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On sandstorms and energy recovery from sandstorms

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Abstract

Arid lands and some of their characteristics are reviewed. Properties of particles, and in particular of sand and sand size, are discussed. A concise account of the characteristics of sandstorms is presented. To this end, the movement of sand particles in saltation, by surface creep and in suspension is reviewed. Accumulation of blown sand particles is considered. Attention is drawn to a common misconception on dust storms and sandstorms. Concepts of wind energy extraction systems are outlined for the recovery and utilization of energy during sandstorm conditions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Dust storms; Energy; Recovery; Sand; Sandstorms; Saltation; Suspension; Surface creep

1. Introduction

Large portions of the earth are classified as arid (Fig. 1), where annual precipitation is meagre. These regions span Africa, Asia, Australia and North and South America [1]. Low rainfall is the most obvious environmental factor in an arid area. Some desert areas, like the Empty Quarter in Saudi Arabia, receive less than 10 cm of rain annually, and this rain comes in brief torrents that quickly run off the ground surface. Intense sunlight and heat are present in all arid areas. Air temperature can rise as high as 60°C during the day. Heat gain results from direct sunlight, hot blowing winds, reflective heat (the sun's rays bouncing off the sand), and conductive heat from direct contact with the desert sand and rock. The temperature of desert sand and rock averages 16–22°C more than that of the air. For instance, when the air temperature is 43°C, the sand temperature may be 60°C. The temperature in shaded areas will be 11–17°C cooler than the air temperature. Temperatures in arid areas may get as low as 10°C at night. Sandstorms occur

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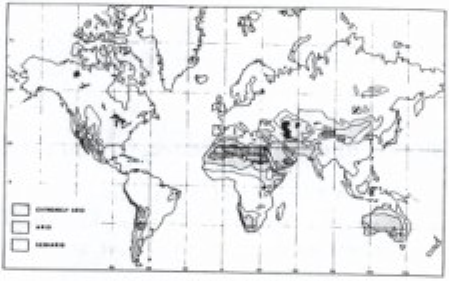

Fig. 1. Distribution of arid zones on earth [1].

frequently in most deserts. The "Seistan" desert wind in Iran and Afghanistan blows constantly for up to 120 days a year.

Sandy or dune deserts are extensive flat areas covered with sand or gravel. "Flat" is a relative term, as some areas may contain sand dunes that are over 300 m high and 16–24 km long. Trafficability in such terrain will depend on the windward or leeward slope of the dunes and the texture of the sand. Other areas, however, may be flat for 3 km and more. Plant life may vary from none to scrub over 2 m high. Examples of this type of desert include the edges of the Sahara, the Empty Quarter of the Arabian Desert, areas of California and New Mexico and the Kalahari in South Africa.

In the interiors of deserts, the observer never fails to be amazed at a simplicity of form, an exactitude of repetition and a geometric order. In places, vast accumulations of sand, weighing millions of tons, move inexorably in regular formation over the surface of the country, growing, and retaining their shape. Elsewhere, the dunes are cut to another pattern, lined up in parallel ranges, peak following peak in regular succession over a landscape so flat that their formation cannot be influenced by any local geographical features. Or again, there are smaller forms consisting of rows of coarse grained ridges even more regular than the dunes [2].

It is believed that hundreds of millions of tons of sand are being displaced annually by the action of sandstorms. One can imagine the massive amount of energy behind these movements and wish to think of a simple extraction system that absorbs the energy in sandstorms while, at the same time, helping to stop sand movements and, hence, halt desertification. The aim of this paper is to discuss some properties of sandstorms and to propose means of extracting part of this otherwise disturbing or even destructive form of energy.

2. Sand

If an object of any size, shape or material is allowed to fall from rest through any fluid, whether air, water or oil, its velocity will increase, at first with the acceleration of gravity but thereafter at a decreasing acceleration till it reaches a constant value known as the terminal velocity of fall. The reason is that the net force on the object is the resultant of the pull of gravity acting downwards and the resisting force of the fluid acting always in a direction opposite to that of the motion. As the velocity of the motion increases, so does the resistance against that motion, till eventually the two are equal. No net force any longer acts on the object which, therefore, moves at a constant speed.

