An Environmental Wind Tunnel Facility for Testing Meteorological Sensor Systems


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ABSTRACT

Reliable and accurate environmental sensing is a cornerstone of modern meteorology. This paper presents a laboratory environmental simulator capable of reproducing extreme environments and performing tests and calibrations of meteorological sensor systems under controlled conditions. This facility is available to the research community as well as industry and is intended to encourage advancement in the field of sensor metrology applied to meteorology and climatology. Discussion will be made of the temperature, pressure, humidity and wind flow control, and sensing systems with reference to specific sensor test programs and future research activities.

1. Introduction

In atmospheric and climate research, a variety of meteorological sensor systems are employed globally. Calibration and cross validation of these meteorological sensors (and sensor systems) is vital for establishing reliable and accurate environmental data. This is especially important under extreme conditions, specifically low temperature, high or low humidity, and reduced pressure (at high altitude). The European Metrology for Meteorology (MeteoMet) project (Szymyka-Grzebyk et al. 2012) aims to promote a metrological approach to the climate and meteorological observations supporting the traceability of measurements involved in climate change—for example, surface and upper-atmosphere measurements of temperature, pressure, humidity, wind speed, and direction.

To achieve robustness and reliability of atmospheric measurements, improved calibration procedures and facilities for controlled laboratory observations are needed. In this manuscript a dedicated environmental simulator is presented with capabilities to control wind flow, pressure, temperature, and gas composition with the aim of allowing testing and calibration of meteorological sensors under a wide range of environmental conditions.

The environmental wind tunnel simulator [Aarhus Wind Tunnel Simulator II (AWTSII)] at Aarhus University is a unique prototype facility (Merrison 2011; Rasmussen et al. 2011) and represents the “state of the art” in simulating environmental conditions from the near surface through high altitude (stratosphere) and to just below the mesopause at around 90-km altitude. Two other low pressure wind tunnel facilities are in operation; though typically used for Mars research and sensor testing (Greeley and Iversen 1985; Wilson et al. 2008), they are not utilized for terrestrial metrology or meteorology. Low temperature wind tunnels are found in the aerospace and automobile industries but have not been applied to metrology.

AWTSII has been used extensively in the testing of anemometer systems and for planetary environment studies [in collaboration with the European Space...
Agency (ESA) and the National Aeronautics and Space Administration (NASA). It is capable of reproducing a wide range of environmental temperature, pressure, humidity, and airflow conditions in a system large enough to allow a high degree of stability, uniformity, and control. Specifically, it enables testing of large sensor systems and equipment, such as solar panels and weather stations, and due to the high degree of repeatability in the wind tunnel environmental parameters, detailed comparisons and calibrations of sensor systems can be performed under equal conditions.

2. Environmental wind tunnel facility

Much of the AWTSII design is based on an earlier prototype (smaller and less advanced) of an environmental wind tunnel system that is still in operation called AWTSII (Merrison et al. 2008). The basis of the AWTSII simulator is a climatic chamber housing a recirculating wind tunnel (see Fig. 1). The climatic chamber consists of a large cylindrical vacuum chamber (2.1-m inner diameter, 10-m length) that can be evacuated to a pressure of around 0.02 hPa and repressurized with gas (or air) to pressures up to 1000 hPa. Within the outer vacuum chamber is a layer of multilayer super insulation (www.jehler.com) used for thermally isolating the outer chamber from a relatively thin inner chamber wall.

Although the outer chamber is made from mild steel, it has been coated with a zinc alloy in order to be resistant to rusting in the presence of humid air. The inner chamber wall is made from stainless steel, and other structures within the wind tunnel are made from aluminum, enabling them also to be resistant to high humidity.

The facility has been constructed in three sections: one end section is dedicated to wind generation (see section 2a); the central section houses the sample mounting and thermal control subsystems (known as the test section); and the upwind section is designed for flow control, monitoring, and other forms of access. The wind tunnel system is also divided vertically into three sections, with the middle section being the main wind tunnel (experimental) volume and the sections above and below are used for the return flow (to recirculate the air/gas).

