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Thermodynamic Effects on Particle Movement: Wind Tunnel Simulation Results

NIU Qinghe[1, 2, 3], QU Jianjun[1, 2, 3], ZHANG Kecun[1, 2, 3], LIU Xianwan[1, 2, 3]

(*1. Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China; 2. Dunhuang Gobi and Desert Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Dunhuang 736200, China; 3. Gansu Center for Sand Hazard Reduction Engineering and Technology, Lanzhou 730000, China*)

Abstract: Sand/dust storms are some of the main hazards in arid and semi-arid zones. These storms also influence global environmental changes. By field observations, empirical statistics, and numerical simulations, pioneer researchers on these natural events have concluded the existence of a positive relationship between thermodynamic effects and sand/dust storms. Thermodynamic effects induce an unsteady stratified atmosphere to influence the process of these storms. However, studies on the relationship of thermodynamic effects with particles (i.e., sand and dust) are limited. In this article, wind tunnel with heating was used to simulate the quantitative relationship between thermodynamic effects and particle movement on different surfaces. Compared with the cold state, the threshold wind velocity of particles is found to be significantly decrease under the hot state. The largest decrease percentage exceedes 9% on fine and coarse sand surfaces. The wind velocity also has a three-power function in the sand transport rate under the hot state with increased sand transport. Thermodynamic effects are stronger on loose surfaces and fine particles, but weaker on compacted surfaces and coarse particles.

Keywords: thermodynamic effect; threshold wind velocity; drifting sand flux structure; sand transport rate; wind tunnel simulation

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1 Introduction

Sand/dust storms are some of the main hazards in arid and semi-arid zones. These storms also influence global environmental changes such as climatic and ecological changes (Martin, 1990; Coale *et al.*, 1996; Wang *et al.*, 2000; Watson *et al.*, 2000; Zhuang *et al.*, 2001; Dong, 2002; Mao *et al.*, 2002; Wang *et al.*, 2002; Shi and Zhao, 2003; Wang and Fang, 2004; Han *et al.*, 2006a; 2006b; Li, 2009). The essence of sand/dust storms is the process of particle initiation, transportation, and sedimentation under wind and local thermodynamic effects. Pioneer researchers in this field have deduced the physical mechanisms of particle initiation and the factors affecting it. They have concluded that slope, humidity, salinity, vegetation, particle size, grain size distribution, particle shape, surface crust, clay, silting soil, and organic content all increase the threshold wind velocity (Bagnold, 1941; Chepil, 1951; Greeley *et al.*, 1974; Svasek and Terwindt, 1974; Howard, 1977; Nickling and Ecclestone, 1981; Allen, 1982; Gillette *et al.*, 1982; Iversen and White, 1982; Willetts, 1983; Hotta *et al.*, 1985; Buckley, 1987; Nickling, 1988; Gillette and Stockton, 1989; McKennaneuman and Nickling, 1989; Iversen and Rasmussen, 1994; Dong and Li, 1998; Li and Ni, 1998; Sherman *et al.*, 1998; Qi *et al.*, 2001; Liu and Dong, 2002; Musick and Gillette, 2006; Dong and Qian, 2007; Han *et al.*, 2009; Sun, 2010; Wu *et al.*, 2010; Lu *et al.*,

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Corresponding author: QU Jianjun. E-mail: qujianj@lzb.ac.cn

2011). Drifting sand flux is the specific representation of particle transport. Previous studies have indicated that the sand flux exponentially decreases with increased height on sandy surfaces (Chepil, 1945; Sharp, 1964; Zou *et al*., 1992; Liu, 1995; Sorensen and McEwan, 1996; Dong *et al.*, 2003; Dong *et al.*, 2006; Wang *et al.*, 2008; Ren and Wu, 2011). Drifting sand flux on different surfaces have also been compared, and a unique 'elephant nose' effect on the flux distribution with the height has been revealed. Apparently, the maximum flux is not at the bottom but at a proper height, as determined by surface characteristics and wind velocity (Zou *et al.*, 1995; Dong *et al.*, 2002; Qu *et al.*, 2005; Huang *et al.*, 2007; Wang *et al.*, 2008; Zhang *et al.*, 2008a; 2008b).