The downward force of gravity depends on the volume of the object and its density. The resisting force depends on the frontal area exposed to the fluid, on the shape of the object and on its speed through the fluid. Hence, since natural solid particles are of irregular and haphazard shape, the particles or grains will not have the same rate of fall.

Small particles in air, those constituting thin smokes and hazes, do not fall at all due to the motion of air. On the other hand, the velocity of the wind is never constant. The short period of variation of speed, or the gustiness, is due to the internal movements of the air. As these movements, or eddies, circulate in all directions, close to the ground, the upward and downward components of the eddy velocity have been found to be less than the components in other directions. Although the ratio of the upward eddy velocity to the mean velocity of the wind is very variable, an average figure of 0.2 for this ratio is probably not far off [3]. If, therefore, there are solid particles in the air whose terminal velocities of fall are less than 20% of the mean velocity of the wind, some of these particles may be carried upwards and may remain for a time in partial suspension. On the other hand, larger particles with greater terminal velocities will remain on or near the ground.

Now, it can be shown that when sand is being driven by the wind, the grains rarely rise higher than 1 m above the ground [2] and that the average height is less than 1 m. Also, it can be shown that the wind velocity, as measured at this height, which is just strong enough to set the grains on the ground in motion, is in the neighborhood of 5 m/s. Taking as a rough estimate the value of $5 \times 0.2 = 1$ m/s as the maximum upward velocity of the eddy currents in this wind, it can be shown that sand grains having this velocity of fall have a diameter of about 0.2 mm.

When erodible particles are present on a bare soil surface, soil movement begins when the wind velocity at 30 cm above the surface exceeds 20 km/h [1] (5.6 m/s). The wind velocity nearly attains its free flow velocity at a height of 1 m above the surface. Dust particles smaller than 0.02 mm are highly resistant to movement by wind until they are disturbed by a saltation process.

When samples of natural sand are analyzed by sifting, it is found that, in general, grains of one diameter predominate and that the weights of sand of diameters both larger and smaller fall off rapidly as the diameter departs from the peak value. In the finest wind blown sands, the predominant diameter is never less than 0.08 mm. Usual values, depending on the locality, lie between 0.3 and 0.15 mm. We can, thus, define the lower limit of size of sand grains, without reference to their shape or material, as that at which the terminal velocity of fall becomes less than the upward velocity of eddy currents. Particles of smaller size tend to be carried up into the air and to be scattered as dust. The upper limit of sand size is that at which a grain resting on the surface ceases to be movable either by the direct pressure of the wind or by the impact of other moving grains.

Any substance consisting of solid non-cohesive particles, which lie within these limits of size, may be classified as 'sand'. Such substances all possess one peculiar characteristic: alone of all artificial or natural solids, they have the power of self-accumulation by utilizing the energy of the wind to collect their scattered components together into definite heaps, leaving the intervening country free of grains. They can do this in open locations, unsheltered by windbreaks other than those of their own making, and the heaps, or dunes, can retain their identity and can move about from place to place.

In air, for the normal wind speeds prevailing on the earth's surface, the critical diameter of sand is about 0.2 mm; and grains of this size are found to predominate in the finest sand that collects at the tops of dunes [2].

3. Sandstorm, dust storm and sand transport

A popular misconception exists regarding sandstorms due to a failure to distinguish sand from dust. When, in any arid country, after a spell of calm weather, a strong wind begins to blow from a new direction, the air becomes charged with a mist of small particles. Where the surface is alluvial, with little or no sand on it, such as in Iraq or the country around Khartoum, the dust rises in dense clouds to a height of several thousand feet, and the sun is obscured for a long period (see Fig. 2) [4]. This is obviously a dust storm, though it is often wrongly designated [5,6] by the possibly more thrilling and clean term "sandstorm".

On the other hand, in an erosion desert, the only free dust consists of those fine rock particles which have been loosened by weathering since the last wind blew and have, therefore, not been carried away. In such country, the wind produces, for the first hour or so, a mist consisting of both dust and sand. Later, although the wind velocity is no less, the mist disappears. But the sand still continues to drive across the country as a thick low flying cloud with a clearly marked upper surface. The air above the sand cloud becomes clear, the sun shines again, and peoples' heads and shoulders can often be seen projecting above the cloud [2]. Where the ground is composed of coarse grains, pebbles or large stones, the top of the cloud may be 2 m above the ground, but it is usually less. Where the surface consists of fine sand, such as that of a dune, the height of the sand cloud is noticeably lower [7–9].

