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Environmental Wind Tunnels

Jonathan Merrison
Aarhus University,
Denmark

1. Introduction

Wind tunnels have been used extensively in industry and research applications over the past 50 years. They vary greatly in scale and geometry, with some large enough to house and test small aircraft (see for example NASA, ATP facilities) and others are miniaturized flow generators used in the calibration of small sensors. However they invariably utilize the same basic technology and design elements. Similarly environmental simulators are also used widely in research, for example in climate and planetary studies. Here again they superficially vary greatly in size and configuration, but basically consist of a hermetic chamber with some form of temperature control [Jensen et al. 2008]. There is therefore a broad array of standard and often commercial technologies and construction techniques which have been successfully applied within the fields of wind tunnel and environmental simulator design. Some of these technologies and techniques will be outlined in this chapter to aid researchers or technology developers in their efforts to design or use environmental wind tunnels and also serve as an informative guide to those new to these fields of investigation.

The fusion of an environmental simulator and a wind tunnel is a natural evolution of laboratory based technology to fulfill the need to reproduce specific physical conditions found in nature. Although facilities of this kind are only now being fully developed, they have the potential to expand into a new research field that could substantially contribute to our understanding of climate and mediate growth in advanced sensor technologies. In this chapter many of the challenges in designing and constructing environmental wind tunnels will be introduced and possible solutions presented, with some emphasis placed on extreme terrestrial and Martian planetary conditions. In addition some of the many and varied scientific and industrial applications will be discussed. Generally environmental wind tunnels are already in current use as a method of testing and calibrating meteorology sensors of various kinds especially wind flow sensors (anemometers). Application of wind tunnels in civil engineering and town planning is becoming common place. Here through wind tunnel simulation and modeling the flow of air around buildings and through built-up areas may be useful to avoid the generation of high wind shear and hazardous vortices at periods of high wind or storms. Such simulations can also aid in the design and placement of wind generation systems such as wind turbines.

The formalized scaling laws developed by ***Reynolds*** (Reynolds equations) allows measurements, for example in smaller scale laboratory wind tunnels, which generate the same (or extremely similar) flow to that generated in the natural setting [Monin and Yaglom

1973, Hall 1988, Mollinger and Nieuwstadt 1996, Fay and Sonwalkar 1991]. This scaling law involves the relationship between wind speed, spatial scale and viscosity such that adjusting and combining these parameters can allow realistic laboratory simulation for example on the cm-m scale of flow dynamics on the 10s to 100s of meters. It can also, for example, allow comparison of effects in one fluid (e.g. air) to be translated into those seen in another fluid such as water. This technique has been successfully applied in the design of all forms of transport, such as aircraft, ships and cars.

Wind tunnel studies have and are contributing powerfully in attempts to understand and describe the action of wind in arid areas. Following the pioneering work of ***Bagnold***, including the use of laboratory (and field) wind tunnels, the study of Aeolian (wind driven) sand transport has evolved into a scientific research field [Bagnold 1941]. It is now clear that Aeolian transport has a great impact on local environments and on the global climate through the production of aerosols, the erosion of surface material and the serious environmental problem of desertification. Aeolian transport of sand/dust under planetary conditions other than Earths is also of great importance to understanding these extreme environments and can help achieve a deeper understanding of our own environment. For example Aeolian processes are seen on Mars, Venus and Saturn's moon Titan, but are probably found on any planetary body with a significant atmosphere. Sand features such as dunes are common on these planets and in the case of Mars dust entrainment is seen to be the most powerful climatic factor. Interesting differences in the Aeolian features seen in these extra-terrestrial environments is the spatial scale compared to those on Earth. The study of extra terrestrial Aeolian phenomena can only effectively be studied in the laboratory using an environmental wind tunnel simulator. Even with such simulators, only some aspects of Aeolian transport on other planets can be successfully reproduced, such as the surface shear stress, wind speed, fluid density, temperature, humidity and (more ambitiously) surface microstructure, adhesive properties. Other physical aspects are extremely problematic, for example gravity and specifics of the surface composition (mineralogy).

An obvious application for an environmental wind tunnel is the study of the upper atmosphere (the troposphere and stratosphere), specifically low temperatures, low pressures and the presence of aerosols of various types. Clearly this is of relevance to the aircraft industry, especially (high altitude) jet aircraft. The recent (2010) disturbance in Atlantic flights due to the generation of dust aerosols by the Icelandic volcano (Eyjafjallajökull) is a good example, where a deeper understanding of these aerosols in the upper atmosphere could possibly have avoided a large degree of disruption. The development of new aerosol sensor technologies also appears to be necessary. In fact wind tunnels can both help to unravel the complex dynamics of aerosol behavior and to understand their formation processes through the generation of fine suspended mineral particulates (dust). It should be stressed here that the study of aerosols is far from being limited to a global climatic factor. Aerosols present a real hazard to environmental and human safety both in the home and in local environments. Conversely aerosols are also used widely in medicine and the pharmaceutical and cosmetics industries. Specifically nano-micro meter scale particulates suspended in the air can penetrate the deep lung as well as be suspended for long periods of time (months) in the atmosphere and transported great distances (globally). Smoke, clouds, dust, are just some of the many forms of aerosol that affect our environment and can be studied in environmental wind tunnels to better understand their (apparently complex) behavior as well as develop new technology in order to quantify and control them.

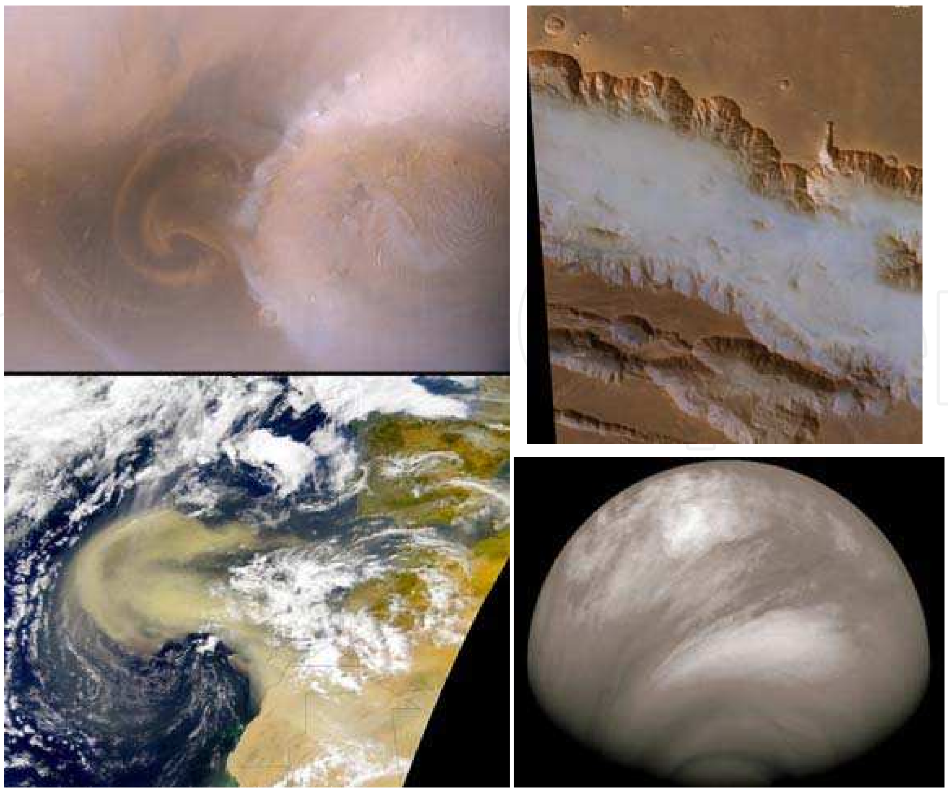

Fig. 1. Left upper and lower; satellite photographs of Mars and Earth, North Africa respectively, showing dust storms and clouds. (Courtesy NASA/JPL-Caltech). Right upper fog in Mars, Valles Marineris taken by the High Resolution Stereo Camera (HRSC) on board ESA's Mars Express spacecraft, Right lower; acid haze seen amongst the thick clouds of Venus, photographed by the ESA's Venus Express spacecraft.

