Centrifuge Health Monitoring of the 50gTon beam centrifuge at the University of Sheffield

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ABSTRACT: In order to fully understand scientific test data it is crucial that we first understand the background centrifuge operational environment and its variation with time and centrifugal acceleration. For example, changes in ambient air temperature or relative humidity in the centrifuge chamber during operation can have a significant impact on the evaporation levels of water from the surface of a clay model. It is vital to understand these temporal changes in order to mitigate drying out of the soil surface as this would have a detrimental impact on model performance. This paper details the development of a centrifuge health monitoring system capable of measuring environmental parameters over natural seasonal variations of the laboratory environment but also during test conditions. The results of a series of preliminary tests of different duration, acceleration and configuration are discussed to demonstrate the significant changes that occur in the scientific environment during operation.

1 INTRODUCTION

The new 4 m diameter 50 g-ton centrifuge facility at the Centre for Energy and Infrastructure Ground Research (CEIGR), at the University of Sheffield (Black et al. 2014), is equipped with a “Centrifuge Health Monitoring” (CHM) system. This system allows direct measurement of many important aspects inside the structural containment chamber and the laboratory environment such as temperature, humidity and pressure. The purpose of the CHM system is to generate a database of environmental measurements that will contribute to improved operations in CEIGR ensuring:

- an intimate working knowledge of the laboratory operational environment and temporal changes that occur with annual variation and locally during centrifuge operation.
- mitigation of test errors / awareness of issues such as potential evaporation of fluids from models in flight that could impact negatively on experimental tests.
- confirmation that adverse effects from the operational environment can be isolated from the test observations of complementary test datasets collated over many years.
- Understanding the machine performance and contributing to towards a maintenance log and scheduling.

The paper describes the development of the CHM sensors and electronics, and briefly outlines a series of preliminary tests that were conducted to demonstrate the extent of the changes that occur during testing. It is hoped that this paper will serve to emphasize the possible impacts that arise from changes in the ambient temperature and relative humidity to model conditions and thus encourage other centrifuge facilities to implement similar CHM systems.

2 DEVELOPMENT OF THE CENTRIFUGE HEALTH MONITORING SYSTEM

Figure 1 shows an overview of all the components included in the centrifuge health monitoring system. At the heart of the CHM system is a National Instruments (NI) 6211 USB data acquisition device comprising of 16 analogue input channels, 8 general purpose digital I/O, and 2 analogue output channels. Sensors are mounted on two plates which are housed in an inclusion, 50 mm in diameter, in the centrifuge chamber wall. One plate is mounted internal within the centrifuge chamber; measuring environmental parameters in the vicinity of the centrifuge, the other plate and associated sensors are mounted externally of the chamber measuring the same variables in the main laboratory environment. A M16 threaded bar connects the two plates through the chamber wall aperture. The internal and external plates are shown in Figure 2 (a) and (b), respectively showing the positions of each sensor.