Thermodynamic effects on sand/dust storms have been extensively researched. Based on a study on aeolian dust and dust deposits, Pye (1987) has indicated that dust commonly develops where the ground surface strongly heated during the day forms a layer of superheated air just above this surface. Many subsequent reports have confirmed this theory (Arens, 1996; Butterfield, 1999; Shen and Wei, 1999; Sun and Yao, 2002). A local unsteady stratified atmosphere caused by thermodynamic effects has also been considered as one of the main conditions of a sand/dust storm breakout (Xia and Yang, 1996; Qian *et al.*, 1997). Strong and very strong sand/dust storms mostly occur during afternoons and evenings when the highest daytime temperature occurs and roughly account for 70% of the whole day (Liu, 1995; Qian *et al.*, 1997; Yang *et al.*, 2003; Man, 2010). After analyzing the role of surface heating fields in spring sand/dust storms in Northwest China, Wang and Liu (2003) have concluded that the upstream area is a heat sink area, whereas the sand/dust storm area is a heat source area. Jiang *et al.* (2010) have analyzed the influence of the surface heating flux on the numerical simulation results of sand/dust storms, and proposed that this flux enhances the storm intensity. The main mechanism of a surface heating flux influencing sand and dust particles involves leading a mixed layer in the lower atmosphere, and enhancing the downward transportation of momentum. The result is increased surface wind velocity.

These above reports based on field observations, empirical statistics, and numerical simulations reveal that thermodynamic effects are positively correlated with sand/dust storms. The unsteady stratified atmosphere caused by local thermodynamic effects influences the sand/dust storm process. However, the relationship between thermodynamic effects and particle movement, including threshold wind velocity, drifting sand flux structure, and sand transport rate, is not fully understood. In the present study, a heating experiment in a wind tunnel was simulated to analyze the changes in threshold wind velocity, drifting sand flux structure, and sand transport rate under hot and cold states. The relationship between thermodynamic effects and particle movement was also discussed. The results showed the relationship of thermodynamic effects with aeolian sand movement and sand/dust storms.

2 Experimental Layout and Parameter Measurements

2.1 Experimental layout

The experiments were conducted in the field wind tunnel of the Key Laboratory of Desert and Desertification, Chinese Academy of Sciences. To simulate thermodynamic effects, an elevating wooden frame was placed in the 1.2 m × 1.2 m experimental section of the wind tunnel (starting from x = 6 m) (where x is the distance to air blower). Sixteen 275 W infrared lamps were hung below the frame for the rapid heating of the sand materials on the bed of the wind tunnel (Fig. 1).

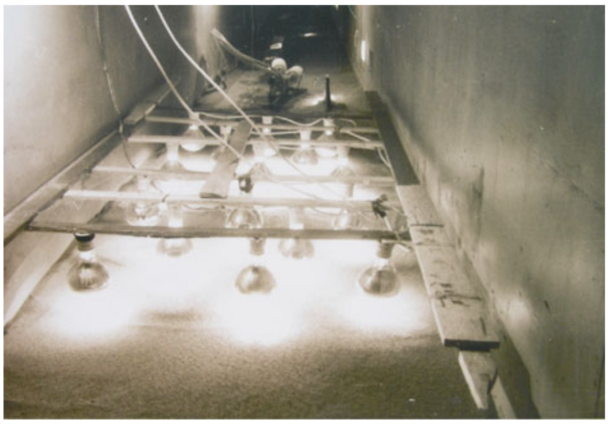


Fig. 1 Schematic diagram of experimental heating layout in wind tunnel

The experiments were performed in mid-November when the air temperature was 0℃ or lower. Hence, the interaction between hot and cold airstreams was setup to be very intense to simulate the hot and cold airstream interaction in spring, which was the high-frequency season of sand/dust storms. To avoid heat loss and to heat the surface particles to 50℃ as rapidly as possible, two layers of a 2-mm glass-fiber cloth were used to cover the lamp hanger on the front side and at the back. When the surface particles were heated to a specific temperature, the lamps were turned off, and the lamp hanger was rapidly raised to conduct the sand movement experiments. The sand transport bed surface was sand fixed by emulsion, which can simulate the natural sandy transport surface and prevent the transport surface sand movement from influencing the sand transport rate calculation of the samples.