In the future the study of aerosols will probably be the single most important application of environmental wind tunnels and it is hoped that the work presented here will contribute towards these types of study.

2. Environmental wind tunnel mechanical design

There are two basic types of wind tunnel design which may be referred to as Open Circuit or Closed Circuit (or closed cycle). In a terrestrial (ambient pressure) open circuit wind tunnel design fresh air is drawn (or blown) into the entrance and expelled at the exit, whereas in a closed circuit wind tunnel the expelled air is fed again into the inlet such that the same air is re-circulated. Either of these two wind tunnel types can be housed in an environmental (or planetary simulation) chamber giving rise to two distinct types of environmental wind tunnel design. These different wind tunnel types (shown schematically in figures 2a-2d) have distinct characteristics, their advantages and disadvantages will be discussed.

The implementation of thermal and flow control within these differing system designs will vary. In the case of the open circuit design flow and thermal control systems should be implemented upwind and focus primarily on manipulating the gas which is inlet. In the case of a re-circulating design, since the system is a closed cycle, flow correction and thermal control can in principle be implemented in any (or all) sections of the circuit. In practice the implementation of thermal control will depend on the thermal control system chosen and general technical restraints of the wind tunnel design. Similarly flow control will depend on the desired flow characteristics and the practical limitations on resources.

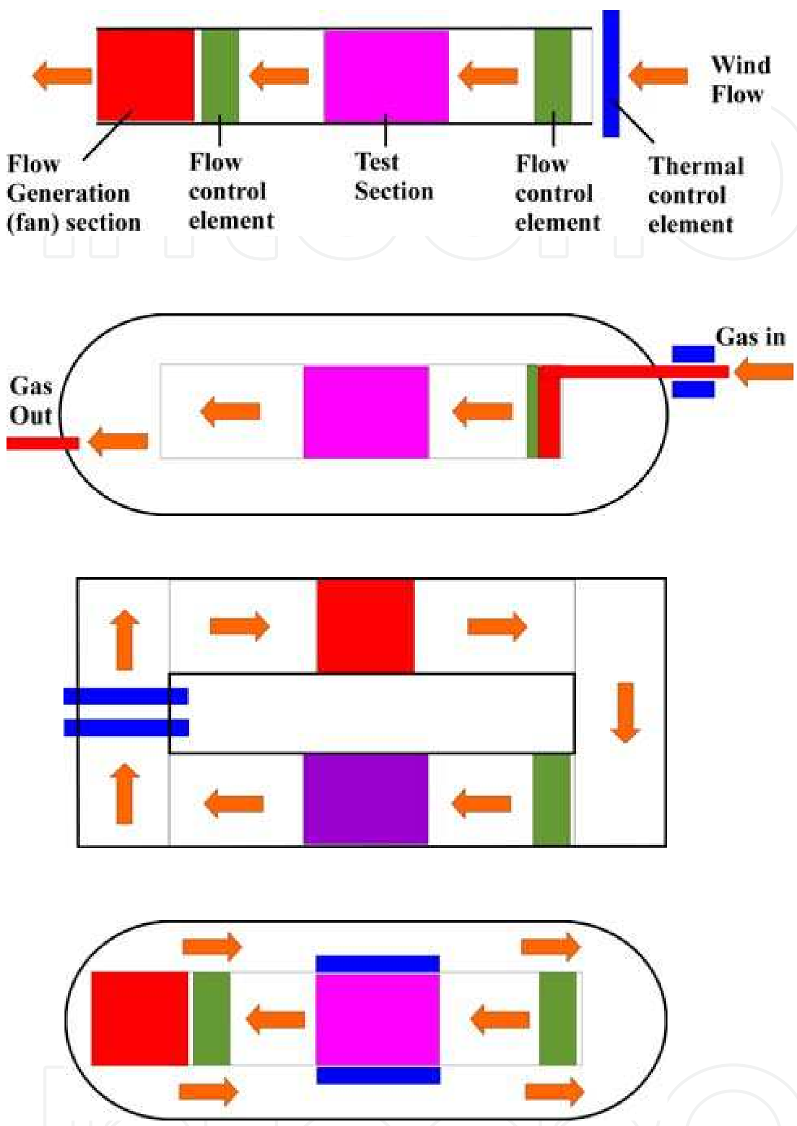

Figure 2a Open Circuit Ambient Pressure

Figure 2b Open Circuit Enclosed (Pressure/Vacuum Chamber)

Figure 2c Closed Circuit Enclosed (Ambient Pressure)

Figure 2d Closed Circuit Enclosed (Pressure/Vacuum Chamber)

Fig. 2. Different types of Wind Tunnel geometry combining open/closed circuit designs and ambient or enclosed (environmental control).

In traditional ambient pressure wind tunnel facilities the choice of construction materials is largely unrestricted. Materials are therefore chosen dependent on mechanical properties (strength, weight, etc.) and possibly also cost and availability, wood for example is used in many wind tunnels. For environmental wind tunnels the choice of materials is generally far more restrictive since, to maintain low pressure or gas purity, materials with low out-gassing properties should be chosen and for temperature control the thermal properties and mechanical properties at low temperatures must be considered. The choice of materials subsequently affects the mechanical design of the wind tunnel structure.

External access to the wind tunnel (especially the test section) is also of great importance in most cases, both during operation and installation or maintenance. Here access includes, for

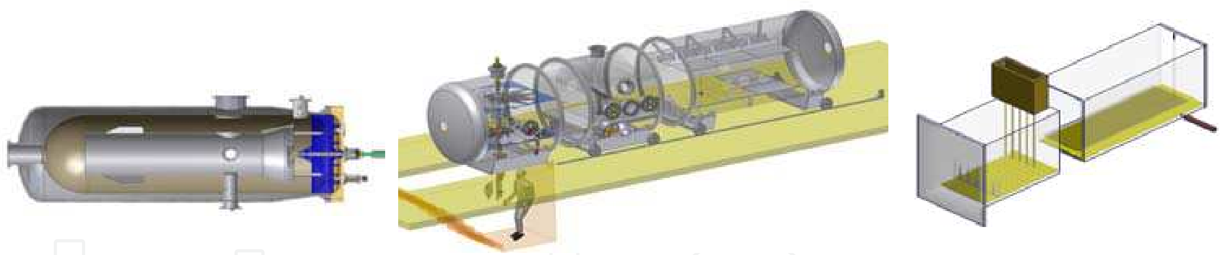

Fig. 3. Schematics of Left; Aarhus University Wind Tunnel I (AWTSI) design, Center; AWTS II design, Right; open circuit ambient showing upwind flow control (see flow control)