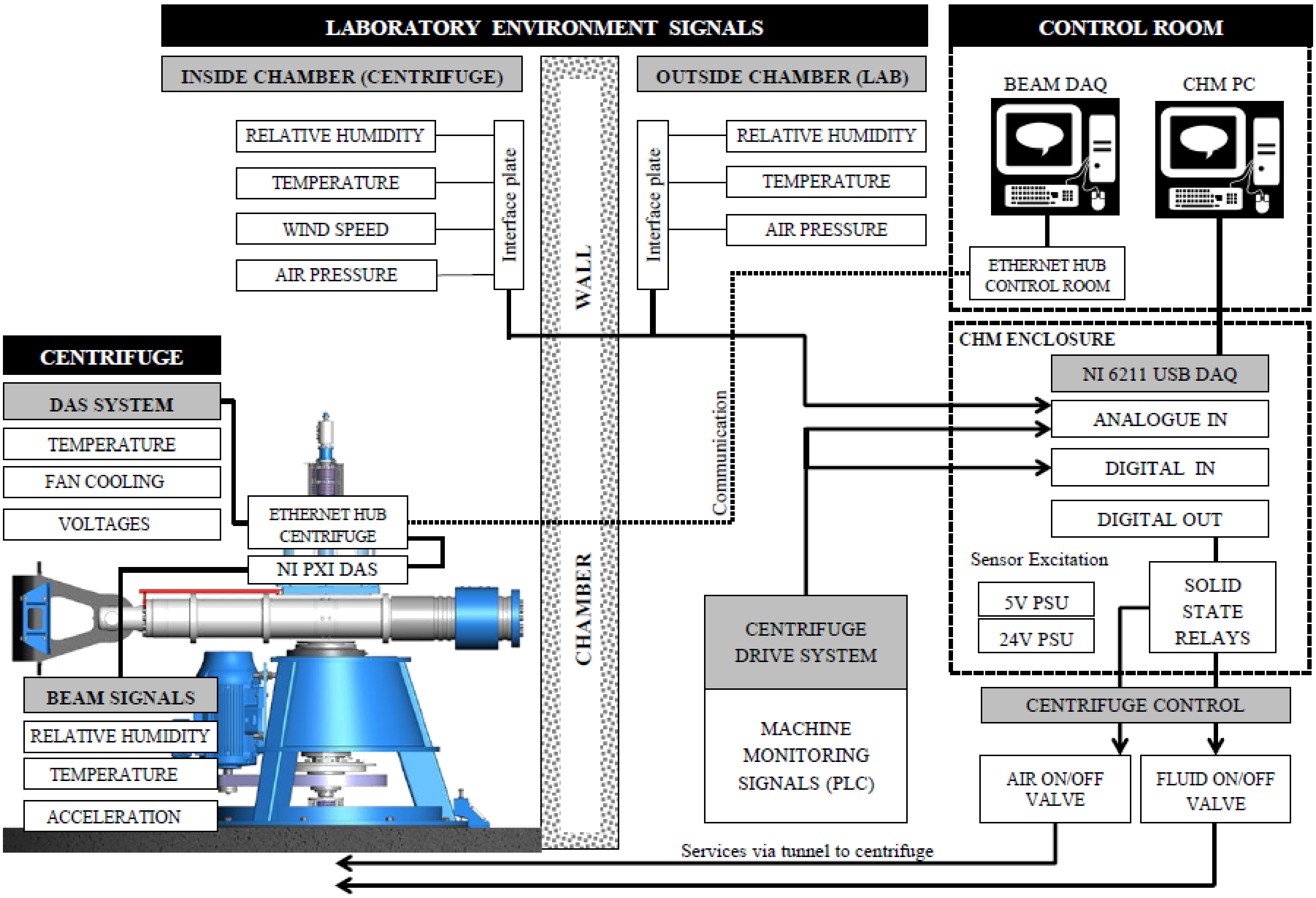

Figure 1. Centrifuge health monitoring system overview.

Low cost off-the-shelf sensors with analogue voltage output were selected to measure temperature, relative humidity, pressure and airflow. Table 1 below gives a summary of characteristics of the mounted sensors.

Table 1. CHM sensor characteristics

	Sensor type			
	Temp	RH	Pressure	Airflow
Range	-20-70	0-100	0-15	0-3
Units	ºC	%RH	psi	m/s
Sensitivity, mV/[unit]	10	31.5	5	~600
Input Voltage, V	5	5	5	5
Rated Current, mA	1	0.5	1.5	15

Two Ethernet signal cables, ≈20 m in length, are used to connect the sensor outputs and a 5 V excitation source to the health monitoring system enclosure located in the control room. The sensor signals are filtered using a simple first order filter with a cutoff frequency of ~5 Hz. The filtering is carried out in order to remove electrical interference noise induced along the cabling.

Provisions have been made for the CHM system to monitor signals used by the centrifuge programmable logic controller (PLC) for machine control and safety (see Figure 1). The PLC will provide information relevant to the machine's operational conditions such as rotational speed and balancing forces.

