20°, $\theta_s$=70°as examples, at a fixed $\theta_p$, over the velocity range of 0.02–0.20 nm/ns, $F_{cp\_tp}$ is always larger than $F_{cp\_ps}$ as the particle separates from the substrate. In other words, the particle moves upward with accelerated motion and leads to a smaller pickup time. It has been shown that the particle-substrate liquid bridge volume and the liquid bridge rupture distance increased with the decreasing of the contact angle at a fixed $v_t$[26]. Therefore, it takes a longer time for successful pickup of the particle from the substrate. For example, at $RH$=50% the pickup time is 200, 145 and 105 ns at $\theta_p$=5°, 45° and 85°, respectively. The influence of different humidity levels on the particle was investigated, too, with similar trend of the pickup time.

The pickup time decreases with increasing $v_t$, but when the $v_t$ is large enough, this trend stops at a critical velocity of $v_t^c$, where the particle is unable to catch up $R_t$, and drops on the substrate finally, hence a failure nanoparticle manipulation.

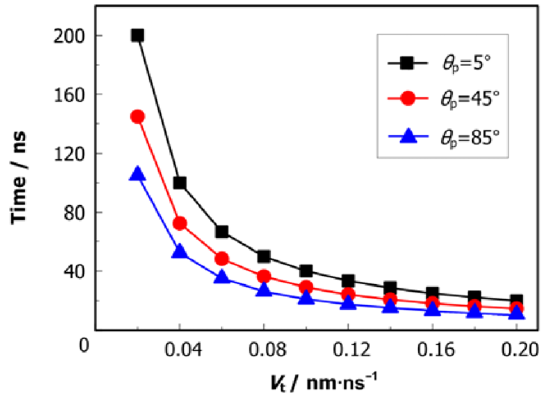


**Fig.2** The pickup time as a function of $v_t$ at $RH$=50%, $\theta_t$=20°, $\theta_s$=70° and $\theta_p$=5°, 45° and 85°.

### 3.2 Critical velocity $v_t^c$

Fig.3 shows the critical velocity $v_t^c$ as a function of $\theta_p$ in 30%–90% of humidity. The $v_t^c$ increases with $\theta_p$ and $RH$. A failure pickup means that the particle stays on the substrate and the tip-particle liquid bridge is ruptures before the particle-substrate liquid bridge. Thus $v_t^c$ is closely related to the tip-particle liquid bridge rupture distance. For the tip-particle system, a lager contact angle is found to result in a rise in tip-particle liquid bridge rupture distance. With a larger rupture distance, the liquid bridge can be stretched longer and $v_t^c$ is higher. This behavior is expected for a higher humidity, which means a greater bridge volume, hence the increased liquid bridge rupture distance. For example, at $\theta_p$=5° and 85°, $v_t^c$ increases from 0.3 nm/ns to 4.5 nm·ns$^{-1}$, from 0.26 nm/ns to 1.68 nm·ns$^{-1}$ and from 0.2 nm·ns$^{-1}$ to 1.3 nm·ns$^{-1}$ at $RH$=90%, 50% and 30%, respectively.

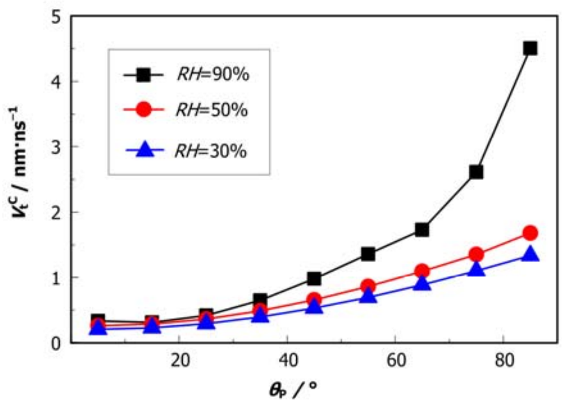


**Fig. 3** Critical velocity $v_t^c$ in presence of friction force *vs.* $\theta_p$ in 30%–90% of humidity at $\theta_t$=20° and $\theta_s$=70°.

### 3.3 Deviation value of critical velocity $\Delta V_t$

In Fig.4, the $\Delta V_t$ as a function of $\theta_p$ in 30%–90% of humidity, it can be seen that the friction force has a little influence on vertical manipulation of the nanoparticles, either in presence or absence of the friction force. The $v_t$* is always greater than $v_t^c$, because of resistance function of the friction force. In a previous paper[26], we presented theoretical approaches for the liquid bridge rupture distance, and found that the $\Delta F$ ($\Delta F = F_{cp\_tp} - F_{cp\_ps}$) increased with the humidity and contact angle. A greater $\Delta F$ means the particle moving upward in a greater speed. It is easier for a fast-moving particle to be slowed down and pulled apart with the tip by the friction force. Then, the interaction between the tip and particle is weakened, hence the $\Delta V_t$ increase with contact angle and humidity. For example, at $\theta_p$=5°and 85°, $\Delta V_t$ increases sharply from 0.7 to 5.5 pm·ns$^{-1}$ at *RH*=90%. We can conclude that the nanoparticle of large contact angle is affected by the friction force more easily.

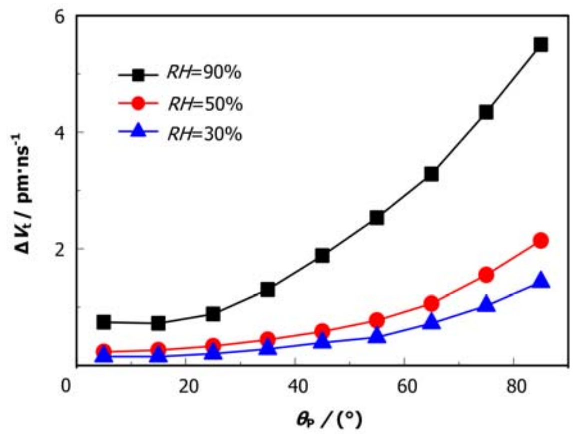


**Fig.4** $\Delta V_t = v_t^* - v_t^c$ *vs.* $\theta_p$ in 30%–90% of humidity. $v_t$* is the critical velocity without the friction force.

## 4 Conclusion

For studying the friction force effects on a nanoparticle in its vertical manipulation, a tip-particle-substrate system connected by the capillary liquid bridge, is used to simulate the pickup manipulation. The results show that the friction force has little effect on the vertical manipulation of the nanoparticle. The increasing tip velocity has a critical velocity, beyond which the pickup manipulation fails. Two situations, i.e. in absence or presence of the friction force, are considered. The critical velocity diminishes in presence of the friction force, because during the pickup manipulation, friction provides an opposing force which tries to slow the particle down. In the present work, apart from the capillary force and friction force, we do not consider the random thermal motion and van der Waals force. A more accurate model shall be used in the future.

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