example mechanical, electrical and optical (visual) systems. Specifically mechanical access could involve being able to orientate a sample or sensor and therefore require rotation or translation mechanisms. Electrical access may be in the form of cabling for power and data transfer. Optical access could be cameras, lighting, spectrometers or other optical sensors. Ideally these forms of access should be as spatially close to the active section of the wind tunnel as possible and preferably large in cross section. For ideal flow (i.e. minimizing boundary effects) a wind tunnel should be cylindrical in cross section, however for the housing and access of samples/sensors, as well as many other practical applications of wind tunnels, it is desirable to use a rectangular cross section. This does not constitute a problem for most ambient-pressure applications; however for an enclosed (pressurized) wind tunnel this does present a technical challenge. The two environmental wind tunnel systems at Aarhus University apply two radically different geometrical solutions to this problem, with the AWTS-I system housing the cylindrical wind tunnel within its own (cylindrical) return flow, giving a rather attractive flow transport and uniform cross-section, though poor access to the test section and a non-optimal (circular) cross-section [Merrison et al. 2008]. The AWTS-II design conversely has an attractive, almost rectangular wind tunnel cross-section and good access to the test section, however the return flow is divided into two, above and below the test section, giving extremely non-ideal flow and constriction of the flow in the return section, which resulted in the need for extensive flow correction. At low pressure (below 100mbar) the highest wind speed achieved by AWTSI is around 15-20m/s, whereas AWTSII has achieved 20-25m/s, with similar degrees of (free flow) turbulence for both wind tunnels i.e. 5-20% increasing with wind speed.

Fig. 4. Photographs of the (10m long) AWTS-II facility showing the mobile environmental chamber sections, the central test section can be removed laterally.

In contrast to the Aarhus environmental wind tunnels the NASA Ames MARSWIT (Mars Surface Wind Tunnel, California USA) is an open-circuit, low pressure wind tunnel powered by a high pressure nozzle ejector system, the total length is 13m with a main test section of 1.2m by 0.9 m and is housed in a 4000 m^3 low-pressure chamber which can operate at pressures down to ~3.8 mbar and wind speeds of 20m/s - 180m/s (at low pressure) [White 1981, Greeley and Iversen 1985]. This system cannot be cooled and has been used for boundary layer studies.

For low pressure wind tunnel systems the structure of the vacuum chamber is one of the primary design features. This will typically require the use of a thick (bulky) steel shell and frame which, for mechanical strength, will optimally be cylindrical/spherical in form. This is similarly true for high pressure vessels. For open circuit environmental wind tunnels the limitations on the pressure vessel will limit the size and geometry of the test section. However for a re-circulating environmental wind tunnel the pressure vessel will even more strongly restrict design of the wind tunnel since, assuming the largest free flow cross section is desired then there must still be sufficient space for the return flow to be housed. It is desirable for this return flow cross section to be comparable to the test section cross section to avoid high turbulence and turbulent losses. The AWTS-II facility is one of the largest environmental wind tunnels with a cross section of around 2m×1m and a chamber volume of around 40m^3, it is significantly larger than the almost 1m^3 volume and cross section of 0.4m×0.4m of the AWTS-I.

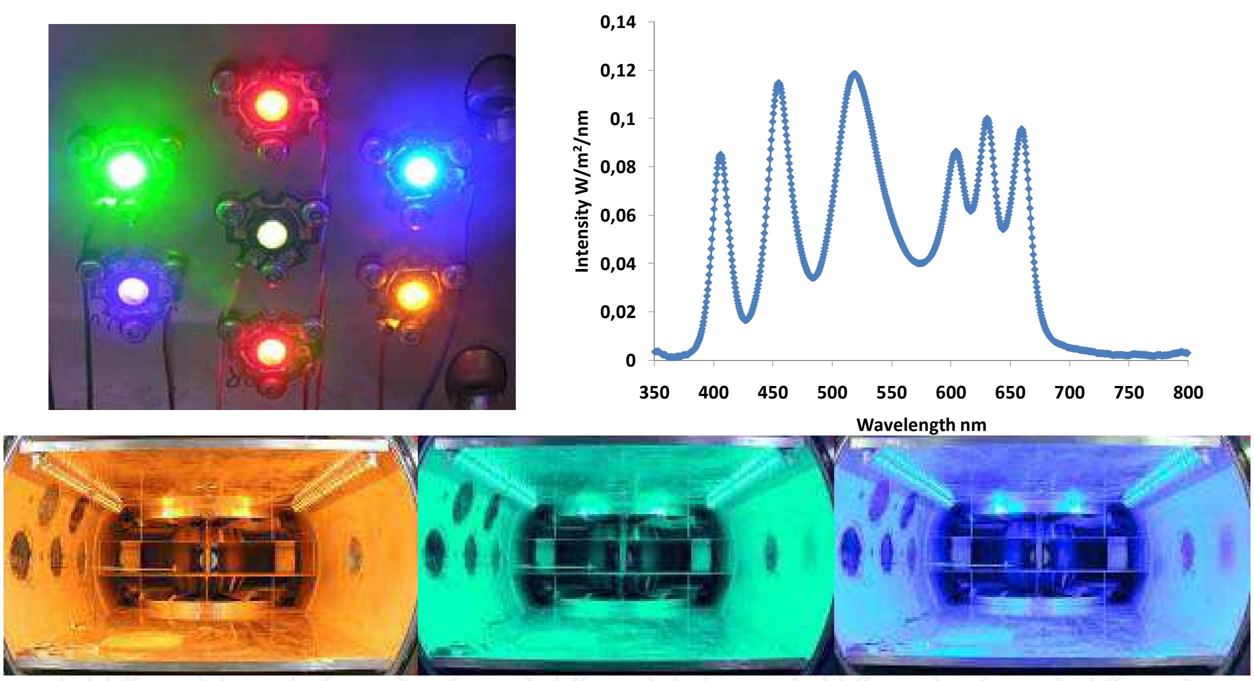

Fig. 5. A Light Emitting Diode based light source for solar simulation, illumination or crude spectroscopy in an environmental wind tunnel. Upper Left shows a photograph of a single array section including one of each of the seven different (wavelength) LEDs, Upper Right shows the irradiance measured within the wind tunnel (with all LEDs activated) showing the single wavelength components, the Lower photographs are taken inside the wind tunnel test section as different colored LED arrays are activated (red, green blue), the LED array strips are mounted in the upper two edges of this section.

In both industrial and scientific applications a common requirement is a light source which simulates the solar irradiance over a broad wavelength range. A problem with many light sources, for example halogen lamps and discharge lamps, is the generation of heat, both conductive and as thermal radiation (infra-red) which can make environmental temperature control difficult. Employing a light source outside the environmental chamber alleviates this problem, however it then restricts the illumination of samples considerably. Compromise here will generally be necessary. An attractive option is the use of light emitting diodes (LEDs) which are efficient and monochromatic, being available as intense sources though generating relatively little heat. LEDs are low voltage making them technically easy to implement in most cases. With the use of arrays of variously colored LED the correct light irradiance can be achieved within broad optical wavelengths and even into the near infra-red (more than 1000nm) and the Ultra Violet, with the latest UV LEDs below 250nm.