The CHM system is also to be used to control the flow of both air and water to the hydraulic/pneumatic union which supplies these services to the model mounted on the machine's platform. This is achieved using digital output signals from the NI 6211 USB unit used to control two solid state relays which switch power to on/off solenoid valves external to the chamber.

Measurements of model temperature and relative humidity are also recorded using the main centrifuge data acquisition system (DAS) which is a NI PXIe-1085 chassis capable of measuring and controlling numerous analogue and digital signals. The sophisticated circuitry inside the chassis carries out measurement of a range of internal signals to monitor the health of the chassis including; temperatures, fan speeds and voltage supply levels. These health signals are accessible through a network connection to the chassis and are recorded by the CHM system.

A LabVIEW Virtual Instrument (VI) was developed as a control panel interface to the CHM hardware for monitoring and recording the environmental signals, displaying live video feeds obtained from IP cameras located inside the chamber, and for controlling air and water supplies to the model.

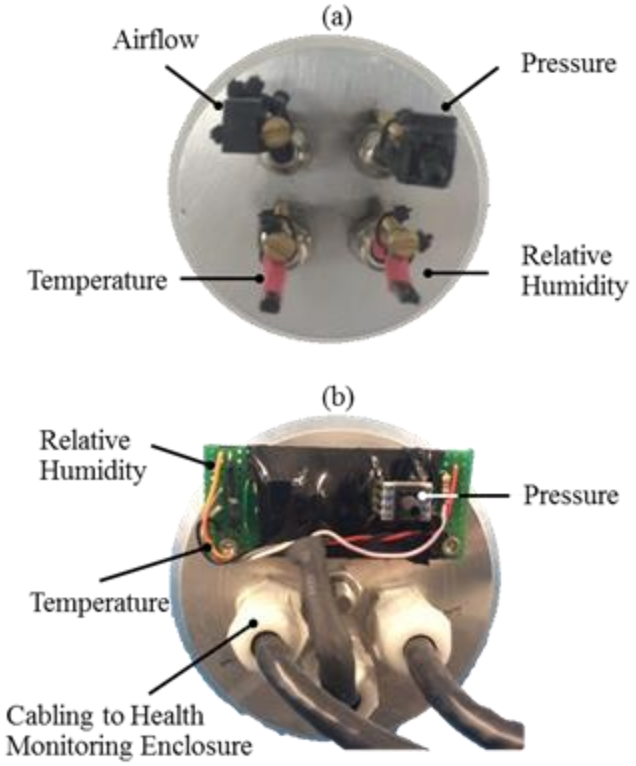

Figure 2. CHM sensors (a) inside the centrifuge chamber and (b) in the laboratory.

3 PRELIMINARY HEALTH MONITORING TEST RESULTS

3.1 *Dry-sample testing, 1hr duration, variation with g-level*

A series of tests were carried out in order to determine changes in environmental conditions occurring during centrifuge operation. Three 1 hour duration tests were conducted over an 8 hour period, during the same day. The g-level, N, for the three tests was 50, 75 and 100g, respectively. Note that in each of these tests a model consisting of dry sand only was tested. The centrifuge tub had a diameter and internal clear height of 0.5 m

Figure 3 (a) shows the temperatures recorded at the model, external and internal to the chamber, T_m, T_e, and T_i, respectively. Figure 3 (b) shows the measured relative humidity at the same locations, RH_m, RH_e, and RH_i, respectively. Figure 3 (c) shows the g-level, N, during the course of the testing obtained from the on-board accelerometer. For the purposes of this study the focus will be the temperature and relative humidity behavior as these are important in understanding changes in the test environment and therefore model characteristics.

It is evident in Figure 3 that fluctuations in temperature occur while the centrifuge is in operation. From a reasonably stable temperature condition, a sharp rise can be observed within the chamber as the 50g test commences. It is also interesting to note that the temperature continues to increase throughout the duration of the test run by approximately 2°C. Also of note is that the model payload indicates a gradual increase, albeit not to the same absolute value as the chamber but at a similar rate. An initial rapid decrease in temperature occurs within the chamber as the beam comes to a halt, noting further reductions but not returning to the original temperature at the start of the test. At 50g little change is observed in the background laboratory conditions.