For detailed observations of particle movement initiation, a 1.3-m fixed focal lens installed at the top of wind tunnel was used for visual observations. Once the particles were set in motion, the rotational speed of the electric motor producing wind power was adjusted to a relative constant. The indicated wind velocity was recorded by using a compensating micropressure gauge, thereby yielding the threshold wind velocity $U_{\infty t}$. To avoid the randomness of particle movement over the bed, the threshold velocity was thrice recorded and the mean ($\overline{U}_{\infty t}$) was calculated.

To measure the drifting sand flux and sand transport rate in the sand blowing and sand/dust storm simulated experiments, 10 m/s, 15 m/s, and 20 m/s wind velocities were employed. Mechanical sand traps (2 cm × 2 cm × 10 layers) designed by our research group were used to trap the sand. Sand blowing and sand/dust storms are the different processes of particle transport. To simulate these processes, different measurement locations were used. The sand blowing measurement location was behind 1 m (x = 9 m) the experimental sample, and the sand/dust storm location was behind 10 m (x = 18 m). The bed surface was undisturbed during the experimental processes. The coarsening of the bed surface itself led to gradual increases in the threshold velocity, in accordance with coarsened sand surfaces in nature.

To measure temperature changes on the sand surface as well as in the middle and lower layers, thermocouples were positioned at –2 cm, 0 cm, 10 cm from the bed surface. A digital voltmeter was used to measure and record temperature. A thermocouple probe was placed in a 15 cm-long and Ø20 mm plastic tube to ensure the stability of the readings in the sand blowing environment. However, for the temperature measurements on the sand surface and at 2 cm below the surface, thermocouples were directly placed on the sand surface and buried in the sand, respectively.

2.2 Parameter measurements

The sand samples used in the experiments included fine, semi-fixed dune, fixed dune, and coarse sands, as well as fine-Gobi sandy gravel. These samples represented the common surface types in the arid and semi- arid regions of China. The grain sizes were determined by the sieve method, and the residue was analyzed by the sedimentation method. The results are shown in Fig. 2.

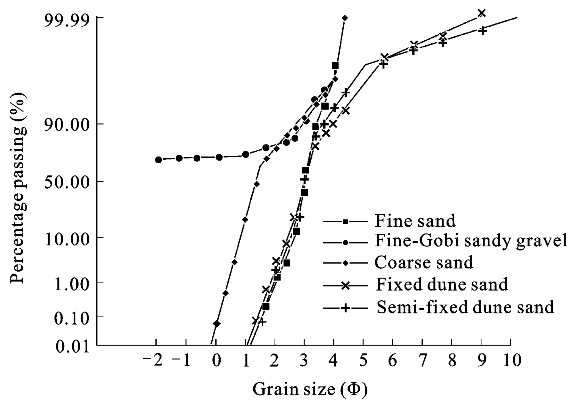


Fig. 2 Analysis of sample grain sizes

Figure 2 shows large differences in grain sizes among the various samples. The coarse particle fraction can be divided into two types. The first type was dominated by the saltation component (1Φ ≤ d ≤ 3.32Φ), including fine, semi-fixed dune, fixed dune, and coarse sands. The second type was dominated by the creep component (d < 1Φ), including fine-Gobi sandy gravel. The fine particle fraction can also be divided into two types. The first type included fine sand, coarse sand, and fine-Gobi sandy gravel with less suspension components (d > 3.32Φ). The second type included semi-fixed and fixed dune sands with relatively abundant suspension components.

3 Results

3.1 Threshold wind velocity

Table 1 lists the threshold wind velocities of the five samples under cold and hot states. Table 1 shows that the threshold wind velocity was generally lower in the

Table 1 Threshold wind velocities ($\overline{U}_{\infty t}$) of samples under cold and hot states

	Fine sand		Coarse sand		Semi-fixed dune sand		Fixed dune sand		Fine-Gobi sandy gravel	
	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot
$\overline{U}_{\infty t}$ (m/s)	6.65	6.00	8.50	7.73	6.88	6.86	6.74	6.47	10.87	10.72

hot than in the cold state, with fine sand and coarse sand having the maximum reduction value of 9% or more. However, the reduction was lower than 4% for fixed dune sand, semi-fixed dune sand, and fine-Gobi sandy gravel. Evidently, the absolute values of the threshold wind velocity depended on the particle size, content, and compactness. The threshold wind velocity in the cold-hot states followed the trend of fine-Gobi sandy gravel > coarse sand > semi-fixed dune sand > fixed dune sand > fine sand.