An important aspect of sensor testing is having adequate access to the sensor, specifically mechanical, electrical, and optical access. It is for this reason that eight large access ports [International Organization for Standardization (ISO) 320 flange] have been included within the test section; nine access ports are also available in other chamber sections (see Fig. 1). Important for anemometer testing, this allows laser-based wind flow sensing systems to quantify flow around the test sensors even during operation. The test section also includes a specially designed rotating sample mounting system to allow for variation of the relative wind angle during operation, as well as an light-emitting diode (LED)-based lighting system to allow for solar simulation (Merrison 2011).

The facility is fitted with a suite of environmental sensors monitoring temperature (section 2b), pressure (section 2c), and relative humidity (section 6); these are monitored using a network-based control and data logging system (http://www.isa.au.dk/consys).

a. Wind generation system

The wind generation subsystem consists of two (horizontal) fans mounted on a single (vertical) axle; each aluminum fan is 1.8 m in diameter (www.multi-wing.com) and driven by an electric motor (www2.nord.com) powered using a frequency generator to achieve rotation rates up to 1200 rpm. To avoid exposure of the (high power) motor to the controlled environment of the chamber, the drive mechanism for the fan system has been mounted externally and coupled to the axle with the use of a commercially available magnetic coupling of type MINEX SE165/24 (www.ktr.com). The magnetic coupling transfers
torque from the drive axle (external) to the fan axle (internal) through a complex of magnetic fields generated by permanent magnets. This avoids physical contact of the two axles and allows this coupling system to be hermetically sealed (vacuum tight). A drawback with this system is that the torque, which can be transferred by such a coupling, is limited. To protect the drive-fan system from damage caused by slippage of the magnetic coupling, limits to the rotation rate have been set in the control system software, resulting in a pressure-dependent maximum rotational rate of the wind tunnel as illustrated in Fig. 2.

Benefits of the recirculating wind tunnel design include the ability to have precise and independent control over the atmospheric parameters—for example, composition, temperature, pressure, humidity, and even aerosol content. These benefits, however, are at the expense of flow control; achieving low turbulence and high wind flow, especially at relatively high atmospheric pressure (>100 hPa), is problematic in this facility.

Within the fan section there is mounted a system of flow guides—that is, metal plates used for controlling the flow, enhancing wind circulation, and reducing turbulence and crosswind. Metal meshes (single and double layers) can also be placed between the test and upwind sections in order to reduce/control the turbulence.

The facility is equipped with an aerosol injection system, allowing for the suspension of particulates (dust and sand) in the wind flow. Depending on the application, aerosol clouds could also be used—for example, a smoke generator or a pure liquid water fogger. The aerosols are necessary for the use of laser-based wind flow sensing (see section 3).

b. Temperature control systems

Thermal control within the test section is achieved with the use of two (identical) aluminum cooling plates that make up the upper and lower surfaces.

Making these cooling plates massive (dimensions: 2 m × 1.8 m × 5 cm, mass: 480 kg) was intended to achieve thermal stability (high thermal inertia) of this system though at the risk of long cooldown times. Cooling is achieved by flowing cold nitrogen gas through a network of tubes embedded in the plates (i.e., injecting liquid nitrogen). The liquid nitrogen inlet is vacuum insulated (doubled-walled flex tubing), such that the gas within the chamber does not come into contact with cryogenic liquid nitrogen temperatures, which could possibly freeze—for example, CO2 gas.

An array of (>10) thermo-resistive temperature sensors [Farnell resistance temperature detector (RTD) pt100] is available within AWTSII. This set of temperature sensors may be placed in different orientations on the cooling plates, which give the advantage that the temperature can be monitored at the locations of most interest.