The bulk of the sand movement takes place considerably nearer the ground than the visible top of the cloud. Evidence of this is given by the effects of the sand blast on posts and rocks projecting from the ground. The erosion is greatest at ground level, and it is inappreciable at a height of 50 cm [10–12].

Fig. 2. Frontal cloud of dust storm.

The total sand flow q consists of saltation (jumping) q_s together with the surface creep q_c (which consists of sliding or rolling along the surface, without jumping) and a small remainder q_s which may be carried in suspension. Measurements, both in the wind tunnel and the open, indicate that the surface creep q_c is approximately equal to a quarter of the whole sand flow q [13–15]. The effect of true suspension can be neglected, except perhaps in the case of a very dusty sand, since its contribution to total sand flow appears to be very small indeed [16–18]. It may be shown [2] that the sand flow q varies as the cube of the excess of the wind velocity over and above the constant threshold velocity at which the sand begins to move. Fig. 3 [2] illustrates how the flow rate of sand carried by the wind varies with wind speed. Accordingly, when the wind speed drops, the sand cloud disappears with it, indicating that this is a true sand storm. Within Saudi Arabia, winds average 3–5 m/s and can reach over 30 m/s.

Thus, of the total sand in motion in the air, about three quarters moves in saltation and a quarter in surface creep. The surface creep consists of the slow jerky advance of the surface grains, which are knocked along the surface by the impact of the descending saltation rather than being ejected upwards into the air stream. An impact by a grain from the saltation can move a surface grain in this manner, even though the latter is six times its own diameter. Hence, a saltation of fine grains can maintain a surface creep over a bed composed of grains far too large to be moved by direct action of the wind [19].

Furthermore, owing to the reduced drag consequent on the change in the motion of the grains from splashing to bouncing, a given wind can drive sand over a hard immobile surface at a considerably greater rate than is allowed by the loose sand surface. This observation is of great

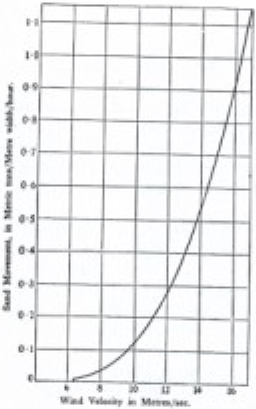

Fig. 3. Variation of the flow rate of sand with wind speed [2].

importance and explains the fundamental property possessed by wind blown sand of accumulating on areas already sand covered in preference to the surrounding country. From the above, it appears that a flat sand surface must be unstable because of the local sand removing action of saltation. This differential effect of the saltation is due to its sensitivity to changes in the angle of incidence between it and the surface.

4. Accumulation

Accumulation of sand can conveniently be classified as follows, according to the special conditions which appear to give rise to them: (a) Deposits caused by fixed obstructions in the path of the sand driving wind, for example by bushes, rocks or cliffs. These sand shadows and sand drifts are dependent for their continued existence on the presence of the obstacle and cannot move away from it. (b) True dunes. A single dune may be defined as a mound or hill of sand which rises to a single summit. Dunes may exist alone or attached to one another in colonies or dune chains. Unlike shadows and drifts, dunes can exist independently of any fixed surface feature and do, in fact, reach their most perfect development on flat featureless country. Although capable of movement from place to place, they are able to retain their own characteristic shape [20,21]. A special feature of all dunes, which have attained a certain stage of development, is the slip face, where the slope of the dune surface reaches the limit of steepness imposed by the angle of shear of the deposited material. Dunes assume two fundamental shapes: (i) the crescent dune and (ii) the seif dune.

4.1. Sand shadows behind obstacles

The material is deposited to form a sand shadow when the wind velocity is locally checked by an obstacle in its path. It will be enough to take one simple example, a single sharp cornered obstacle such is a wood packing case standing by itself on a flat open sand sheet. Since we are now dealing with air streams which are deflected from the straight path, it must be borne in mind that the direction of travel of the air and of the sand grains will not necessarily coincide. The sand grains are not readily deflected by sudden changes in the direction of the air stream and, therefore, tend to pass straight on. For this reason, it will be well to consider separately the flow of air and of sand round the obstacle.