3. Flow control

Wind tunnels vary in their requirements for flow uniformity, while some are designed for low turbulence (close to laminar) flow, others apply techniques in order to reproduce particular boundary layer conditions (often referred to as boundary layer wind tunnels) whereas for some a specific free-flow degree of turbulence is required. In these differing cases it is probably fair to say that they are attempting to reproduce differing turbulence regimes present in nature and that it is therefore difficult to generalize about these wind flow designs. However it is worth discussing differing flow control techniques which are commonly employed and how specifically they can be applied.
Flow guides are smooth plates of differing geometry which are installed in order to steer the wind flow to obtain a desired wind pattern. For example they may be; curved in order to guide the flow around bends, they may be planar in order to straighten the flow or they may be used to partition the flow into sections in order to prevent unwanted lateral flow/eddies. In open circuit wind tunnels flow control should (obviously) be installed upwind. However, in a re-circulating wind tunnel they should generally be installed at the source of the unwanted flow pattern, which could be upwind or down wind. In the case of the European Mars Environmental Wind Tunnel (see figure 6) flow guides have been used to great effect at the entrance to the wind generating fans system and prevented extremely destructive back-flow caused by the rotation of the fan blades. Meshes are used to reduce turbulence in the wind flow and to obtain a more homogeneous flow profile, especially on scales larger than the mesh size which is typically of the order of 1mm. This is done at the expense of wind speed. Meshes are often utilized as a set of two separated by some mm-cm. In this case a pressure gradient is generated across the meshes, this helps to disrupt turbulence and non-uniformities in the flow. It should be noted that both flow guides and meshes while improving flow properties, will typically increase friction and therefore reduce the (net) wind flow for a particular wind generation power. The use of upwind roughness blocks and turbulence spires manipulate the vertical wind flow profile (at the test section) in order to emulate an infinite upwind 'fetch' i.e. to reproduce the surface boundary layer flow which would be produced if the wind tunnel were infinite in length. Clearly this is of great importance when studying boundary layer effects such as the entrainment and transport of sand or the flow patterns around a surface feature [Irwin 1981, Shao and Raupach 1992]. Expansion and compression stages can be used in wind tunnel design to increase wind speed, improve flow linearity and reduce turbulence. Here compression of the wind tunnel will increase the downwind flow speed and reduce the relative transverse turbulence. Clearly this is done at the cost of wind tunnel cross-sectional size and is not always possible to implement especially within a re-circulating wind tunnel. Often in open circuit wind tunnels and invariably in re-circulating systems wind generation is provided by a fan or fans. Fan design is in many cases non trivial, involving modeling and calculation regarding

the specific choice of fan blade size, number, form, angle and also motor power, torque and rotation rate. Such modeling and calculation can be aided by computational fluid dynamic calculations. Here one begins with the required parameters of wind speed (and ambient pressure), based on the wind tunnel design. The flow calculations will then predict a certain degree of frictional loss as a function of wind speed. The fan system can then be modeled as a system to generate a pressure gradient necessary to balance this frictional loss and maintain the desired flow rate. Given the flow rate and the required pressure differential a particular fan design can be chosen i.e. these are the required input parameters for the choice of fan design. In the case of environmental wind tunnels the choice of fan material must also be considered, for example to be compatible with out-gassing limits and low/high temperature.

Fig. 6. Photographs into the flow generation section at the AWTS-II facility, Left shows the 1.8m diameter fans installed, Center shows with the upper and lower flow separators and Right the system of vertical and horizontal flow guides compartmentalizing the flow, preventing rotation and excessive turbulence.

Since almost all forms of high power motor are incompatible with the demands of (low) pressure and temperature within an environmental chamber, the drive mechanism for a fan system must be mounted externally. This presents a problem for the transfer of torque to the fan since passing a rapidly rotating axel through a pressure seal system is also incompatible with avoiding pressure leaks and maintaining low temperatures. A possible solution which has been employed in the various facilities at Aarhus University is the use of a magnetic coupling [Merrison et al. 2008]. Such couplings are commercially available and transfer torque from the drive axel (external) to the fan axel (internal) through a complex of magnetic fields generated by permanent magnets. This avoids physical contact of the two axels and allows this coupling to be completely hermetic (vacuum tight). A drawback with this system is the limited degree of torque which can be transferred by such couplings before they begin to slip which may limit the rotation rate (wind speed) within the wind tunnel. It does however have the benefit of protecting the drive-fan system from damage as slippage of this coupling is not hazardous.

A type of open circuit environmental chamber has been employed for Mars simulation conditions at Oxford University. Here gas is injected from an array of (relatively small) inlets into a flow volume which is continually being evacuated by a pump. In this case an extremely low turbulence flow can be achieved along with high flow speeds as well as cooling. A drawback can be that the flow rate is dependent upon the chamber pressure such that control of low flow speed involves inlet and pump rate control. Such a system can be well suited to anemometer calibration and high wind speed tests [Wilson et al. 2008]. Discussion here has focused on low wind speeds (subsonic flows). There are however, forms of wind tunnel which generate and utilize supersonic and even hyper sonic flows for various studies. Specific applications are in the design and testing of supersonic aircraft or re-entry devices. It should be noted that such wind tunnels utilize specialized techniques and the flow in such high velocity regimes differs from that at wind speeds significantly below that of sound [Barlow 1999]. Generally environmental wind tunnels will involve compromising the 'ideal' wind flow characteristics due to geometric constraints imposed by the environmental chamber or environmental control systems, for example reduced cross section, increased turbulence, reduced maximum wind speed or the use of cumbersome flow control systems.

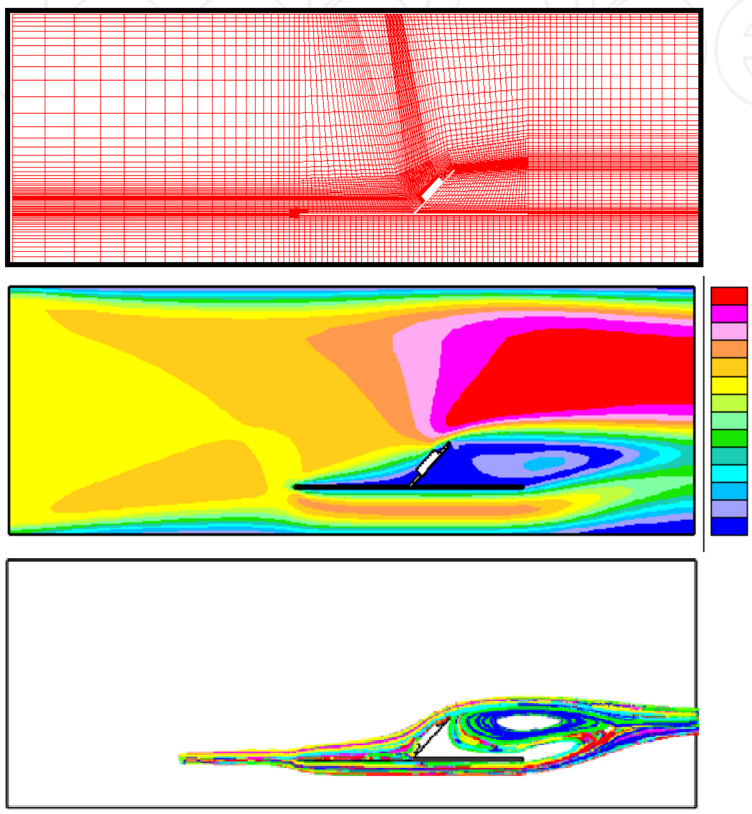

Fig. 7. Computational Fluid Dynamic calculations of an object within a wind tunnel showing: Upper; the finite element structure, Center; the calculated wind speed flow from red (high) to blue (low)and Lower; suspended (aerosol) particulates added to the flow and their trajectories traced.