Each cooling plate can be independently cooled using computer-controlled liquid nitrogen valves (see Fig. 3). Temperatures as low as −170°C (around 100 K) have been achieved. This system was intended to allow sensors to be mounted on one cooling plate and held at a stable (cryogenic) temperature while the other plate could be used to adjust the frost/dewpoint and thereby control the humidity within the system (see section 6). Conversely, injecting water vapor into the chamber can allow for frost deposition—that is, a relative humidity of ≥100% at the sensor.

Because of the cold nitrogen entering on one side of the cooling plate and despite their thickness and high thermal conductivity, thermal gradients are seen across the cooling plates (see section 5).

Heating of the thermal control plates in the test section is achieved with the use of thin film heating elements (X-Mat) on the cooling plates. In total these may deliver up to 4 kW, and temperatures up to 80°C (around 330 K) have been reached with this system.

The test section is the only actively temperature-controlled component of the chamber (at present); however, recently a secondary cooling plate has been constructed (dimensions: 50 cm × 35 cm × 12 cm, mass: 60 kg) that may be mounted within the facility. This cooling plate is also based on a liquid nitrogen flow-through system, but it has an open internal structure (reservoir) that gives improved thermal stability and uniformity. It can therefore be used for applications where precise thermal control is required (<1-K fluctuations and <5-K temperature variance across the plate).

The two cooling systems available for use at the facility have inherently different characteristics due to their design. The choice of cooling system will ultimately depend on the test requirements. Typically, when seeking thermal control of a sensor system within the facility, the
greatest problem is not control of the cooling plate temperature, but rather establishing effective thermal contact (transfer) between the cooling plate and the sensor. This can be especially problematic if the sensor has a complex structure, has low thermal conductivity, and/or generates heat (during operation).

### c. Pressure control system

There are two types of pressure sensor used in the AWTSII chamber. A capacitance-type pressure sensor (Pfeiffer APR 250) is used to monitor the chamber pressure in the range 1–1100 hPa, independently of gas composition. For pressures below around 3 hPa, a Pirani gauge (Pfeiffer TPR 280) is used. This is accurate at low pressure and has a reliable range of around 0.01–100 hPa, though it becomes highly inaccurate for gasses other than air, especially at pressures above 1 hPa.

A specially adapted Edwards rotary (scroll) pump is used for evacuation of the AWTSII chamber. It is oil free and includes a dust protection filter. The pump is rated for 600 L s$^{-1}$ and can evacuate the chamber to 10 hPa in around 25 min. The ultimate pressure of the chamber is below 0.1 hPa. Figure 4 (left) shows the pressure measured during evacuation using both a capacitance and Pirani pressure sensor; they agree reasonably well in the range 1–100 hPa in air.

Although specialized gas mixtures can be produced, water outgassing is a source of impurity (especially at low pressure). Using the network-based control system, it is possible to regulate the input of gas and pumping of the chamber with remotely controlled valves. In this way it has been possible to establish a gas flow-through system capable of removing impurities while maintaining pressure within a certain range (e.g., ±0.5 hPa).

![Fig. 3.](image-url) The underside of the lower (sample mount) cooling plate showing the inlet (thicker) and outlet coolant pipes on the right, and also several pt100 temperature sensors mounted across the underside. (right) The liquid nitrogen inlet tube connected to a liquid nitrogen tank: 1) tube divides into two, with each having a remotely controlled valve; 2) flanges through which the coolant enters the chamber (lower and upper plates) can be also be seen; and 3) place at which the pumping line, valve, and pressure sensors are mounted.