Increases in temperature of up to 4°C are observed for proceeding 75g and 100g tests, although it is highlighted that the rate of increase is considerable and temperatures increase at a higher rate during the test. While some effect may be evident from the previous test runs hence the heat generated has not fully dissipated to the original level; it serves to illustrate that during testing the centrifuge environment can vary extensively which must be appreciated and considered.

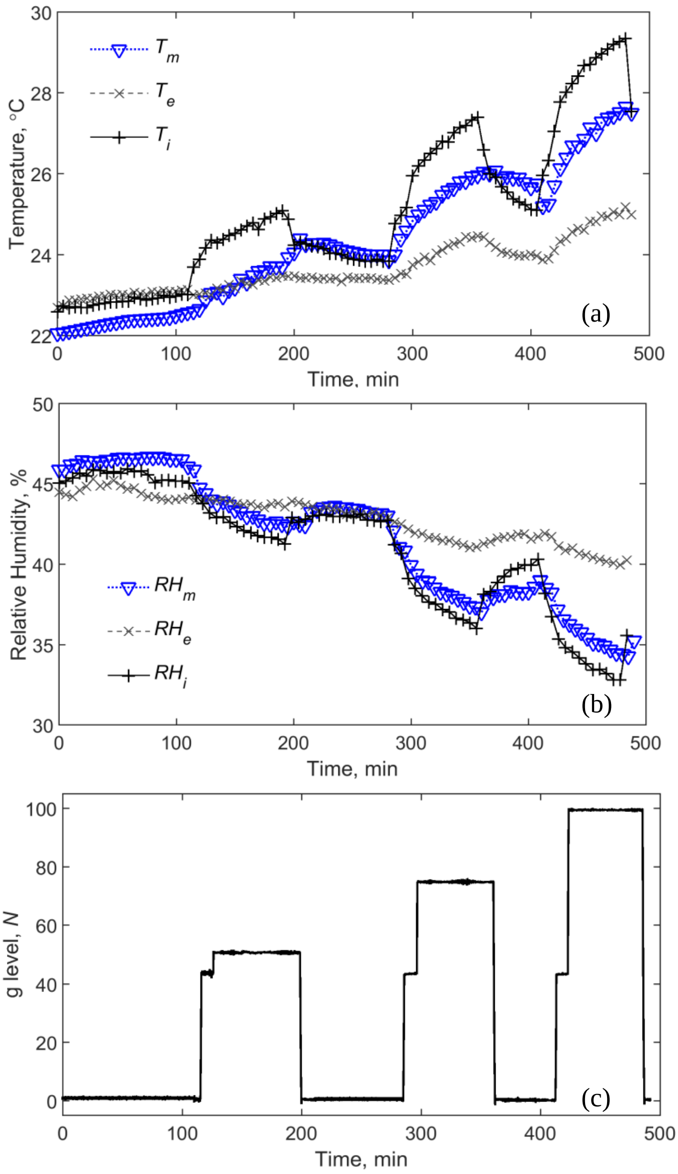

Figure 3. 1 hour duration tests; (a) temperature, (b) relative humidity, (c) g-level.

Referring to the relative humidity measurements, a decreasing trend is observed as temperature increases. This effect is observed at all locations, but is more prominent internal to the chamber and at the model. In general, humidity decreases with increasing temperatures. The water vapor carrying capacity of the air effectively doubles with every incremental increase in temperature. The humidity level is reduced accordingly (by twice the temperature change) as the water vapor, or gaseous phase of water, is transformed to airborne moisture. This trend is clear in Figure 3; for example, the total increase in internal chamber temperature of 4ºC, during the 100g test, is reflected by a reduction in relative humidity of around 8%. This inversely proportional relationship is consistent across all tests in Figure 3, and at all three locations. Based on this simplistic relationship between temperature and relative humidity, relative humidity, RH_{est}, can be estimated from the internal chamber temperature from Equation 1:

$$RH_{est} = RH_a - 2\partial T_i \tag{1}$$

where RH_a is the ambient relative humidity recorded either at the start of testing, assuming relatively static ambient conditions are maintained, or from continuous ambient measurements recorded during the test.