4. Computational fluid dynamics

This chapter has focused upon experimental/laboratory studies using environmental wind tunnels, however discussion should be made of the use of computational fluid dynamic modeling in this regard as in some cases this may be an alternative to laboratory simulation. However in most cases these two techniques are complementary. When constructing a fluid dynamic model in order to perform computational flow analysis it is necessary to make simplifications and assumptions which in most cases must be verified experimentally in order for confidence to be placed on the results [Peric et al. 1999]. A specific example is the calculation of flow around an irregular shaped object. In this case it is necessary to construct a finite element representation of this geometry before inputting wind flow boundary conditions. Although the resolution of this finite element array can be increased in order to ascertain convergence, this will also be limited by computing power. Here comparison with experiment can be of great benefit in identifying sources of high sensitivity in the flow such that resolution be enhanced in this volume (see figure 7). A combination of targeted laboratory measurements and computational analysis can be ideal in simulating complex and difficult flow problems [Kinch et al. 2005]. Typically CFD is employed in the design phase of wind tunnels, though often the flow is complex and multi-dimensional such that empirical measurement and the implementation of correction elements is necessary to arrive at the most satisfactory flow characteristics.

5. Environmental sensing technology

A crucial aspect to any application of wind tunnels and/or environmental simulators is the use of accurate and reliable sensor systems for control and reproducibility of the simulated conditions. Some sensor systems are readily and commercially available at a well evolved level, for example for temperature and pressure. Other sensor systems can be complex, expensive and require adaptation, examples are wind sensors (anemometers) and gas composition. For some sensor systems there is a clear demand for new technology, yet this technology awaits development, examples are shear stress sensing and aerosol analysis.

In ***temperature*** sensing thermo-resistors are widely available (for example 100 Ohm platinum resistors i.e. Pt100), these are typically inexpensive and are accurate (typically around 1°C) over a wide range. The same could also be said of thermocouples (e.g. K-type), though these generally have a limited low temperature range. Thermocouples can also be difficult to integrate into an environmental chamber due to the need to maintain the contact potential i.e. maintain the exotic metal cables. ***Pressure*** sensor systems are available either for high pressure use, low pressures or specific to terrestrial conditions, i.e. limited to around 1 bar. Low pressure sensors are typically (generically) referred to as vacuum gauges. A type of vacuum gauge which is ideal for moderate low pressures (down to say 0.1mbar) and which is accurate even in differing gas compositions is the capacitance vacuum sensor, it is therefore well suited to study of Earth's upper atmosphere or Mars. Such capacitor based techniques are also useful for determining pressure differentials which can be important in wind tunnel design or wind sensing (see Pitot tube). Although absolute humidity (water vapor pressure) sensors are typically complex and expensive, relative humidity sensors are often extremely compact and operate over wide temperature and pressure ranges. Specifically thin polymer film type sensors are commercially available and are easily implemented into an environmental system (e.g. Honeywell HIH series).

In environmental systems where the ***atmospheric composition*** may be controlled it is important to be able to monitor it. There are few available options in this case and typically a sensor system called a Rest Gas Analyzer is used. These are often a type of quadrapole (radio frequency) mass spectrometer. They operate by ionizing the gas at low pressure (i.e. leaked through a valve) and extracting the ion fragments individually to determine their mass to charge ratio. It may then be possible to re-construct the original molecular structure of the gas, it is however difficult if the atmosphere contains several species where some fragments are ambiguous and it is often difficult to precisely determine abundances without careful control/calibration of the system and some expertise. Although these systems are relatively expensive and cumbersome to install, there is at present a lack of viable alternatives.

Finally in any application where an array of sensory systems is used, it is desirable to implement a data-logging system which records the various sensor outputs during measurement cycles. For environmental wind tunnel systems it is also natural then to integrate this data logging capability into a computer system which also interfaces (and records) some of the control parameters of the facility such as wind generation (driving fan rotation rate), vacuum/pressure control system (pumps, valves etc,), cooling/heating systems or lighting subsystems. Although this constitutes an added level of complexity it allows for a higher level of reproducibility, sensor correlation and possibly safety.

6. Flow sensing technology

Clearly of primary importance with regard to wind tunnels is the accurate sensing of wind flow (Anemometry). There is a wide variety of available anemometer techniques, some dating back over 500 years, others are still being developed. These wind sensing systems vary in accuracy, complexity, price, size, and so on. In the following paragraphs some of the most common wind sensing technologies will be presented and briefly discussed, specifically with respect to their application in wind tunnels.

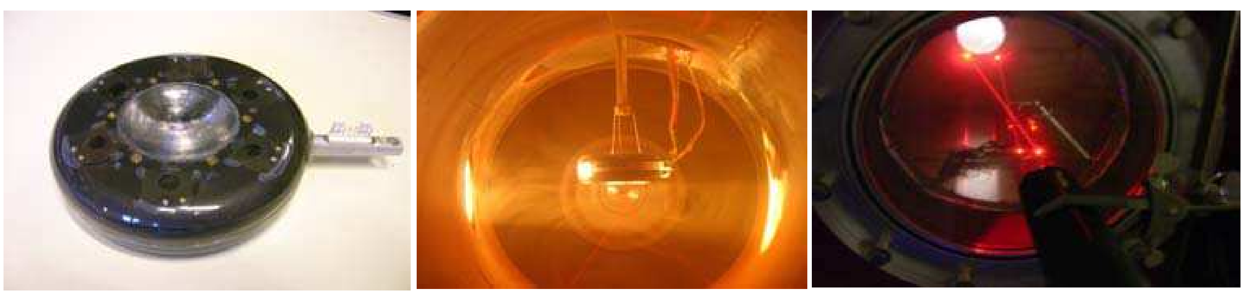

Fig. 8. Photographs of Laser Anemometers (acting also as suspended dust sensors), Left prototype time of flight instrument, Center the sensor during aerosol testing in an environmental wind tunnel, Right A commercial Laser Doppler Anemometer operating through an environmental wind tunnel access window, note the beams illuminating the suspended dust in the flow.

6.1 Laser anemometers

These are probably the most advanced and desirable type of wind sensor which have been applied in wind tunnels, specifically the Laser Doppler Anemometer (LDA) is used extensively. Several more recent variations on this instrument can measure in multiple dimensions, image and determine suspended grain size. This technique has the benefit of being non contact, such that it is independent of the environmental conditions within the flow (pressure, temperature, composition, etc.), it is also accurate and does not normally require external calibration. In fact LDA based systems are widely used in wind tunnel applications for the calibration of other types of wind sensor. The principle behind the technique is the scattering and detection of light by suspended aerosol particles, by measuring the frequency shift due to the velocity induced Doppler effect. More specifically two (or more) beams are use to produce an interference pattern, measurement of the shift in this pattern allows single velocity components of the grains to be determined. The system does have the disadvantage of requiring the presence of suspended particulates within the flow, which are introduced as smoke in many systems. However, for systems studying aerosols this is a major advantage since the suspended grain concentration can be quantified using this technique. Typically LDA systems are expensive and bulky, though can use optical fibers and therefore achieve a relatively compact sensing head. Miniature (even micro-scale) laser based wind sensors are being developed, though have yet to advance from prototyping. One such system is based on a time of flight principle in which a light pattern is generated within the sensing volume. Single suspended aerosol particulates traversing this light pattern will scatter light with a modulated signal from which its velocity can be established, specifically in the case of the prototype shown in figure 8 a three line light pattern is used and the scattered light signal will consist of three pulses the time separation is then directly related to the velocity [Merrison et al. 2004, Merrison et al. 2006]. This type of technology has the potential to become miniaturized (on the sub-cm scale) and have low power consumption as well as being robust. Although limited in precision compared to LDA systems, it may be applied in systems too small or inaccessible for larger sensors and provide an affordable (and portable/battery driven) aerosol sensor. The current advancements in solid state laser and other optoelectronic technology give sensors of this kind a promising future.