The air both in front of and behind the obstacle is divided into two parts by a somewhat ill-defined surface of discontinuity whose approximate shape is sketched in plan and elevation in Fig. 4a [2] by dotted lines. Outside this surface, the air stream flows smoothly by, but the volume within the wind shadow of the obstacle is filled with swirls and vortices of air whose average forward velocity is less than that of the air stream outside. As we go down wind from the obstacle, the forward velocity of the air inside the shadow gradually increases, and the shadow fades away to merge eventually with the general flow of the wind [22].

The sand grains which strike the obstacle rebound off it and come to rest in the relatively stagnant air in front (Fig. 4f). When the resulting heap has grown so that its slopes stand at the limiting angle of repose (about 34°), all additional material slides down the slopes to join the sand stream passing along the side of the obstacle. The grains of this stream, as can be seen from Fig. 4a,

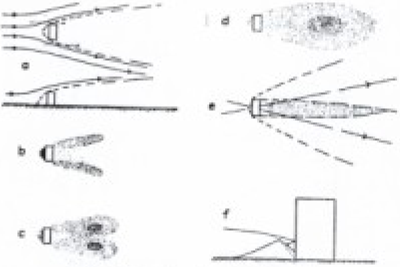

Fig. 4. Formation of sand shadows [2].

pass straight through the surface of discontinuity into the zone of lesser forward wind velocity inside. Here, they, therefore, tend to settle. Successive stages in the growth of the shadow are sketched in Fig. 4b–d. The two wings gradually coalesce as the swirls of air within the wind shadow carry the grains towards the middle.

The above refers to an ideal wind which is truly constant in direction. Usually, the shape of the shadow is modified to something more like that shown in Fig. 4e. Here, the wind is supposed to swing between two limiting directions which are indicated by the arrows. The sand shadow is confined to the space occupied by the overlap between the two limiting wind shadows.

It should be noted that as sand cannot stand at an angle steeper than the angle of repose (friction angle), the height of the sand shadow is always limited by the size of the ground plan of the wind shadow in which it is formed. Any sand which slips down the sides and protrudes beyond the boundary of the wind shadow is very soon swept away by the stronger wind outside. The size of deposit is, therefore, very sensitive to the shape of the bottom of the obstacle. A round boulder, or a bush beneath which a strong current of air can blow, will allow the formation of little or no sand shadow.

4.2. *Sand drifts between obstacles*

A sand shadow is, as its name implies, an accumulation formed in the shelter of, and immediately behind, an obstacle. A drift, on the other hand, is formed in the lee of a gap between two obstacles and is due to 'funneling', the concentration of the sand stream on the windward side from a broad front to a narrower one. Fig. 5 [2] represents two sections of a low wall with a gap between them. The wind as it flows initially is sketched in Fig. 5a. It goes over the top of the walls as well as through the gap, but the oncoming sand is unable to rise over the walls (whose extremities always remain unburied owing to their vertical ends). Hence, the sand, which arrives over a wide frontage, drifts sideways and is concentrated to pass through the gap. The sand flow through the gap must, therefore, exceed in intensity the equilibrium flow in the open.

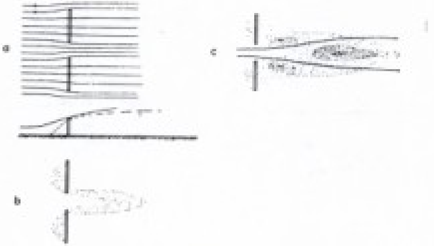

Fig. 5. A sand drift formed behind a gap [2].

The wind through the gap is also stronger, but a short distance down wind its velocity begins to slacken as the air stream merges with the general flow. So, it is inevitable that the surplus sand must be dropped from the air stream to form a growing deposit. The early stage is sketched in Fig. 5b. At a later stage, the deposit has risen to such a height as to become, of itself, an additional obstacle round which the wind is again deflected. Further oncoming sand, being deflected to a lesser degree, tends to pass straight on and is deposited on the drift in the comparative shelter of its lee side. The limit of growth is reached when the frontage of the drift, off which sand can stream away at the equilibrium rate, becomes equal to the frontage of the up wind collecting area, i.e. the frontage between the wall centers.