3.2 Drifting sand flux structure

Figure 3 and Fig. 4 show the drifting sand flux structures of the different samples under cold and hot states in the sand blowing and sand/dust storm simulations, respectively. The percent contents (q) were obtained by the curve-fitting method following the rule of the structure of sand flow distribution, and were then plotted. Fine-Gobi sandy gravel had no curve under the hot state because the surface coarsened before the experiment under the cold state. As shown in Fig. 3, most hot-state percent content-height (q-z) curves lie below the cold-state curve of the same wind velocity during the drifting sand simulation experiment. Hence, the percent content decreased at the bottom of the drifting sand flux under the hot state, which became more uniform in height distribution. However, the opposite was true for coarse sand when the wind velocity was 10 m/s, for fine sand when the wind velocity was 15 m/s, as well as for fixed dune sand and fine-Gobi sandy gravel when the wind velocity was 20 m/s. This may be associated with the decreased particle content in the drifting sand flux because of the sample surface coarsened. However, during the sand/dust storm simulation experiment, the top to bottom distribution of the q-z curve did not depend on the cold and hot states. Only semi-fixed dune sand exhibited a cold-top and hot-bottom distribution pattern. Therefore, thermodynamic effects rapidly decreased with increased distance of the heating area. Compared Fig. 3 with Fig. 4, under the same condition, the range of q in the curve largely decreased or only reached 1/2 to 1/4 of the sand blowing cases. This finding indicated that the drifting sand flux became more uniform in height distribution during the sand/dust simulation experiment.

3.3 Sand transport rate

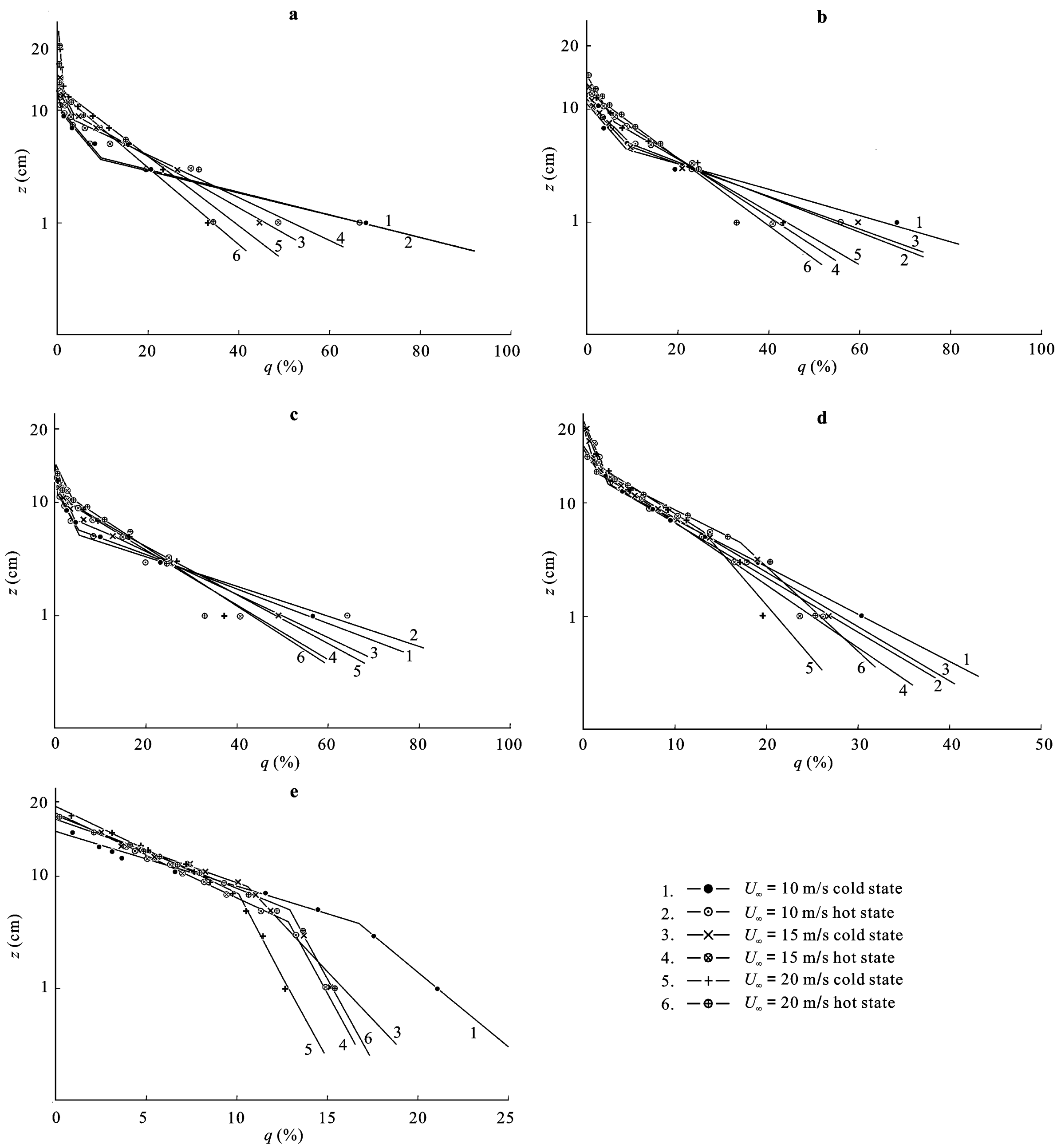
Figure 5 shows the results of the changes in the sand transport rate with the wind velocities under cold and hot states. The sand transport rates Q and wind velocity U_∞ satisfy the function:

$$Q = AU_\infty^3$$

where A is a constant coefficient and changes with the samples and heating states. A is greater under the hot than under the cold state, which means that the sand transport rate is greater under the hot than under the cold state. The sand transport rates of fine, semi-fixed, and coarse sands were larger under the cold than under the hot state (up to 30% or more). In contrast, the rates of fixed dune sand and fine-Gobi sandy gravel were slightly larger under the cold state than under the hot state.

3.4 Analysis of temperature changes near bed surface

Figure 6 shows the temperature changes near the bed surface with wind velocity and duration. Except for fine-Gobi sandy gravel, the temperature changes were roughly similar under various wind velocities at 2 cm below and 10 cm above the surface. The subsurface temperature slowly changed and almost formed a vertical distribution. About 20 s after the machine was started, the temperature below the surface still rise. The temperature above the surface very rapidly changed. However, once the machine was started, the temperature rapidly dropped. The temperature at 10 cm above the surface or higher showed a similar distribution trend. On the same curve, they tended to stabilize rapidly, and became close to the lower air-stream temperature in the



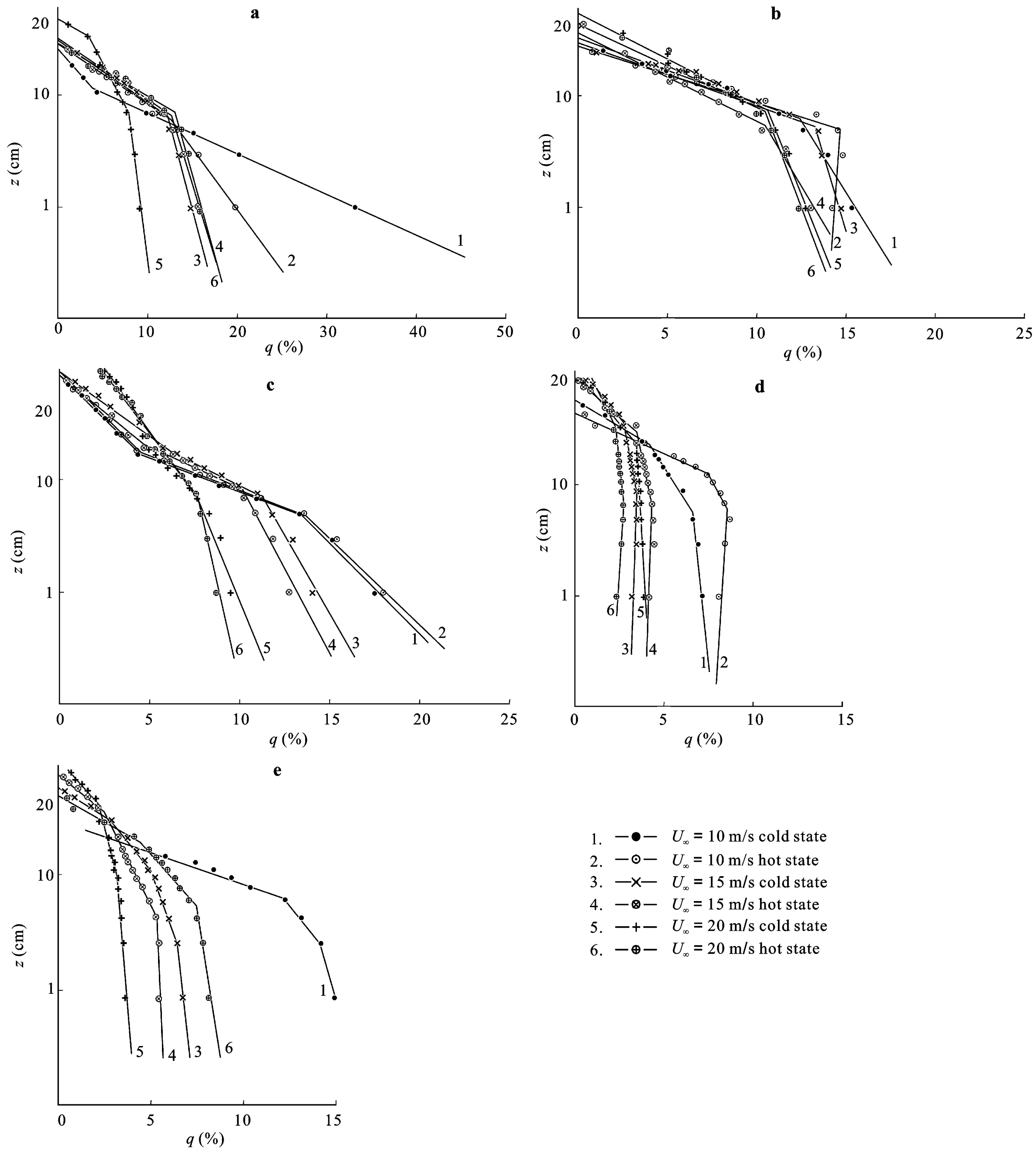
a. fine sand; b. semi-fixed dune sand; c. fixed dune sand; d. coarse sand; e. fine-Gobi sandy gravel;
z is hight; *q* is pecent content; U_∞ is wind velocity

Fig. 3 Drifting sand flux structures during sand blowing simulation experiment (sand trap located at distance of 9 m to air blower)