For the relatively short duration tests considered, the change in internal temperature appears to follow a pattern where an initial transient increase is followed by a roughly linear increase with duration. Analysis of the test data revealed the gradient of increase in internal temperature, the linear portion of the response, to be a function of g-level. Once the acceleration has reached 50g, the temperature increases at a rate of approximately 12 mºC/min, whereas at 100g the rate observed is around 40 mºC/min. Figure 3(a) shows this characteristic is apparent at the model, where temperatures increase at roughly the same rate. Model temperatures are less sensitive to the initial increases in g-level (the initial transient portion of the response) since the sensor is located on the rotating beam; where it is subjected to higher airflow inducing cooling effects which are related to the rotational acceleration and speed of the machine.

The characteristics of Figure 3 clearly show that dynamic changes are occurring; environmental conditions have not reached a steady-state after an hour, the rate of change decays, implying that longer duration tests would reach static temperature and relative humidity levels.

3.2 *Dry-sample testing, long duration, constant g-level*

Examination of the temperature trends of Figure 3 shows an inverse exponential relationship which is proportional to duration. In order to characterize the temperature-humidity response over longer durations at constant g-level, tests were conducted where the g-level was maintained at $N = 50$ over 6 and 12 hour periods. Note, as these tests were conducted on different days the initial relative humidity conditions were different in each case and ranged between 34% and 52%.

Figure 4 (a) shows changes in measured internal chamber temperatures during these tests. Test 1 was conducted for 6 hours; tests 2 and 3 for a duration of 12 hours. Figure 4 (b) shows the changes in measured relative humidity.

The temperature rise can be approximated using the inverse exponential relationship to duration given in Equation 2.

$$T_{est} = T_a + A(1 - e^{-t/\tau}) \tag{2}$$

where t is the elapsed time in minutes, A is an estimate of the total increase in temperature (when it has reached equilibrium) and τ is the time constant, which is the time taken for a signal to rise to 67% of its steady-state value. The change in temperature at steady-state for tests 1 and 2, A, can be approximated to be ≈4.5ºC. In Test 1, which is the standard configuration for the CHM test series, it takes a time constant, τ, of around 155 minutes to reach 67% of this change.

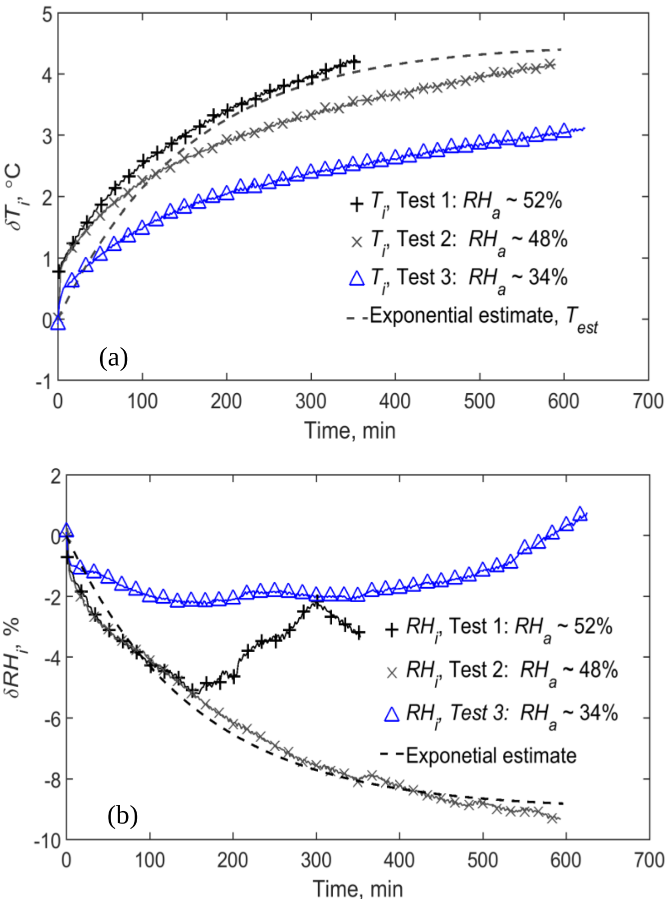

Figure 4. Long duration centrifuge tests; (a) internal chamber temperature, (b) internal relative humidity.

