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A theoretical note on aerodynamic lifting in dust devils

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ABSTRACT

The stress distribution of a known rotating flow near the ground in fluid mechanics indicates that the horizontal aerodynamic entrainment of particles within dust devils is attributed to friction force rather than pressure force. The expression of dust emission rate on Earth was theoretically discussed based on simulated flow field and our current understanding of the physics of aeolian dust. It seems that transition flow is vital to dust devils on Mars.

1. Introduction

Dust devils are particle-laden rotating vortices commonly forming over strongly heated surfaces in arid and semi-arid areas (Warner, 2004). They have been regarded as an important atmospheric dust-entrainment phenomenon because of their frequent occurrence both on Earth and Mars (Kok et al., 2012), although the related physical processes are still poorly understood. During usual wind erosion events, dust particles are emitted through aerodynamic lifting, saltation bombardment, and/or disaggregation (Shao, 2008). It is generally accepted that direct aerodynamic lifting is much less significant than the other two mechanisms. In dust devils, the processes of particle emission become more complicated. Shear stresses are sufficient to lift the aeolian particles sizing from dust to pebble (Balme et al., 2003), and a "saltation skirt" occurs near the surface (Metzger, 1999). Moreover, owing to the spatial pressure gradient the central core of dust devils can "suck up" particles from the surface (Greeley et al., 2003; Balme and Hagermann, 2006). The last unique phenomenon within dust devils was traditionally termed as the "ΔP" effect.

The general characteristics of dust devils, such as shape, size, duration, and wind speed, have been observed (Sinclair, 1969; Hess and Spillane, 1990; Balme and Greeley, 2006). For a typical dust devil, three vertical regions were distinguished by Sinclair (Balme and Greeley, 2006). In the surface interface region, wind flows toward the center and dust particles are lifted. The middle region is characterized by a near-vertical dust column. At the top of the dust devil, the rotation decays and dust particles begin to disperse. An analytical model, comprising a Prandtl layer, an Ekman inflow layer, and an inviscid region from bottom to top, was timely developed for prescribing the velocity fields reported by Sinclair (Logan, 1969). Subsequently, the Rankine, Burgers-Rott, Lamb-Oseen, or other idealized vortex models, *i.e.* several exact Navier–Stokes vortex solutions, are often used to quantitatively describe the velocity (or pressure) distribution within the middle region of dust devils (Kanak, 2005; Kurgansky, 2005; Lorenz, 2014). Since the surface effects are not well taken into account in derivations, these models are generally unsuitable for the surface interface region which is deeply involved in the physical processes of dust emission. Another type of theoretical models associated with the surface interface region investigates the heat convection responsible for the maintenance of the pressure gradient within a dust devil (Renno et al., 1998), and neither is a powerful tool to predict particle emission.

Here a known axially symmetrical three dimensional flow is applied to theoretically simulate the aerodynamic behavior in the surface interface region of dust devils. It is expected that some helpful insights into the relative importance of pressure force and friction force in the aerodynamic lifting of dust emission mechanisms will be provided.

2. Theory

2.1. Flow near the surface

As summarized by Balme and Greeley (2006), stable, simple dust devils are characterized by radial inflow near the surface and upward rotational flow within the dust column. The vertical flows at the central could be either upward or downward. For the surface interface region where particle emission occurs, the central downdrafts should be weak because radial inflow dominates and the surface is a wall-type boundary. For the dust devil with a central updraft, the steady flow in the surface interface region is just like that induced by a rotating fluid adjacent to a stationary disc. The solution of the Navier–Stokes equations for the later case had been found (Schlichting, 1979; Childs, 2011).

It is convenient to describe this problem under a cylindrical coordinate system (r, φ, z), where r, φ, z denote the radial, azimuthal, and axial coordinates, respectively. The surface and the center of the dust devil are $z = 0$ and $r = 0$. Three velocity components in the respective directions are u, v, and w. All derivations with respect to φ are equal to zero because the flow is symmetrical about z-axis. The Navier–Stokes equations can be written as,

$$u\frac{\partial u}{\partial r} + w\frac{\partial u}{\partial z} - \frac{v^2}{r} = -\frac{1}{\rho_a}\frac{\partial p}{\partial r} + \frac{\mu}{\rho_a}\left[\frac{\partial^2 u}{\partial r^2} + \frac{\partial}{\partial r}\left(\frac{u}{r}\right) + \frac{\partial^2 u}{\partial z^2}\right] \quad (1a)$$

$$u\frac{\partial v}{\partial r} + w\frac{\partial v}{\partial z} + \frac{uv}{r} = \frac{\mu}{\rho_a}\left[\frac{\partial^2 v}{\partial r^2} + \frac{\partial}{\partial r}\left(\frac{v}{r}\right) + \frac{\partial^2 v}{\partial z^2}\right] \quad (1b)$$