wind tunnel. Hence, under the simulated conditions, the temperature above the surface was only maintained for a very short time (10 s). Among the different samples, fine and coarse sands were the most easily warmed and cooled; fine-Gobi sandy gravel was not easily warmed and cooled; and semi-fixed dune and fixed dune sands were not easily warmed and rapidly lost heat. Therefore, the specific heats of fine and coarse sands were low, those of semi-fixed and fixed dune sands were higher, and that of fine-Gobi sandy gravel was the highest.

4 Discussion

Contrast experiments of sand movements (i.e., threshold wind velocity, drifting sand flux structure, and sand transport rate) under hot and cold states were performed



a. fine sand; b. semi-fixed dune sand; c. fixed dune sand; d. coarse sand; e. fine-Gobi sandy gravel;
z is hight; q is pecent content; U_∞ is wind velocity

Fig. 4 Drifting sand flux structures during sand/dust simulation experiment (sand trap located at distance of 18 m to air blower)

on the five most common surface particle types in arid and semi-arid areas in China. The threshold wind velocity decreased, the relative sand content near the surface of the drifting sand flux deceased, and the sand transport rate increased after heating. The thermo-dynamic effects on particle movements were examined, and the following conclusions were drawn. First, when the ground surface is heated, the air on the ground is also heated and rises. Consequently, the vertical up velocity increases, the moving particles are driven higher, and the drifting sand flux becomes more uniform in vertical distribution. Second, air between the particles expands after heating, increasing the uplifting force on the surface particles. The particle force equilibrium changes, and the