![Fig. 4.](image-url) (left) AWTSII pressure recorded using the control system (data logging facility) showing the evacuation to low pressure. (right) Pressure calibration performed on the capacitance pressure sensor from AWTSII. Absolute pressure is calculated via the ideal gas law using a known mass of CO$_2$ injected into a measured volume evacuated vacuum chamber.
Calibration of the wind tunnel capacitance pressure sensors has been performed using a technique involving injecting a measured mass (weight) of CO₂ gas ($m_1$) into a measured volume ($V$)—that is, an evacuated vacuum chamber. Knowing the mass density of CO₂ at standard pressure and temperature (ST) and corrected for the measured temperature ($T_1$), the ideal gas law gives

$$P_1 = \left(\frac{P_{ST}}{\rho_{ST} T_{ST}}\right)(T_1 m_1 / V). \tag{1}$$

Note that typically gas density is used as the control parameter for quantifying the gas; the benefit here is that unlike the pressure, it is independent of the gas temperature [see Eq. (1)]. Figure 4 (right) shows the pressure measured by the AWTSII capacitance sensor against a calibrated capacitance sensor (SensorTechnics BTE6001). For pressures above 10 hPa, the greatest uncertainty in this determination became that of the volume of the chamber that was normalized at 1000 hPa to atmospheric pressure. Based on the most precise measurements, the AWTSII capacitance sensor has an accuracy of <5% for pressures below 11 hPa and 2%–3% for pressures above 100 hPa. More accurate pressure sensors could be considered for the higher pressure ranges, depending on the circumstances.

### 3. Wind flow characterization

Understanding the wind flow is crucial in order to perform anemometer testing within the AWTSII wind tunnel. Wind speeds and turbulence in the facility have been quantified using a commercial FlowLite 2D laser Doppler anemometer (LDA) (www.dantecdynamics.com) with a high spatial and temporal resolution (more details in section 7). For wind flow measurements, tracer dust is typically used with diameters of around 1 μm, such that at wind speeds of 10 m s⁻¹, structures as small as 1 mm still correspond to a Stokes number of around 0.1 (i.e., have low tracing errors).

The wind flow is controlled by the rotation frequency of the fans, measured using an internal tachometer (rotation sensor), which can be related to wind speed within the wind tunnel. Wind flow measurements have been made across the width of the test section for a combination of pressures (3–1000 hPa) and driving fan rotation frequencies (75–1100 rpm), yielding a calibration curve such that the generation of a particular wind speed can be produced; see Fig. 5. Although there is generally a linear relationship between axle rotation and wind speed, variations in flow characteristics and turbulence do occur, as environmental conditions are varied (see also section 4). Given the specific pressure, temperature, and sample position, the wind speed may be reproduced with even greater accuracy. Note that the maximum wind speed attainable falls as pressure increases (see section 2), with the maximum average wind speed obtainable at the center of the test section being around 18 m s⁻¹ for pressures around 10 hPa and around 3 m s⁻¹ at 1000 hPa (Earth atmospheric surface pressure). Preliminary experimental work shows that the wind speed in the test section can be increased by a factor of 3 for all pressures by reducing the wind tunnel cross section at the test section by a factor of 10.

Average wind speeds are not constant across the width of the test section (see Fig. 6) due to influences...
from the walls and flow irregularities generated mostly within the fan section. Wind speeds vary by as much as 40% across the entire (2.1 m) cross section. Despite the use of flow guides to hinder crosswind, rotation of the fans imparts an asymmetry in the flow.

The flow distortion created by the fans results in a wind direction that veers left from the wind tunnel axis when looking in the flow direction with an angle that depends on pressure and applied fan rotor rate. The effect is most pronounced at the lowest pressures (<30 hPa) and lowest wind speeds (<4 m s⁻¹), where the angle can reach up to 25°, resulting in a measured wind speed deviation of about 10% as compared with the actual flow speed. For higher pressures (above 30 hPa), and especially higher wind speeds, the deflection is less than 10° and the reduction in measured wind speed is typically lower than the turbulence (2%–5%).