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$$u\frac{\partial w}{\partial r}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho_a}\frac{\partial p}{\partial z}+\frac{\mu}{\rho_a}\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}+\frac{\partial^2 w}{\partial z^2}\right) \tag{1c}$$

where ρ_a and μ are the density and viscosity of air, p is pressure.

The boundary conditions are,

$$u=0,\quad v=0,\quad w=0,\qquad \text{at}\quad z=0 \tag{2a}$$

$$u=0,\quad v=\omega r,\qquad \text{at}\quad z=+\infty \tag{2b}$$

where ω is the constant angular velocity of the dust devil.

A commonly used assumption in the boundary-layer theory is that pressure does not change in the direction perpendicular to the wall. This means that the term of $-\frac{1}{\rho_a}\frac{\partial p}{\partial z}$ in Eq. (1c) vanishes. For the frictionless flow at $z=+\infty$, the governing equation of p obtained from Eqs. (1a) and (2b) is,

$$\frac{dp}{dr}=\rho_a r\omega^2 \tag{3}$$

It is necessary to emphasize that the present model is only constrained to the surface interface region. Otherwise, the above assumptions don't hold. The expression of (3) has been taken to be the surface radial pressure gradient caused by a dust devil (Greeley and Iverson, 1985). As a result, the pressure distribution is,

$$p=p_0+\frac{1}{2}\rho_a r^2\omega^2 \tag{4}$$

where p_0 is the pressure at $r=0$.

After introducing a dimensionless coordinate $\xi=z\sqrt{\frac{\rho_a\omega}{\mu}}$ and assuming that the three velocity components have the form of $u=r\omega F(\xi)$, $v=r\omega G(\xi)$, $w=\sqrt{\frac{\mu}{\rho_a}\omega}H(\xi)$, Eqs. (1) and (2) become,

$$F''-HF'-F^2+G^2-1=0 \tag{5a}$$

$$G''-HG'-2GF=0 \tag{5b}$$

$$H'+2F=0 \tag{5c}$$

and

$$F=0,\quad G=0,\quad H=0,\qquad \text{at}\quad \xi=0 \tag{6a}$$

$$F=0,\quad G=1,\qquad \text{at}\quad \xi=+\infty \tag{6b}$$

Eqs. (5) were numerically solved under the boundary conditions (6) by many researchers. The velocity functions of F, G, and H varying with ξ were given in table form (Schlichting, 1979; Childs, 2011). Substituting the detailed expressions of velocity components into the constitutive relation of Newtonian fluid, the fluid stress can be found. Two shear stress components $\tau_{z\varphi}$ and τ_{zr} we will utilized hereinafter are,

$$\tau_{z\varphi}=\mu\frac{\partial v}{\partial z}=r\omega\sqrt{\mu\rho_a\omega}G' \tag{7a}$$

$$\tau_{zr}=\mu\frac{\partial u}{\partial z}=r\omega\sqrt{\mu\rho_a\omega}F' \tag{7b}$$

where the first derivatives of two velocity functions at the surface are $F'|_{\xi=0}\approx 0.6974$ and $G'|_{\xi=0}\approx 0.7668$.

2.2. Aerodynamic lifting

The dominant forces acting on a static dust particle include aerodynamic force, gravity, and adhesive force. Adhesive force, consisting of van der Waals force, capillary force, and electrostatic force, etc., depends on many factors such as particle size, contact area, and environmental humidity (Zimon, 1982; Shao, 2008). None of these adhesive forces can be predicted precisely. The toroidal approximation is applicable to capillary force (Wang, 2006). What we are concerned about is the relative importance of two aerodynamic force components. For simplicity, all adhesive forces are neglected here. Aerodynamic force is exactly equal to the integral of fluid stress over the particle surface (Wang et al., 2013). It is well known that fluid stress can be expressed in terms of two independent variables, *i.e.* normal stress and shear stress. Therefore, two components of aerodynamic force can be named as pressure force and friction force correspondingly.