The temperature calculated from Equation 2 can then be used to calculate changes in relative humidity using Equation 1, requiring only a single value of initial ambient temperature to approximate temperature and humidity changes with duration.

The estimation using the above derived values of A and τ is plotted in Figure 4 (a) and shows good overall agreement with the measured response for Test 1 and Test 2. During test 3, the initial relative humidity was only ≈34% therefore the test was started under relatively drier conditions than those of Tests 1 and 2. Under such circumstances it is to be expected that the changes to humidity (and temperature) generated from the machine's rotation will be lessened as the amount of both water vapor and moisture in the atmosphere is reduced.

In Test 1 the exponential estimates show a reasonable agreement with temperature and humidity up until a time of around 150 minutes for the tests conducted at the higher relative humidity of 48% and 52%. However, after 150 minutes the measured relatively humidity value in Test 1 (RH= 52%) begins to diverge from the estimated values considerably. While the centrifuge was spinning in Test 2 other clay mixing/preparation activities were taking place in parallel within in the main laboratory. Consequently, increased levels of water vapor and moisture would be expected in the main lab external to the chamber, which was confirmed by the CHM RH sensors located in the main laboratory. It is inevitable that the air within the laboratory will be circulated into the chamber (via the perforated roof shroud) by air currents generated by the motion of the centrifuge. Hence, the environmental conditions inside the chamber are likely to also be affected to some degree by outside activities in the main laboratory. This explains the observed behavior in Test 1 whereby following the initial decrease in RH, an increase is observed in the period of the other clay preparation activities. After around 300 minutes, the relative humidity response begins to decrease once again along a similar gradient to that estimated. Interestingly no consequential change in the temperature characteristic was observed which is possibly nullified by temperature lag effects or the relatively rapid wetting/drying of the air.

Initial relative humidity and subsequent ambient humidity changes play an important role in the rates of chamber temperature and humidity variation. The inter-dependency between the connected laboratory preparation and centrifuge chamber spaces is an important factor. Further tests considering (i) durations, (ii) g-levels, (iii) different initial temperature and humidity conditions and (iv) parallel activities are currently being conducted to establish more comprehensive knowledge of the centrifuge environment to establish best practice guidelines.

3.3 *Wet-sample testing.*

A 6 hour duration test was conducted in order to simulate the environmental effects of a saturated sample being tested. A worst-case condition was considered whereby the cylindrical container detailed in the Section 3.1 was filled with water.

The water level was checked manually after approximately each 2 hour period, requiring the machine to be momentarily stopped during the test run. Figure 5 (a) and (b) show the temperature and humidity responses, respectively. The periods in the responses where levels change sharply indicate intervals of machine deceleration, stoppage and reacceleration, to record the water level.