Within the test section area, the boundary layer is about 15 cm in height, while at 25–75 cm above the lower cooling plate, measurements have shown that there is no vertical variation in wind flow (i.e., significantly below turbulence levels). Variation in the wind speed along the flow direction can occur as a result of the use of turbulence-reducing meshes, which is discussed in section 4. Although it has yet to be verified, the wind flow is not thought to vary strongly upwind of the test section and it may be possible in the future to utilize some of this section for testing, given suitable calibration.

4. Turbulence control

Turbulence is a measure of random macroscopic fluid motion and can occur on different temporal and spatial scales and in all dimensions. Turbulence is of importance, since it can be related to the shear stress applied by a flow (i.e., the friction velocity) (Merrison et al. 2008). Turbulence in the wind flow direction is typically defined as the standard deviation (σ) of a large set (n) of wind speed measurements (u)—

\[ \sigma = \sqrt{\frac{1}{n} \sum (u - U)^2} \]

and it is often expressed as a percentage of the mean wind speed (U). Note that the standard error of the mean wind speed (i.e., the uncertainty in the determination of the absolute mean wind speed) is given by σ/√n. Hence, even given high turbulence (large standard deviation), the accuracy of the wind speed determination can be made small by extensive measurement taking (large n). In this section, the focus will be on turbulence in the flow direction.

Without use of turbulence reduction, the turbulence levels are generally in the range 10%–20% at all pressures and wind speeds obtainable in the wind tunnel, as seen in Fig. 7 (solid lines). Although this is typical of turbulence levels in nature, lower values are desirable for anemometer testing and calibration. Turbulence can be dampened by the insertion of meshes in the wind tunnel at the boundary between the test section and the upwind section. Using a single fine stainless steel wire mesh (0.24-mm thread, 14-mm hole size), the turbulence can be reduced to below 10% for low pressures (<10 hPa). Two such meshes (a double mesh) are required to reduce turbulence to similar levels for all pressures higher than 10 hPa. The dashed lines in Fig. 7 demonstrate the effect of the double mesh at three pressures, where the turbulence is generally lowered to around 5% or less. Meshes are generally less efficient at lowering turbulence for higher pressures. As seen in Fig. 8, inserting meshes can lower the wind speed, but the effect is pressure dependent and insignificant for pressures above 100 hPa.

5. Temperature control

As outlined in section 2b, the cooling system within the test section is based on a computer-controlled liquid nitrogen valve steered by a pt100 temperature sensor mounted on each cooling plate close to the liquid nitrogen inlet.

The cooling plates in the test section can be cooled at a rate of up to 30°C h⁻¹, corresponding to a liquid nitrogen consumption of around 170 L h⁻¹ during cooldown (per cooling plate). Note that cooling lowers the gas temperature within the chamber and therefore pressure stabilization is required during cooldown. When the control system has reached the target temperature, it can take up to 2 h for the temperatures across the plate to stabilize. Once the plate temperatures have stabilized, they stay within ±1°C and liquid nitrogen...
consumption falls to around 40 L h\(^{-1}\). Thermal uniformity of the large cooling plates, however, is poor and temperatures across the plate can vary by 10°–30°C for plate temperatures between 0°C and −120°C. This non-uniformity is most extreme during the first few hours of cooling, when temperatures are relatively unstable. The gradients decrease as the AWTSII inner chamber cools. The temperature gradient across the central (1 m) region of the test section will be, at worst, around 10°–15°C at the lowest temperatures. Typical subsequent heat-up times for the cooling plates are on the order of 12 h, imposing timing restrictions on testing.

Little use has been made of heating and high-temperature operation of this facility. Testing demonstrated that, once stabilized, temperatures could be maintained within ±1°C at a temperature of 50°C, with temperatures across the plate varying by up to 20°C.