For a static spherical dust particle on a flat surface shown in Fig. 1 where O is the center of the dust devil and L is the radial coordinate of the particle, pressure force can be computed as,

$$F_p=\int_S p\cos\theta\, dS=2\pi R^2\int_0^{\pi}p\cos\theta\sin\theta\, d\theta \tag{8}$$

where S and R are the surface and radius of the particle.

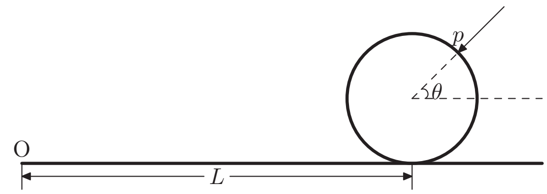

Fig. 1. The distributed force p acting on the surface of a dust particle.

An appropriate estimation of friction force is (Klose and Shao, 2013),

$$F_\tau=\pi R^2\sqrt{\tau_{z\varphi}^2+\tau_{zr}^2}\Big|_{z=0} \tag{9}$$

Substituting (4) and (7) into (8) and (9), we have,

$$F_p=\frac{4}{3}\pi\rho_a R^3 L\omega^2 \tag{10}$$

and

$$F_\tau=\alpha\pi R^2 L\omega\sqrt{\mu\rho_a\omega} \tag{11}$$

where $\alpha=\sqrt{F'^2+G'^2}\Big|_{\xi=0}\approx 1.03$.

The gravity is,

$$F_g=\frac{4}{3}\pi\rho_s R^3 g \tag{12}$$

where ρ_s is the particle density, g is the gravitational acceleration.

At the motion instant of the dust particle, the equilibrium condition for moments about the supporting point must be satisfied. The directions of the aerodynamic force and the gravity are horizontal and vertical, respectively. Both moment arms scale as the particle radius. For this reason, the ratio of aerodynamic force to gravity is a rough criterion for dust emission. According to the force expressions of (10)–(12), pressure lifting and friction lifting driven by the horizontal aerodynamic force can be judged by two dimensionless parameters,

$$\lambda=\frac{L\omega^2}{g} \tag{13}$$

and

$$\eta=\frac{\omega^2L^2}{gR}\sqrt{\frac{1}{Re}} \tag{14}$$

where $Re=\frac{\rho_a\omega L^2}{\mu}$.

The particle will be lifted if,

$$\lambda>\lambda_*=\frac{\rho_s}{\rho_a},\qquad \text{for pressure lifting} \tag{15}$$

or

$$\eta>\eta_*=\frac{4\rho_s}{3\alpha\rho_a},\qquad \text{for friction lifting} \tag{16}$$

3. Results

The discovery of analogous phenomena on Mars stimulated current interests in the particle emission and mass transport caused by dust devils (Neakrase and Greeley, 2010). In this section, we will use the model mentioned above to investigate the possible physical mechanisms. The typical values or ranges of the parameters characterizing air, dust particles and dust devils for Earth and Mars in Table 1 are sourced from the previous works of Metzger (1999), Balme and Greeley (2006), Barlow (2008), Lorenz (2009), Kok et al. (2012), and Lorenz et al. (2014).

The ratios of pressure and friction forces to gravity, roughly reflecting the direct lifting effects of the horizontal aerodynamic force, are plotted in Figs. 2 and 3. Under both terrestrial and martian conditions, the relationships of $\lambda\ll\lambda_*$ and $\eta>\eta_*$ hold in most cases. In other words, pressure force is too weak to lift particles but friction force is just the opposite. This is a theoretical confirmation of the friction lifting observed by Balme et al. (2003). Some similar dust emission mechanisms induced by shear stresses were also suggested elsewhere (Klose and Shao, 2013; de Vet et al., 2014). The pressure force computed by (8) will be hardly larger than the gravity, even the more realistic pressure profiles than (4) are introduced. This result seems contradictory to the vertical "ΔP" effect for an impermeable surface investigated by Balme and Hagermann (2006). The partial derivative of p with respect to z was neglected in order to solve the strongly non-linear Navier–Stokes Eq. (1) as accurately as possible. For a fully developed flow, this conventional method has been frequently proven valid. Eqs. (4)–(6) cannot provide any information on the vertical