5. Energy extraction

Because of the fact that a dust storm is different from a sandstorm with regard to the amount of available energy and the distribution of the energy density, an effort is being made here to highlight utilization of energy from sand storms. This can be done by considering the energy in sandstorms as wind energy with high mass density.

A sandstorm is a form of sand transport system. The flow density of the moving sand stream is high close to the earth surface. Nearly all sand transport is confined to the first 50 cm above the surface.

As it was stated earlier, when erodible particles are present on a bare soil surface, soil movement begins when the wind velocity at 30 cm above the surface exceeds 20 km/h [1]. This signals the beginning of a dust or sand storm, depending on the size of particles entrained. On the other hand, the wind velocity nearly attains its free flow velocity at a height of 1 m above the surface. This indicates that the full energy of the wind is available for retrieval during a sandstorm at heights of a meter or more from the surface. It is further clear from the above discussion that the wind above the sand cloud is clear and clean.

With the advent of satellite technology, it has become a routine activity to observe winds and their properties [23] and to report related findings in the open literature. The erosion caused by wind forces, on the other hand, has been a subject of considerable research interest [24,25]. Still other researchers have studied the effect of wind erosion as related to sand blasting [26] and sand cutting [27,28]. The Internet is flooded with advertisements concerning the sale of wind eroded objects.

5.1. Wind energy

As a source of energy, the possibility of harnessing wind energy, including the energy possessed by sandstorms, is of prime importance for small desert and rural communities located far from utility electric power networks. At present, these communities use either diesel engines or animal and human labor to pump underground or surface water for irrigation, watering cattle and other agricultural uses. Diesel generator sets are used in some of these communities to supply electric energy for domestic applications and for small industries.

One of the prime conditions for utilizing wind energy is knowledge of the properties of wind in the region under consideration. The variations in wind speed on time scales ranging from seconds to years are very important for the designing, testing and operation of wind energy conversion systems. The methods of wind speed measurement and the choice of the measuring instruments suited to these time scales should receive careful attention. The influence of the topography on the energy output from a windmill is so great that the selection of the site for its installation is a matter on which the economy of the whole project may depend.

Most of the information on wind speeds and directions exists in the records of national meteorological services. Also, oil companies have in their records the surface wind data for the OAPEC countries. Wind data obtained by both sources have not been based on wind power requirements. They are related to the general wind regime for the sites surrounding the observation station and not to particular windy sites. For example, recorded data in Saudi Arabian sites are collected at the airport of that site where the wind energy density is not necessarily maximum. Nevertheless, they are reliable long-term records and are used in estimating the wind energy potential in some selected countries.

According to one source [29], data collected from 67 stations in nine different countries were, in the majority of cases, in the form of tabulations for annual and monthly surface wind speeds, directions and percentage frequency over periods ranging from one year up to 10 years. Some of these stations are off shore, others are in coastal areas and some of them are inland. The sites of some selected stations located in areas where wind energy seems to be promising are listed in Table 1. The effective wind speed, V_e, is computed for each site from the available wind data. The effective wind speed is defined as the speed with which wind blows 8760 h in a year and produces the same amount of energy per unit swept area which is produced by the actual wind in the site under consideration. The effective speed is computed as:

$$V_e = (0.01 \sum V^3 \delta f)^{1/3}$$

where δf is the percentage of the total time for which the wind blows at a speed V. In the computation, V is taken always greater than the cut-in speed, which ranges between 3.5 and 5 m/s. The

Table 1
Availability of wind energy in selected sites [29]

Country	Site	Effective wind speed (m/s)	Available wind power (W/m^2)
Bahrain	Muharraq	6.12	141
Egypt	Alexandria	5.49	102
Kuwait	Al-Ahmadi	6.50	170
Lebanon	Bekaa	4.93	75
Morocco	Tanger	8.4	361
Qatar	Doha	5.34	93
Saudi Arabia	Dhahran	6.49	170
Tunisia	Tunis	6.6	175
UAE	Sharejah	5.31	92

term effective speed is much more indicative when considering wind power generation than the average speed. The energies per unit swept area that could be extracted from winds of the same average speed are not necessarily equal.