There is presently no dedicated air temperature control system within AWTSII, and air temperature is monitored by free-hanging pt100 temperature sensors. Air temperature is affected by the heat exchange between the cooling plates (within the test section), the inner chamber walls and windows, and the heating due to friction when operating at high wind speeds and from energy deposited from the fans. As only the test section is actively cooled, the upwind and fan section walls change little from room temperature. In the absence of wind flow, air temperatures comparable to those of the cooling plates can be achieved locally within the test section. Air temperature falls below 0°C over the course of several hours when cooling plates are at −100°C; however, the average (total) air volume is difficult to reduce to temperatures significantly below zero. Operation of the wind tunnel (wind flow) while at low temperatures (cooling plates active) causes an enhanced heat exchange with the air (gas), leading to measured cooling plate temperatures increasing by as much as 20°C at the highest wind speeds. Corresponding cooling of the gas is also observed, with an air temperature decrease of 3°–20°C h\(^{-1}\) for atmospheric (995 hPa) to low (10 hPa) pressures. A dedicated air temperature control system is desirable for future operations of the facility.

The secondary cooling plate (see section 2b) has a more efficient design than the main cooling plates. Figure 9 shows this smaller plate being cooled to −120°C, which takes just under 1 h. The prolonged temperature increase after about 1.5 h is due to an increase in pressure locally on the cooling plate during experimentation. Once cooled, the individual plate temperatures are stable to within ±0.5°C of the target temperature, and the temperatures across the plate do not vary by more than 4°C, making the secondary cooling plate significantly more stable than the main cooling plates.

![Fig. 8. Average wind speed at the center of the test section for (left) 10 and (right) 100 hPa with no mesh inserted as compared to the influence of a single or double mesh. Higher pressures are not displayed, as no change in wind speed is seen.](image)

![Fig. 9. Temperature measured at two opposing corners on the small cooling plate as the plate is cooled and temperature is held stable. Small increase in temperature during cooling is caused by changing the liquid nitrogen tank, and temperature increase at 1.5 h is due to the experiments being performed. Periodic cooling cycles used to maintain the target temperatures are evident in these data.](image)
6. Humidity control

The technique employed in the AWTSII facility for humidity control is through control of the frost/dewpoint—that is, the use of a condensation region held at a known temperature ($T_c$), which limits the partial pressure of water. This should be the lowest temperature region within the chamber. Typically, the test sensor would be mounted on one of the (lower or upper) cooling plates, while the other plate would be used for frost-point (humidity) control.

The humidity within AWTSII can be monitored with a (Honeywell) thin polymer film sensor. This sensor determines the relative humidity (RH). A specialized routine has been configured in the control system in order to run and readout this instrument. When combined with the temperature determination of this sensor ($T_{RH}$), the absolute humidity or partial pressure of water [pp(H$_2$O)] in the chamber atmosphere (at the sensor) can be determined through the relation $pp(H_2O) = pp_{max}(T_{RH}) \times RH$, where $pp_{max}$ is the saturated partial pressure of water at temperature $T_{RH}$ [i.e., the “expected frost point” curve in Fig. 10 for the RH temperature, taken from Weast (1972)]. Note that the advantage of conversion into absolute humidity is that it is independent of temperature and the pressure (of other gaseous components).

In Fig. 10 the measured absolute humidity is plotted for varying (upper plate) temperatures together with the expected partial pressure of water given the control frost-point temperature (at either upper or lower plate). As can be seen, although this humidity control system appears to function, there are large deviations in the measured humidity compared to the expected value; this is probably due to effects of residual outgassing and poor thermal control (uniformity/stability).

7. Anemometer testing

Each wind sensor technique has its own advantages and disadvantages—for example, laser-based anemometers are insensitive to local environmental conditions (fluid density, temperature, composition, etc.), but they require the presence of some form of suspended particulates (aerosols or dust).