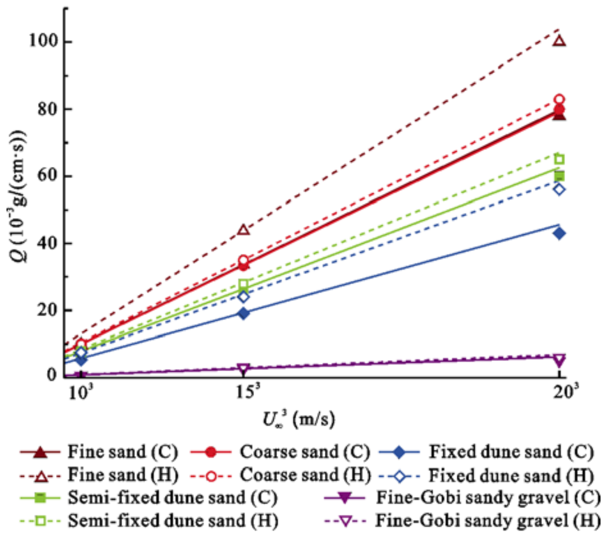


Fig. 5 Sand transport rate (Q) of experiment samples under hot (H) and cold (C) states

particles are moved by a relatively smaller horizontal force. In other words, the particles move at a relative lower wind velocity, and the sand transport rate increases at the same wind velocity.

The threshold wind velocities and sand transport rates of the five different surface types under hot and cold states were compared. These movement parameters largely changed for fine, coarse, and semi-fixed dune sand surfaces, but only slightly changed for fixed dune sand and fine-Gobi sandy gravel. This result is related to the surface character. Fine, coarse, and semi-fixed dune sands are looser and more porous. Consequently, air has a stronger uplifting force on them after heating, enabling the particles to move easier. On the other hand, fixed dune sand has a tighter structure and minor porosity. Air in the pores between the particles restrictedly expands, and the uplifting force is also limited. Hence, particle initiation becomes more difficult. Although the surface of fine-Gobi sandy gravel is not very tight, the grain size is much larger, and the threshold wind velocity is higher. As a result, the effect of the uplifting force on the particle movement is minor.

Based on the above analyses, thermodynamic factors indeed affected particle movement, although the effect was limited to fine particles. The drifting sand flux also changed when the surface coarsened during the drifting sand simulation experiment. A comparison of drifting sand fluxes during the drifting sand and sand/dust storm simulations also revealed that the thermodynamic effect was obvious near the samples, but not away from them. Hence, long-distance transport as well as turbulent mixing and exchange more significantly affect particle movement than thermodynamic effects.

Temperature changes near the surface indicate that fine and coarse sands with lower specific heats were easy to heat, and therefore easy to move. An unsteady stratified atmosphere forms, and the sand/dust storm eventually breaks out. These phenomena are also some of the main reasons for the high-frequency, short-lived local sand/dust storms in and around aeolian desert regions.