The available annual average wind power density is calculated as $P = 0.60V_e^3$. The annual average power that can be effectively collected per square meter of swept area is calculated as $P_e = 0.25V_e^3$ W/m^2. This formula is derived considering that the part of wind power which is theoretically recoverable is only 0.59 of the total wind power, and that the windmill efficiency is around 70%, i.e. a power coefficient of 0.42 is assumed. The annual effective wind speed and the available annual average power per square meter of swept area are also given in Table 1.

The general picture that emerges from this UN sponsored study [29] indicates modest possibilities for wind energy utilization in some desert and rural areas, especially in areas located not very far from the coasts. The annual average wind power density may exceed 200 W/m^2 in some locations like Morocco and is approximately 170 W/m^2 in Egypt, Kuwait, Saudi Arabia and Tunisia.

With 1979 fuel prices and equipment costs, it was found in the same study that wind technology is more economical than traditional technologies for small scale electric or mechanical power generation in remotely located areas with favorable wind characteristics. With the progress in development of wind driven water desalination plants, it was concluded that wind technologies could find significant markets in arid regions.

A variety of wind turbines appropriate for installation in rural areas or desert communities is currently available. Wind turbines can be classified, in general, into horizontal axis and vertical axis types. The horizontal axis wind turbines have been known for a long time. There is evidence that the ancient Egyptians used them as early as 3600 BC to pump water for field irrigation and grain grinding. This type of wind turbine may serve both high and low torque loads. The basic disadvantage of these machines is that the rotor axis must be kept parallel to the wind direction, requiring special mechanical devices. On the other hand, vertical axis wind turbines may be powered by wind coming from any direction. Moreover, generating equipment can be coupled to the drive shaft at ground level, thus reducing tower structural costs. Vertical axis types of wind turbines, however, are capable of powering relatively low torque loads, and some designs require supplemental starting. Within both the horizontal and the vertical axis types of windmills, it is possible to find windmills with mechanical power output and wind generators with electrical power output.

The most significant measure of the efficiency for wind turbines is the power coefficient, which represents the efficiency of conversion from wind power to mechanical power. This coefficient depends on the type and shape of the rotor blades, and it is very sensitive to the tip speed to wind speed ratio. The maximum theoretical value of the power coefficient is 0.593. Horizontal axis wind machines generally have higher power coefficients than the vertical axis types.

Perhaps the most viable of all wind turbines currently in operation is the propeller type wind generator. These wind turbines have two, or more generally, three propeller shaped blades. They are used extensively for electric power generation at a commercial scale and are typically connected to the grids of electric utility companies. Power outputs can range from a fraction of a kW up to nearly 2 MW [30]. The cut-in wind speed is typically 5 m/s, reaching full power at a wind speed of about 12 m/s. Constant speed and power are maintained by controlling the blade pitch up to wind speeds of about 25 m/s, at which speed the blades are feathered until the storm abates [31]. The maximum power coefficient of the propeller type wind turbine is about 0.5. Rotor diameters of these three bladed machines may be as large as 65 m, and the tower height may reach 80 m. Rotor speeds may be as low as 15 rpm for the largest diameter rotors, the speed rising with decreasing diameters [30].

Since wind speed is not constant, wind energy is considered an intermittent source of energy. Utilization of this intermittent energy resource becomes practical only if some means of energy storage is possible. Wind energy conversion systems operating independently may require up to several days of energy storage capacity depending on the wind regime where these units are installed. This is especially true for applications that fall within the constraints of desert and rural communities. When wind energy conversion systems are used mainly for water pumping, the energy can be stored in the form of potential energy by pumping water to a reservoir at a high level and allowing it to flow down to a lower reservoir for direct utilization when required. This system will be efficient if a natural basin of appropriate size is found near the water resource to act as a higher level reservoir. The well known conventional lead acid battery is still the most appropriate electrical energy storage device that is available, especially for low demand communities.