There are therefore special requirements to environmental testing for each different anemometer type; these will be discussed in the following section. These discussions are based on specific anemometer tests that have been performed in the AWTSII wind tunnel facility and are intended to give the reader a deeper appreciation of the problems encountered during laboratory (wind tunnel) calibration/testing of these anemometer types.

a. Laser anemometers

Laser-based anemometers, specifically the LDA, are used extensively in wind tunnel applications. The principle behind the technique is the scattering and detection of light by suspended aerosol particles. By measuring the velocity-induced frequency shift (the Doppler effect), the particle velocity can be quantified. More specifically, two beams are used to produce an interference pattern, and measurement of the shift in this pattern allows for single-velocity components of the grains to be determined.

This technique has the benefit of being noncontact, such that it is independent of the local environmental conditions (temperature, gas pressure, composition, etc.). The technique is accurate, with high sampling rates (>1 kHz), and it 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. There are several variations on this instrument that can measure wind flow characteristics in multiple dimensions as well as image and can determine suspended grain size.

The system has the disadvantage of requiring the presence of suspended particulates within the flow. Typically, these are introduced as smoke, water droplets, or dust. For systems studying aerosols, this can be an advantage, since the suspended grain concentration can be quantified using this technique. Other disadvantages of LDA systems are that they are large in size/mass, high relative cost, and require optical access.

A FlowLite 2D LDA (www.dantecdynamics.com) is used as the primary wind sensor for AWTSII. It can...
access the width of the test section, but it is constrained in the vertical direction by the optical access granted through the flanges. The geometry of the measurement volume of the LDA is dependent on the choice of optics but is typically in cubic millimeters.

Miniature and potentially low-cost laser-based wind sensors are being developed, though they have yet to advance from prototyping. One such prototype system has been extensively tested in AWTSII and is well suited as an in situ flow validation sensor (see Fig. 11). It 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 (Merrison et al. 2004, 2006).

b. Mechanical (cup anemometers, vanes, and wind socks)

Mechanical anemometers are the most common form of wind sensor, with cup anemometers being most widely used for long-term meteorological studies. A cup anemometer consists typically of conical cups mounted on an axle 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. They are a typical component of weather/climatic stations and are seen to be robust, though are limited in range, accuracy, and response time. Since they measure applied wind shear stress, they are sensitive to gas density (pressure, temperature, and composition).

There are two problems associated with cup anemometers. First, they measure only in a single axis, giving an integrated measurement of two wind directions \([i.e., \, U = \sqrt{(u_x^2 + u_y^2)}]\) and not an average wind speed in an average wind direction. Second, they are prone to a problem termed “overspeeding,” which results from their inherent aerodynamic asymmetry: in a changing wind flow, the cup anemometers accelerate more easily than they decelerate. They therefore have a tendency to overestimate wind speed in turbulent flows (e.g., Hyson 1972).

The dependency of this type of sensor on gas density and turbulence requires detailed calibration if they are to be used in extreme environments. This sensor type has yet to be studied in the AWTSII facility.

c. 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 in wind tunnels. The principle is to measure the overpressure generated in a wind-facing tube compared to a nonwind-facing aperture. This pressure differential is a function of the wind speed relative to the tube \([\Delta P = \rho U^2 A]\), where \(A\) is the tube orifice area). They are therefore well suited to situations where the direction of the wind flow is known. For varying wind flow, Kiel probes are applicable for yaw directions of wind up to 45°, whereas multihole probes should be considered for 3D applications. Despite their wide use, the Pitot tube is typically limited in range (due to its strong dependence on wind speed) and requires careful calibration, since it is dependent on atmospheric density, specifically gas pressure, temperature, and composition. They also have poor response time (typically around 1 s) and are relatively inaccurate at low wind speeds and pressures where dynamic pressure cannot be accurately measured, or in situations where the gas temperature, and thus density, cannot be determined accurately.
A Pitot tube is permanently installed within the upwind section of AWTSII and is typically used as a crude wind flow validation when LDA operation is not possible (typically when particle injection cannot be performed); see Fig. 11. This sensor is not well suited to extreme environmental tests (e.g., low pressure and temperature) where accurate determination of the atmospheric conditions, especially the air temperature, becomes difficult (see section 5).