5 Conclusions

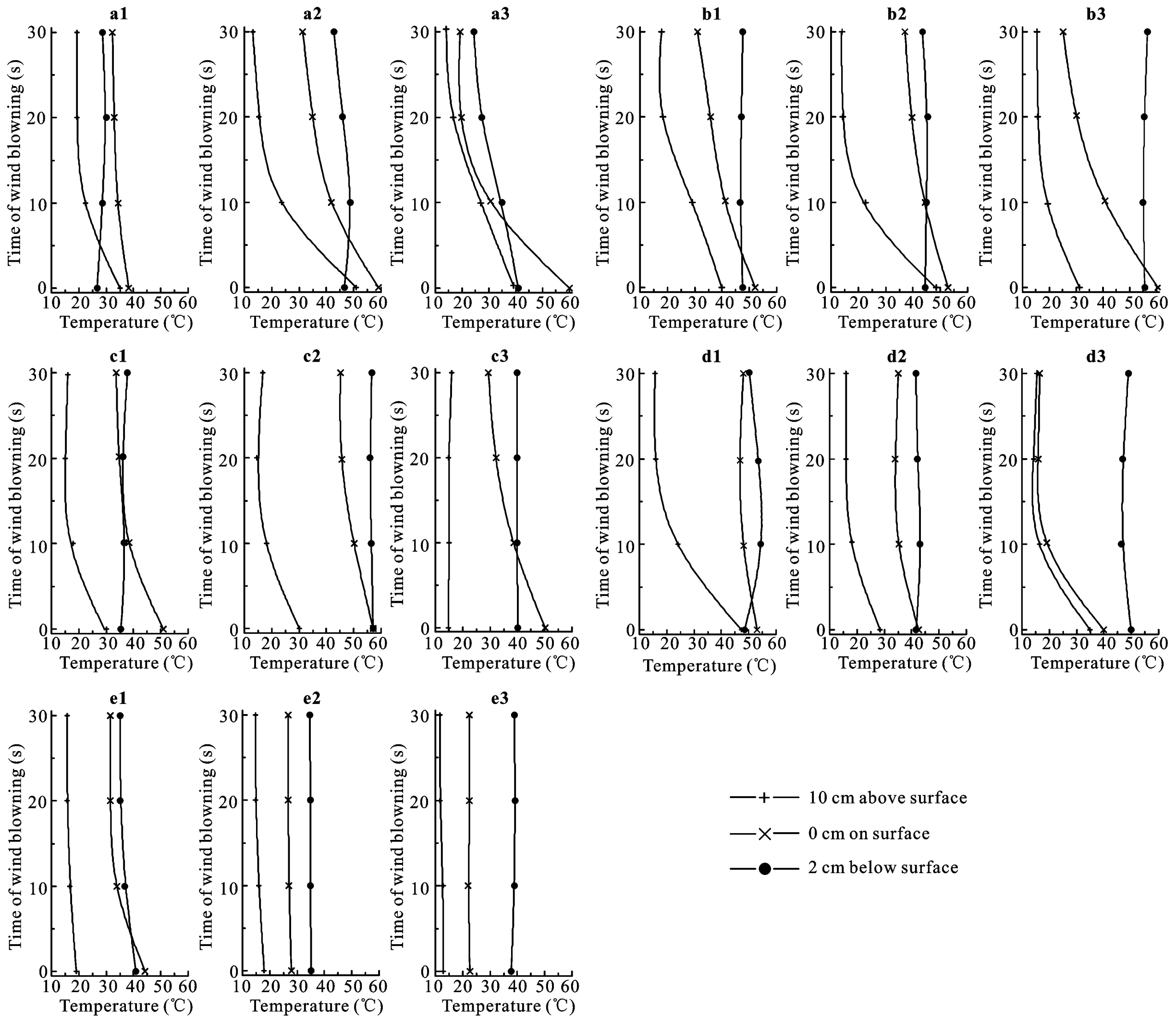
Thermodynamic effects on particle movement were examined by simulation experiments in a wind tunnel, and the following conclusions were drawn.

(1) Thermodynamic effects on sand/dust storms include increased surface wind velocity caused by an unsteady stratified atmosphere, and strengthened uplifting force caused by air, resulting in increased uplifting height of particles and more uniform drifting sand fluxes. Air in pores expands during heating and uplifts particles to decrease the threshold wind velocity and increase the sand transport rate.

(2) Under the hot state, the threshold wind velocities of all particles from different surfaces decrease, with the largest decrease percentage exceeding 9%. Wind velocity has a three-power function in the sand transport rate under hot and cold states. The sand transport rate increases under the hot state.

(3) Thermodynamic effects are stronger on loose surfaces and fine particles, but are weaker on compacted surfaces and coarse particles.

(4) The results of the present study are valuable for controlling sand/dust storms. Soil structure must be improved by increasing its adhesion to decrease the sand transport rate under hot states. Loose sand and mine tailing wastelands should also be covered with gravel to increase the threshold wind velocity and decrease the sand transport rate. Agricultural lands should be protected as well. Irrigation before sand/dust storms can increase the tightness of soil and rapidly decrease the surface temperature, thereby decreasing particle initiation and transport.



a1. Fine sand (U_∞ = 10 m/s); a2. Fine sand (U_∞ = 15 m/s); a3. Fine sand (U_∞ = 20 m/s);
b1. Semi-fixed dune sand (U_∞ = 10 m/s); b2. Semi-fixed dune sand (U_∞ = 15 m/s); b3. Semi-fixed dune sand (U_∞ = 20 m/s);
c1. Fixed dune sand (U_∞ = 10 m/s); c2. Fixed dune sand (U_∞ = 15 m/s); c3. Fixed dune sand (U_∞ = 20 m/s);
d1. Coarse sand (U_∞ = 10 m/s); d2. Coarse sand (U_∞ = 15 m/s); d3. Coarse sand (U_∞ = 20 m/s);
e1. Fine Gobi sandy gravel (U_∞ = 10 m/s); e2. Fine Gobi sandy gravel (U_∞ = 15 m/s); e3. Fine Gobi sandy gravel (U_∞ = 20 m/s)

Fig. 6 Temperature changes near bed surface with wind velocity and duration after heating

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