



Short communication

Heat transfer coefficients of natural volcanic clasts

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ABSTRACT

Heat transfer coefficients used in numerical simulations of volcanic eruptions are typically borrowed from industrial settings where the coefficients are well determined for non-permeable, machined (spherical) materials. Volcanic clasts, in contrast, are permeable and have irregular shapes. We performed a series of laboratory experiments to determine heat transfer coefficients for natural volcanic particles. We measured the surface and interior temperatures during cooling at wind speeds ranging from 0 to 10 m/s. We also measured the permeability and density of the particles. We find that the permeability of the particles has little effect on clast cooling. In the absence of any wind, heat loss occurs by free convection, and we find no relationship between the heat transfer coefficient and particle density. However, for non-zero Reynolds numbers (finite wind speed), the heat transfer coefficient decreases with increasing porosity. We obtain a correlation for the dimensionless heat loss, or Nusselt number, of the form $Nu = 2 + aRe^{1/2}Pr^{1/3}$ where a is a density dependent coefficient given by $a = 0.00022\rho + 0.31$, with ρ in kg/m³, and Re and Pr are the Reynolds number and Prandtl number, respectively. Compared with non-porous particles, heat transfer coefficients for natural pumice clasts are reduced by a factor of 2–3 for particles with similar Re . Numerical simulations show that this leads to an increase in depositional temperature by 50–90 °C.

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1. Introduction

Heat transfer from particles to the surrounding gas during explosive volcanic eruptions affects the buoyancy of the gas–particle mixture and the gas pressure (e.g., Woods and Bursik, 1991). Thus the rate of heat transfer can influence the runout of pyroclastic density currents and elutriation of fine ash. The time scale over which particles cool also affects their degassing (Hort and Gardner, 2000), oxidation (Tait et al., 1998), expansion and quenching (Kaminski and Jaupart, 1997). For these reasons, numerical simulations of pyroclastic density currents and explosive eruptions often include models for particle–gas heat transfer (e.g., Dobran et al., 1993; Neri and Macedonio, 1996; Darteville et al., 2004; Dufek and Bergantz, 2007a).

Heat transfer properties are typically characterized by a so-called “heat transfer coefficient”, and are usually measured for spherical, non-porous particles (e.g., Mallory, 1969; Touloukian and Ho, 1972). In contrast, natural volcanic particles are irregular in shape and porous. Particle shape can alter heat transfer coefficients by changing the properties of the thermal boundary layer around particles across which heat is conducted. Porous particles may also alter heat transfer coefficients by allowing increased airflow through the particle pores, thereby expediting cooling.

Here we performed a series of laboratory experiments to determine the sensitivity of volcanic particle heat transfer coefficients to variations of permeability and density. We find values that can differ by factors exceeding 3 compared with standard engineering values for spherical particles. We also present an example numerical simulation in which we assess the role of error or uncertainty in the heat transfer coefficient on the depositional temperature of centimeter-sized clasts.

2. Samples

We measured heat transfer coefficients for a range of natural volcanic particles to encompass different densities and permeabilities. We also made the same measurements on glass spheres in order to compare our results with well-established literature values (e.g., Whitaker, 1972).

The volcanic samples are air fall from the ~850 BP Glass Mountain eruption at Medicine Lake volcano, California (numbered samples), and basaltic scoria from Coso, California (Scoria 1 and 2). Sample properties are summarized in Table 1 and photographs of particles are shown in Fig. 1.

3. Methods

Heat transfer coefficients were measured by recording the cooling rates of the particles shown in Fig. 1 and listed in Table 1. A 1 mm diameter thermocouple wire was inserted into a 1 mm diameter hole drilled into

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Table 1
Properties of volcanic clasts and glass beads.

Sample	Density (kg/m ³)	c_p (J/kg K)	r_c (m)	$K \times 10^{14}$ (m ²)
1	830	826	0.00895	2.17
2	593	815	0.00782	1.78
3	846	817	0.00895	1.29
6	1,450	853	0.00755	<0.02
7	982	826	0.00874	1.49
11	720	835	0.00914	0.05
14	726	851	0.00831	1.06
16	1,290	835	0.00620	0.05
20	1,500	859	0.00807	<0.02
21	1,630	856	0.00807	<0.02
22	2,510	834	0.00659	<0.02
Scoria 1	709	865	0.00853	8.54
Scoria 2	685	860	0.00895	107
Glass bead	2,390	818	0.00805	<0.02

the interior of each sample. We heated samples to 200 °C in a convection oven. Once the internal temperature reading from the thermocouple was steady, we removed the sample from the oven and recorded its cooling. We monitor internal temperature with the thermocouple and the surface temperature with an infrared camera (FLIR A3280). We report average surface temperatures using factory calibration. Sampling rate was 1 s⁻¹ for both temperature measurements.

To simulate the motion of the particles relative to the gas phase, we used a fan to produce different wind speeds and held the particles fixed in space in a wire cage. For each particle, temperature measurements were recorded at four wind speeds ranging from 0 to 10 m/s. To measure the velocity of the airflow past the particle, a velocimeter was placed on the wire stand used to hold the particle

prior to the particle being removed from the oven. The fan was turned on and the wind speed was recorded and averaged over a period of 30 s. The velocimeter was then removed so as not to interfere with the flow past the particle. Temperature measurements were recorded for 200–500 s, depending on the observed cooling.

The heat transfer coefficient, H , is defined from

$$q = HA_s(T - T_\infty),$$

where q is the heat flow from the particle, A_s is the particle surface area, T is the mean particle temperature in °C, and T_∞ is the ambient temperature. To calculate H from our temperature measurements, we assume a lumped capacitance model (e.g., Incropera et al., 2006) so that the heat transfer coefficient can be calculated from

$$H = -\frac{\rho c_p V}{A_s t} \ln \left(\frac{T - T_\infty}{T_i - T_\infty} \right) \quad (1)$$

where ρ is the density of the particle, c_p is the specific heat, V is the volume, t is time, and T_i is the initial temperature. The lumped capacitance model assumes that the particle temperature is close to uniform and that cooling is limited by heat loss from the particle surface.

The lumped capacitance model is strictly valid for Biot numbers

$$Bi = \frac{H r_c}{k_p} \ll 1 \quad (2)$$

where r_c is a characteristic particle dimension, and k_p is the thermal conductivity of the particle. This dimensionless group can be interpreted as the ratio of the boundary layer thermal resistance to the internal thermal resistance of the solid. In our experiments, Bi



Fig. 1. Particles for which we measured heat transfer coefficients. Properties are listed in Table 1. In some particles, the hole into which the thermocouple was placed can be seen.

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