d. **Hot wire or hot film**

The principle of hot wire (or hot film) anemometry is to quantify the cooling rate of an electrically heated element by the air/gas (Bruun 1995). This increases when there is wind flow. Such anemometers are typically accurate (given detailed calibration) and sensitive in terrestrial conditions. They can also be multidimensional and have fast response times (<1 ms). Compared to mechanical (or Pitot) wind sensing techniques, they provide improvement in precision. There are many variations on 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 generally poorly suited to harsh environments. Prototype sensor systems have, however, been shown to function well at the low temperature, low pressure environment found at high altitude (>10 km), and through testing in AWTSII (Hudson et al. 2011).

Clearly of great importance is the environmental temperature (air temperature). In the present design of AWTSII, although there is control over the surface temperature within the test section, the air temperature is not well constrained with heating from the wind generator and upwind sections, but cooling within the test section. Details of air temperature control are presented in section 5.

Lacking effective air temperature control, it would be desirable to have effective thermal contact of the sensor (hot wire) head to a cooling plate. This is also problematic given the typically complex geometry of these sensor systems and the desire not to influence wind flow.

e. **Sonic anemometers**

Sonic anemometers are commercially available wind flow sensors used widely in meteorology. They utilize the transmission of high-frequency sound (ultrasonic) in order to measure wind flow by quantifying differences in the propagation speed. Using multiple transmitters/receivers, sonic anemometers can simultaneously measure wind velocity in all three dimensions and at high sampling rates. These sensors are precise and being three-dimensional, they are capable of quantifying vertical fluxes as well as lateral flow rates simultaneously. They can have relatively rapid response time (<0.05 s) and are well suited for turbulence determination (see section 4), though they typically have a relatively large measurement volume (>10 cm³), which limits their ultimate turbulent-scale sensitivity.

Although sonic anemometers are insensitive to gas pressure (density), they are sensitive to gas composition and temperature (section 5). Humidity strongly affects the transmission of ultrasound, and for meteorology there is also the effect of precipitation on the sensor. It is therefore of great importance in the testing (calibration) of sonic anemometers to be able to quantify and control the water vapor concentration within the chamber as well as air temperature (Richiardone et al. 2012). This is of particular importance to advanced sonic anemometers developed for low pressure (high altitude) operation (Banfield et al. 2012); see section 5.

8. **Conclusions**

Here we present a unique laboratory simulation facility for sensor testing and calibration in extreme environments, both terrestrial and other planetary bodies. It is hoped that this manuscript will help metrologists and meteorologists to gain a deeper appreciation of the capabilities and challenges of environmental simulation and sensor testing.

The facility is based on a recirculating wind tunnel within an environmental chamber and is capable of reproducing a broad range of atmospheric conditions, including pressure from 0.1 to 1000 hPa (i.e., altitude from 0 to 90 km) with a 2% accuracy; surface temperatures of the cooling plates in the range of −150° to 50°C with stability of 1°C; humidity control with partial water pressure from <0.1 hPa to relative humidity >100% (frost deposition) and wind flow up to around 20 m s⁻¹, though over a limited pressure range, specifically a maximum wind speed of around 3 m s⁻¹ at 1000-hPa pressure. Preliminary experimental work shows that the wind speed in the test section can be increased by a factor of 3 for all pressures, if the wind tunnel area upwind from the test section is reduced by a factor of 10. Wind turbulence can be controlled in the range of a few percent to around 20% with flow stability being better than this turbulence level.

Of special interest is the testing/calibration of wind sensors and discussion has been made of the specific requirements for a variety of common anemometers with regard to facility operation. Future major improvements
of this facility include implementation of a dedicated air temperature control system, boundary layer control inserts, and modifications to allow increased maximum wind speed at the highest pressure.

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