6. Concluding remarks

Consider next the moving sand in a sandstorm. It would be of interest to estimate the amount of available energy per unit area. Table 2 has been suggested [32] for helping predict the amount of available energy for different sandstorm speeds and densities. Wind speed in a sandstorm is varied in this table from 1 to 30 m/s. Considering the regular clear air visibility distance to be 10 km, it is possible to predict roughly the air density during a sandstorm. In Table 2, the density of moving air during a sandstorm is calculated based on the visibility distance in meters. The table also presents the corresponding percentage of sand suspension in the air, and the corresponding air density.

It can be deduced from Table 2 that sandstorms can possess impressive amounts of energy. It needs to be pointed out, however, that the last column in Table 2 seems to represent estimates of upper bound values for the available energy. Referring to Table 2, one is led to believe that the energy of a sandstorm blowing at a speed of only 4 m/s and featuring a visibility of 200 m is nearly

Table 2
Available energies from sandstorms

Visibility distance (m)	Suspension (%)	Air storm density (kg/m^3)	Storm speed (m/s)										
			1	2	4	6	8	10	12	15	20	25	30
10,000	0 clean air	1.20	0.6	4.8	38.4	129.6	307.2	600	1036.8	2025	4800	9375	16,200
2000	0.17	6	3	24	192	648	1536	3000	5184	10,125	24,000	46,875	81,000
1000	0.35	12	6	48	384	1296	3072	6000	10,368	20,250	48,000	93,750	162,000
400	1.8	30	15	120	960	3240	7680	15,000	25,920	50,625	120,000	234,375	405,000
200	3.5	60	30	240	1920	6480	15,360	30,000	51,840	101,250	240,000	468,750	810,000
100	7	120	60	480	3840	12,960	30,720	60,000	103,680	202,500	480,000	937,500	162,000
50	14	240	120	960	7680	25,920	61,440	120,000	207,360	405,000	960,000	1,875,000	3,240,000

equivalent to that possessed by clear wind blowing at a speed of 15 m/s. Assume now that a suitable extraction system is available for harvesting energy in moving sand at low height (less than 1 m from the ground surface) and assume again that this system has a 50% efficiency (a 30% power coefficient). For a sandstorm blowing at 10 m/s, then the available energy per unit area comes out to be an unlikely 60 kW for sandy air with a 7% suspension. There seems to be a need to verify the predictions of Table 2.

Wind speeds decrease as the ground surface is approached in a sandstorm, such that the total kinetic energy of the wind, including the kinetic energy of the sand the wind is transporting, remains nearly constant. Thus, wind speeds at altitudes less than 0.5 m from the ground would be expected to be greatly reduced from the free stream velocity. It is unlikely that a speed of 10 m/s can be realized during a sandstorm at a height of less than 0.5 m from ground level. A further issue that faces any attempt to extract energy from sand laden wind is that, as soon as the energy is removed from the wind, a corresponding deposition of sand will take place. What to do with such piles of sand while recovering energy from the wind may pose a serious challenge to the very viability of the concept.

On the other hand, it must be remembered that it is the very presence of winds that starts sandstorms, and that the free stream possesses the highest energy. Moreover, as it was presented earlier, air in the free stream generally remains clean (free from sand and dust) during a sandstorm. It would be reasonable to conclude, therefore, that existing wind machines can be expected to perform well in regions that experience frequent sandstorms, although maintenance and erosion problems can be expected, since the machines may be shrouded by dust clouds at times. For proper utilization of energy from sandstorms, wind speeds, durations and directions must be measured at potential sites of interest and at various altitudes throughout the year.