6.2 Mechanical (cup anemometers or wind socks)

Mechanical anemometers are by the far the oldest, simplest, most common and varied form of wind sensor. Most widely used are cup anemometers and forms of wind sock or wind vane. A cup anemometer consists typically of conical cups mounted on a axel such that wind drag causes rotational motion which can be sensed by a tachometer in order to relate the rotation rate to the wind speed. Wind vanes and socks are typically more primitive and consist of a structure (tube/sock or plate) which is deflected by the wind such that the deflection angle is a measure of the wind speed and the direction may often be seen in the direction of the deflection. Such mechanical wind sensors are rarely used in wind tunnel applications due to their poor accuracy/precision and often limited dynamic range. They are however an invariable component of weather/climatic stations on Earth and have even been adapted for the extreme environment of Mars and Venus. Such systems can potentially be extremely compact, light weight, sensitive and robust given careful design and testing [Gunnlaugsson et al. 2008].

6.3 Hot wire or hot film

These sensors have been used extensively in wind tunnel experiments over several decades. They are typically accurate and sensitive in terrestrial conditions, they can also be multi dimensional and have reasonably fast response times. Compared to mechanical wind sensing techniques they therefore provide improvement in precision. The measurement technique relies on (electrically) heating a thin wire or foil which is then cooled by the flow of air. The cooling rate is therefore related to the wind speed. There are many variations on the this concept including specialized geometries, multiple heated elements (to determine wind direction), pulsed operation and heater-sensor feedback circuitry. Challenges to this technique are thermal (conductive) losses and temperature dependences in addition to the sensitivity to atmospheric properties. Also the heated sensors are often physically fragile and poorly suited to harsh environments. However it has been demonstrated that careful design, testing and importantly calibration can allow these sensors to be used even in low pressure, thermally unstable environments such as Mars. The first successful wind sensor system developed by NASA was such a hot film anemometer.

6.4 Pitot tubes

Pitot tubes are a simple and widely applied wind velocity sensor. This type of sensor is used in the aerospace industry (airplanes) as well as wind tunnels. The principle is measuring the overpressure generated in a wind facing tube compared to a non wind facing aperture. This pressure differential is a function of the wind speed relative to the tube. It is therefore well suited to situations where the direction of the wind flow is known. Despite their wide use, the Pitot tube is typically limited in range (due to its strong dependence upon wind speed) and requires careful calibration, since it is dependent upon atmospheric conditions (pressure, temperature, etc.).

6.5 Sonic anemometers

Sonic anemometers are a relatively modern and commercially available sensor for determining wind flow, they utilize the transmission of high frequency sound (ultrasonic) in order to measure wind flow by determining the acoustic propagation speed. Sonic anemometers can simultaneously measure wind velocity in all three dimensions and at high sampling rate. These sensors are precise and being three dimensional are capable of quantifying vertical as well as lateral flow rates. This makes them the instrument of choice for the study of boundary layer transport. They are currently used widely in climatic/atmospheric studies, though not usually in wind tunnel applications. Unfortunately sonic anemometers are sensitive to the physical properties of the atmosphere (composition, pressure, temperature, humidity etc.). This makes them poorly suited to many environmental applications. Research groups have attempted to adapt sonic anemometers to extreme environments such as that on Mars, though have been hindered by the low pressure.

6.6 Shear stress

The quantification of surface shear stress within a wind tunnel is crucially important when trying to evaluate the threshold or transport rates of granular material or more generally mass transport rates or heat transfer. Currently a large body of semi-empirical work allows the measurement of surface wind velocity to be related to the surface shear stress (friction velocity). More crudely measurement of the wind velocity, turbulence and surface roughness can be used to obtain estimates of shear stress [White 1991]. However experimentally these are often difficult and indirect approaches to the determination of surface shear stress. Ideally the application of nano-micro scale force/pressure sensors could now allow the direct measurement of wind shear stress [Xu et al 2003], however these are not commercially available and have not advanced from research prototypes.

7. Thermal control

Most of the discussion here will concern cooling within environmental wind tunnels rather than heating, though in many respects the problems and solutions are essentially the same. In industry environmental wind tunnels typically refer to wind tunnels within which the temperature can be controlled, with heating and cooling over the range typically expected on earth i.e. around -60°C to +50°C, though with no control of pressure. Such wind tunnels are used extensively in the automobile and aerospace industries and are often on a scale (many square meters cross section) such that full size vehicles can be housed. In this case commercial refrigeration (freezer) technology can be employed. Cooling systems vary depending on the temperature range and power requirements, typically for temperatures above -80°C closed cycle refrigeration (using refrigerants such as haloalkanes, ammonia, alcohol, etc.) can be used. Below this and down to around -190°C it is common to use liquid nitrogen flow through systems of some kind, since this is readily available and relatively cheap [Jensen et al. 2008]. Cryogenic pumps (e.g. closed cycle helium refrigeration systems) are used for very low temperatures (a few K) or smaller systems which operate for long periods of time and require stability. A convenient cooling or rather heat exchange system is the Peltier element. This is a low voltage DC driven thermo-electric device for generating a temperature gradient across thin plate type bimetallic networks. Thermal power exchange of the order of 100W and temperature gradients of the order of 70°C (from room temperature) are typical. These are easily installed and relatively cheap and often used for thermal control of small detectors, solid state lasers, etc. A limitation is that they operate poorly at low temperature with a decrease in operating voltage (power) and temperature gradient, for example at around -130°C the maximum temperature gradient possible falls to around 10°C. In the case of heating systems, although electrical heaters are commonly available and a well established technology, their use in an environmental simulator imposes certain restrictions on the applicable materials and geometry, for example that the material should not outgas, should be compatible with cryogenic temperatures, be fully electrically encapsulated and available in various geometries depending on the wind tunnel structure. A commercially available solution which has many of these qualities are custom manufactured encapsulated heater mats (X-Mat®) they consist of copper conductors encased in Capton foil (3 mm thick) with silicone encased cables.

In addition to an effective cooling/heating system there is the need for efficient transport of thermal power to the sample or test section from the cooling system and possibly also to the ambient wind tunnel gas. Similarly there will be the desire to prevent thermal transport to the sample/test section from external sources or even heating due to power generated by electrical systems. Thermal transport is therefore of importance and an understanding of it necessary. Three thermal transport processes are relevant in wind tunnel and environmental chamber design. Conductive thermal transport is generally of most importance and the method by which most thermal control can be achieved. Specifically, metals with high thermal conductivity are used, such as copper or aluminum. When dealing with fluids (such as gas) thermal transport can also occur by convective transport, here thermal power is transported by the physical flow of mass. This must be considered even when dealing with low pressure gases (a few mbar) since thermal conductivity is not strongly dependent upon pressure/mass density and is therefore still significant at low pressure. An added complication is the possibility for volatiles, such as water, to condense/freeze, evaporate and transfer heat through this mechanism. Radiative thermal transport i.e. the transport of heat through light emission/absorption (typically at infrared wavelengths) is significant even in the absence of fluid/solid contact. It can be of comparable importance in the thermal balance of samples or gas within the wind tunnel. Manipulation of this effect can be achieved by alteration of the surface properties of materials within the environmental chamber for example with the use of coatings (paints).