References

[1] Dregne HE. Soils of arid regions. Amsterdam: Elsevier; 1976.
[2] Bagnold RA. The physics of blown sand and desert dunes. London: Chapman and Hall; 1971.
[3] Manual of sedimentary petrology. Appleton Century, 1938.
[4] Web site www.gcrio.esto.or.jp.
[5] Malin JC. Dust storms. Part I: 1850–1860. Kansas Histor Quart 1946;14:129–44.
[6] Malin JC. Dust storms. Part II: 1861–1880. Kansas Histor Quart 1946;14:265–96.
[7] White BR. The dynamics of particle motion in saltation. In: Barndorff-Nielsen O, Maller JT, Rasmussen KR, Willetts BB, editors. International Workshop on the Physics of Blown Sand. Aarhus, May 28–31, 1985. p. 101–40.
[8] Tsuchiya Y, Kawata Y. Characteristics of saltation of sand grains in wind. Proceedings of the 13th Coastal Engineering Conference, 1972. p. 1617–25.
[9] Nickling WG. The initiation of particle movement by wind. Sedimentology 1988;35(3):499–511.
[10] Sidwell R. Sand and dust storms in the vicinity of Lubbock, Texas. Econom Geograph 1938;14(2):99–102.
[11] Skidmore EL. Wind erosion control. Climat Change 1986;9:209–18.
[12] Blowing sand control in Madinat-Aljubail Alsenaia. Final Technical Report, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, 1985.
[13] Vasilyev GI, Bulgakou DS, Gaurilenko LN, Kalnichenko AS. Conditions under which dust storms develop in the northern Caucasus. Soviet Soil Sci 1978;10(2):60–9.
[14] Barndorff-Nielsen OE. Sand, wind and statistics: some recent investigations. Acta Mech 1986;64(1/2):1–18.
[15] Bondy E, Lyles L, Hayes WA. Computing soil erosion by periods using wind energy distribution. J Soil Water Conserv 1980;35(4):173–6.

[16] Dyer KR. Velocity profiles over a rippled bed and the threshold of sand movement. Estuar Coast Marine Sci 1980;10:181–99.

[17] Horikawa K, Hotta S, Kubota S. Field measurements of vertical distribution of wind speed with moving sand on a beach. Coast Engng Jpn, Jpn Soc Civil Engrs 1986;29:163–78.

[18] Werner BT. A physical model of wind blown sand transport. PhD Dissertation, California Institute of Technology, Pasadena, CA, 1987. p. 442.

[19] Roth R, Tuchtenhagen M. Evaluating near ground wind velocities in considering the risk of wind erosion. Appl Sci Develop 1978;11:122–30.

[20] Mainguet M. Use of satellite images for detecting wind dynamics sand deposits, fixed dunes, wind erosion and desertification in the Sahel, South of Sahara. Proceedings of the International Symposium on Remote Sensing of Environment, Cairo, 1982. p. 551–2.

[21] Rognon P, Coud-Gaussen G, Bergametti G, Gomes L. Relationship between the characteristics of soils, wind energy and dust near the ground in the western Sandsea (N.W. Sahara). In: Leinen M, Sarnthein M, editors. Palaeoclimatology and palaeometeorology: modern and past problems of global atmospheric transport. Dordrecht: Kluwer Academic; 1989. p. 167–84.

[22] Whitney MI, Brewer HB. Discoveries in aerodynamic erosion with wind tunnel experiments. Michigan Academy Sci Arts Lett 1968;53:91–104.

[23] Mainguet M, Canon-Cossus L. On the use of meteosat imagery for the determination of ground wind trajectories in the Sahara and regions bordering on the Sahel: interpretation of meteosat images recorded between May 29, 1978 and February 9, 1979. Proceedings of the International Symposium on Remote Sensing of Environment, San Jose, Costa Rica, 1980. p. 743–50.

[24] Rollin EM. The influence of wind speed and direction on the reduction of wind speed leeward of a medium porous hedge. Agri Meteor 1983;30:25–34.

[25] Liu T, Ding Z, Chen M, An Z. The global surface energy system and the geological role of wind stress. Quater Int 1989;2:43–54.

[26] Rowley E, Rees D, Robertson A. Wind erosion and sand blasting. J Agri 1981;1:10–2.

[27] Thiesmeyer LR, Digman RE. Wind cut stones in Kansan drift of Wisconsin. J Geol 1942;50:174–88.

[28] Whitney MI, Dietrich RV. Ventifact sculpture by wind blown dust. Bull Geol Soc America 1973;84:2561–82.

[29] Anon A. New and renewable energy in the Arab world. UN Economic Commission for Western Asia, Beirut, 1981.

[30] Wind Powers America, June 1999. e-mail: michelle_montague@awea.org.

[31] Coal Clough wind farm (web site), June 1999, Wind Resources Ltd.

[32] Abu Al Khair AMS. Analysis and forecasting of sand and dust storms in Jeddah. MSc Thesis, King Abdulaziz University, Jeddah, Saudi Arabia, 1987.