For extreme temperatures (especially cryogenic) environmental chambers are necessarily going to have to employ some form of thermal insulation, preferably with good efficiency such that there is as little thermal contact (loss) between the test section and the ambient environment as possible. There are many types of ambient pressure insulation material available, varying in insulation efficiency, price, mass, volume etc. For low pressure systems the use of double walled (vacuum) insulation techniques (such as that used in Dewar flasks) is effective and widely applied, however this technique essentially requires two nested vacuum systems and is therefore generally expensive and complex to construct. Efficient vacuum compatible thermal (cryogenic) insulation is available. One example is multi-layer thin film super-insulation developed at CERN-CryoLab and commercially available (JEHIER). Despite its high price relative to ambient pressure insulation, it is simple to apply multilayer super insulation within an environmental chamber design, it is also reasonably efficient and affordable compared to a multi-walled vacuum insulation solution.

In a closed circuit systems the frictional loss of power within wind tunnel can cause significant heating at elevated wind speeds (of the order $100W/m^3$). This can become problematic for thermal control systems in such situations. Specifically heating of the gas will ensue and heat deposition on surfaces in contact with the gas. This must be considered when designing thermal control systems if stable temperatures are to be achieved.

As mentioned previously with respect to sensors, in addition to a thermal sensor system and a cooling/heating system an automated (intelligent) control network needs to support these sub-systems in order to achieve effective thermal control. In many research and industrial applications it is necessary to perform complex *thermal cycling*. Such cycling may involve specific thermal ramp rates and extend over long periods of time (days) necessitating computer control.

Even in a thermally controlled system where effective thermal insulation has been employed, effective thermal conduction to the sample has been used and sufficient heat is exchanged, this does not ensure thermal stability since typically the cooling system will not be continuously in operation and will have a certain time delay between activation and the onset of cooling. In practice therefore thermal control will consist of a feedback system of thermal sensors and thermal control which will introduce oscillation of the test section temperature. Additionally ensuring thermal stability may not ensure thermal uniformity as the application of cooling may not be physically at the same location as the source of heating or thermal loss which therefore leads to spatial temperature gradients. An obvious method to both stabilize the test section (or sample) temperature and achieve improved thermal uniformity is the use of a massive conductive (metal) test section element or sample mounting section. Here the thermal inertia of the mass achieves thermal stability and the high thermal conductivity of the mass ensures uniformity. It is however often difficult to find space to house such a massive element and the cooling/heating time of this element will necessarily be long. In the case of the AWTSI and AWTSII facilities a compromise has been reached between the desired stability/uniformity and the available space/required response time. In the case of the AWTS-II facility at a temperature of around -120°C the uniformity of the test region is around 15°C/m and the stability is around ±2°C despite the use of a 0.1m thick sample (aluminum) mounting plate.

8. Ice formation and sensing

The transport of water vapor is often an important physical parameter for environmental simulators, both with regard to industrial and research applications. For example on Mars the desiccation of surface materials and subsequent frost formation (re-hydration) may lead to geophysical changes in the surface materials, specifically salt crust formation (which are widely observed) or even erosion. Similarly man made materials can be susceptible to weathering by the transport of water vapor from the surface. For the control of humidity at low temperatures it is necessary to both cool the sample and another element within the environment. Typical research environmental chambers rely only on mounting the sample on a cold finger, in this case the sample will typically be at the lowest temperature within the environment and therefore attract out gassed water vapor and be hydrated (often forming surface ice). Other environmental chambers either cool the outer chamber or the atmosphere directly. In this case the sample will typically be warm compared to this environment and lose water vapor i.e. become desiccated. If the sample and environmental element(s) are thermally controlled independently then water diffusion to and from the sample can be regulated allowing detailed study of water transport phenomena. This does however require more sophisticated cooling and (computer) control systems. It is also then additionally desirable to have both cooling and heating systems for enhanced thermal regulation. Environmental (cooled) wind tunnels have been used occasionally in studies of snow transport, often involving processes of electrification which is relevant to the generation of electrical thunder storms and lightening [Maeno 1985, Schmidt et al. 1999]. This field of research is sparsely investigated and still largely empirical, despite being of great importance to human safety (anywhere that people interact with snow and ice) and relevant to understanding a variety of (dangerous) meteorological phenomena including the vast Arctic/Antarctic regions. The technology for such research is readily available and straightforward to implement, involving the combination of a wind tunnel structure and (sub-zero) refrigeration techniques.

9. Aeolian sand and dust transport

Desertification involves the erosion and degradation of drylands which affects 25% of the Earths landmass and more than 2.1 billion people. Each year 12 million hectares of land are lost to desertification. This is the UN launched decade for deserts and the fight against desertification. The relevance of this work into Aeolian grain transport is to understand, predict and control this environmental effect [Ofori and Showstack 2010]. As well as being affected by the climate (and climate change) through changes in wind and surface conditions, Aeolian transport can also strongly affect the climate through the generation of aerosols (e.g. suspended dust). As an example, every year of the order of 1 billion tons of dust is removed from north Africa into the atmosphere and is carried great distances, around 200 million tons is subsequently deposited on south America. The affect of such aerosols in the atmosphere, also including smoke, clouds, ash etc., is complex. There is the need for a lot more research to understand the role of aerosols, including laboratory studies (environmental wind tunnel studies), remote and in-situ sensing as well as modeling.
The definition of sand in the context of wind tunnel operation is granular material which cannot be suspended by the flow, but can be entrained i.e. can be removed from the surface by the wind shear. The definition of dust in this regard is therefore granular material which is fine enough to be suspended. Typically in nature sand particles will be transported by **saltation** wherein they are repetitively removed (entrained) from the surface, but cannot remain suspended and return to the surface in a ballistic impact referred to as a splash [Pye and Tsoar 1990]. This definition of sand and dust is not a strict size/mass scale since it is dependent upon many physical parameters for example; the wind shear, atmospheric properties, gravitational conditions, etc. Under terrestrial conditions sand is typically greater than around 60μm up to mm size. Particulates larger/more massive than this can be moved by wind shear without leaving the surface either by rolling, sliding or by impact of sand, this transport process is referred to as creep.

Saltation is an effective erosion process due to the destructive nature of the splash. These impacts typically lead to chipping and the generation of dust sized particulates. Aeolian (wind driven) particulate transport is also effective at sorting granular material, specifically separating sand, dust and stones/pebbles. This leads to the generation of the many sand dune forms observed, their character depending on the nature of the wind flow. The threshold wind conditions (surface wind shear) required for sand saltation transport has been widely studied, both in wind tunnel simulators and in nature following the pioneering work of Bagnold [Owen 1964, Greeley and Iversen 1985]. Despite this the work remains semi-empirical, mainly due to the complexity of the physical parameters involved, such as; wind induced lift and torque, adhesion, gravitation and the effect of splash. Similarly a large body of work exists in which the transport rate (above threshold) has been studied. Again resulting in an array of increasingly sophisticated and intricate semi-empirical expressions with especially the effect of splash being problematic [Shao and Raupach 1992, Rasmussen and Sorensen 2008]. Interesting aspects to be noted is that the rate of sand transport increases rapidly above the threshold wind speed (varying as the cube of the wind speed) and that due to the effect of splash saltation can be maintained below (by around 20%) the initial threshold speed once the process has begun.

As discussed in the introduction the different gravity on other planets is problematic to reproduce in terrestrial laboratories. However, it is possible to vary the effective mass density either by using low density material or hollow structures (glass bubbles), this has been effectively utilized in wind detachment studies. Unfortunately a complex process such as the splash in saltation involves both the inertial mass (on impact) and the gravitational mass (during the trajectory) of the sand particulates. This makes this process impossible to entirely reproduce in a terrestrial laboratory and can probably only be studied through partial experimental simulation, modeling and observation in the respective gravitational field [Merrison et al. 2007].

Wind tunnels involved in sand transport are typically of the order of a square meter cross section, several meters long and are constructed as boundary layer simulators with the use of (upstream) flow control to reproduce the correct surface boundary layer (and shear stress) [Young 1989]. These flow control units include roughness arrays, inlet meshes, turbulence spires, and systems for injecting sand upstream (see figure 3). The results of laboratory based wind tunnels can be complemented by the use of field wind tunnels. These are portable wind tunnels which are taken into the field and thereby use real surface material and environments and possibly even the actual wind flow.

Dust can be entrained and therefore transported by wind shear in two ways. The generally accepted process of dust entrainment on Earth is through the action of saltating sand grains impacting dust particulates and ejecting them into suspension. This process is extremely effective at wind speeds above the threshold for saltation. The entrainment of single (e.g. micron sized) dust grains directly by wind shear requires extremely high shear stress (extremely large wind speeds), however dust grains generally cohere and form larger aggregates, often up to mm sized. The mass density of these aggregates can be low (below 1 g/cm^3) and can therefore be mobilized at much lower wind stress than solid sand grains. Once detached from the surface the dust aggregates may disintegrate and liberate free dust grains into suspension. This process has been observed and quantified in (environmental) wind tunnel studies and helps to explain the otherwise paradoxical observation of dust transport in the Martian atmosphere (at wind stress below the sand transport threshold) [Merrison et al. 2007]. This transport mechanism may also be important for dust transport in areas not rich in sand, though dusty.

An interesting erosion effect which has emerged as a result of studies in a Mars simulation wind tunnel is the possibility that saltation may also lead to alteration in mineralogy and thereby not just the generation of dust, but also for example oxidation. This may explain the presence of the reddish iron oxide giving Mars its distinctive hue. On earth mineral change due to presence of liquid water and high atmospheric oxygen content probably makes such erosion induced mineral change only a minor and not easily identified process, though may also have importance through the chemical reactivity of the erosion generated dust. The mineral change appears to occur through mechanical activation of freshly cleaved surfaces, for example in the case of silicate leading to an oxidizing surface which may be hazardous to organic material [Merrison et al. 2010]. This phenomenon is as yet poorly researched and requires the further application of laboratory simulation.

10. Aerosol formation and sensing

Open circuit wind tunnels are poorly suited to studies of suspended particulates, i.e. aerosols, due to problems of contaminating the environment with the aerosol particulates and also since the aerosols only perform a single pass through the detection volume. This limits the type of aerosol dynamics which can be studied, for example investigating their temporal evolution would not be possible. In a re-circulating wind tunnel the aerosol can be confined and studied for long periods of time, limited only by loss due to settling and adhesion [Merrison et al. 2002, Merrison et al. 2008].

As discussed previously fine solid particulates (i.e. dust grains) generally tend to cohere and are found as large aggregates. In order to inject dust particulates into suspension these aggregates must be dispersed. A problem affecting many dust injection systems (aerosolizers) is that of blockages caused by dust aggregation (clumping). A system which functions well and is widely used in the medical industry for dry powder aerosol dispersion, is the use of a gas jet. When merged with the dust material, the process of gas expansion (usually from a nozzle) disperses and separates the aggregates. This same technique has been successfully employed in planetary aerosol simulation where (relatively) high pressure gas is passed through a chamber containing the dust material and subsequently expands at high velocity into the wind tunnel flow. This system of gas injection is also successfully applied in the case of liquid (droplet) aerosols. Liquid aerosols are commonly used in pharmaceutical applications, for example inhalers and the many types of commercial 'aerosol cans'. Another method for entrainment (suspension) which resembles that seen in nature, involves emplacing a thick dust layer in the wind tunnel and increasing the wind speed briefly in order to suspend it. Aerosols may also be formed as a result of condensation/precipitation from the gas phase. In this case a system of vapor injection from an external source may be utilized. Alternatively the vapor source could be internal to the system and be generated by heating to generate sublimation/boiling. This may be especially effective if the process of condensation (or nucleation) is to be studied. Surprisingly there is still a great deal yet to be understood about the properties of ice/water aerosols (e.g. clouds and snow). For example; the electrification process or processes which are responsible for generating lightening, the details of nucleation (for example by dust, radiation or ions), the micro/nano structure and adhesive/cohesive properties. It seems likely that this will be an active research field in the near future and that this will involve the construction of new low temperature environmental simulators, possible including re-circulating wind tunnel systems.

Particulate deposition from suspension is of great importance with regard to the climate as well as being a hazard to instrumentation, machinery and human health. Lacking commercial instrumentation to quantify this deposition process, a prototype optoelectronic instrument has been developed to determine the deposition rate of particulates [Merrison 2006]. This instrument also employs electrodes to generate electric fields and thereby attract electrified aerosol particulates. This method of determining the electrical charge (and sign) of suspended particulates could be of great use in industries dealing with aerosols. Electrostatic fields are already used routinely in industrial applications to remove or control particulates both in suspension and otherwise. Granular electrification is a ubiquitous effect and must be considered wherever granular material is found [Rasmussen et al. 2009]. In the case of dust particles electrification leads to the formation of aggregates which is key to the process of entrainment at low wind speeds (in the absence of saltating sand) [Merrison 2004a].
On earth aerosols may include (or consist) of biological material or micro organisms (such as pollen, virus, bacteria, spores, etc.). Bio-aerosols of this kind are clearly of great environmental interest with regard to health and ecology. It would be of much interest to study bio-aerosols and their production/transport mechanisms in a controlled environmental wind tunnel. Although such research is not currently active, there are plans to begin studies of this kind with relation to planetary protection (i.e. the protection of other planets from terrestrial micro organisms) by the space agencies NASA and ESA.

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Although great advances in computational methods have been made in recent years, wind tunnel tests remain essential for obtaining the full range of data required to guide detailed design decisions for various practical engineering problems. This book collects original and innovative research studies on recent applications in wind tunnel tests, exhibiting various investigation directions and providing a birdâ€™s eye view on this broad subject area. It is composed of seven chapters that have been grouped in two major parts. The first part of the book (chapters 1â€“4) deals with wind tunnel technologies and devices. The second part (chapters 5â€“7) deals with the latest applications of wind tunnel testing. The text is addressed not only to researchers but also to professional engineers, engineering lecturers, and students seeking to gain better understanding of the current status of wind tunnels.ã€€Through its seven chapters, the reader will have an access to a wide range of works related to wind tunnel testing.

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