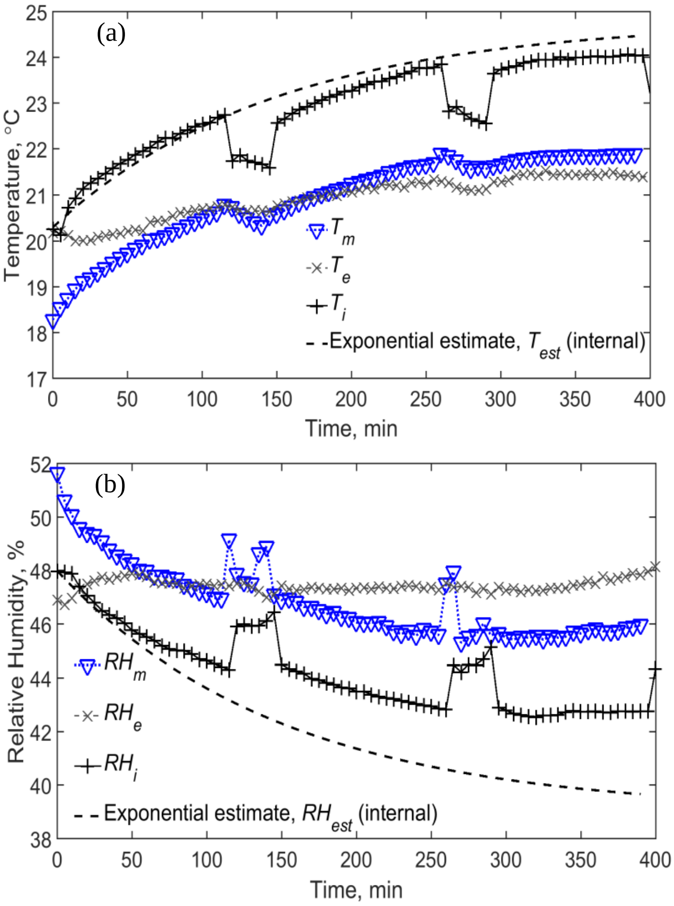

Figure 5. Wet sample tests at 50g; (a) temperature, (b) relative humidity.

Changes in temperature and relative humidity are inversely proportional and appear to tend towards zero after a total duration of around 300 minutes at N=50, implying an environmental equilibrium is approached where the temperature and humidity are relatively static. Although the machine was stopped for intervals of around 20-25 minutes the data shows the temperature and humidity trends continue to follow a general exponential pattern with time, regardless of the interruption. The internal chamber humidity estimate (Equation 1), derived from the estimated increase in temperature from Equation 2, appears to diverge significantly from the measured values. As the machine rotates, evaporation of the fluid in the tub will occur; evaporation is further increased also by the subsequent rise in temperature in the chamber.

Comparing humidity changes between the dry sample test of Figure 4 (b) and Figure 5 (b) in the initial 150 minutes and noting the initial RH were similar; the change is around 5%, and 3% for the dry and wet samples respectively. During this time the equivalent temperature increase was around 2.5ºC in each case. The general relationship where humidity reduces at double the increase in temperature (see Equation 1) no longer holds true, as evaporation effects act to lessen the desiccation rate of the internal chamber and model environments.

Table 2 shows the water level, and calculated volume of evaporated water, v_e, taken at intervals of approximately 2 hours.

Table 2. Evaporation of wet samples.

t, min	w_l, mm	v_e, ltr	RH_i,%	T_i,ºC
0	450	0	48	20.0
110	448	0.38	44.3	22.7
260	446.5	0.66	42.5	23.7
390	444.1	1.11	42.4	24.0

The trend is approximately linear with duration, indicating that a roughly constant rate of evaporation was occurring throughout the test duration. The rate of evaporation depends on both the heat available to the liquid and the strength of the intermolecular forces between the molecules.

At a humidity level of 100%, the air is at saturation point and evaporation is inhibited. As the humidity level, relative to saturation, is lowered, the pressure difference between the gaseous and liquid phases is reduced such that the intermolecular forces of attraction are more easily broken and the molecules migrate to a gaseous state with greater ease, and evaporation increases. This, in turn, has a cooling effect on the surface of the water, causing the relative humidity to increase, and consequently the evaporation rate to reduce in a cyclic fashion. This interaction between temperature and relative humidity is complicated by the evaporation process, which is in turn dependent on humidity and temperature as well as other factors including: the area of the water surface, airflow across it, and pressure differential between gaseous and liquid phases.

As established, the airflow conditions in the chamber cause the temperature to increase over time, in dry sample testing and with relatively static conditions the humidity appears to decrease at an inversely proportional rate to temperature. With saturated samples, the evaporation of the surface water appears to arrest the rate of humidity decline to equilibrium where the evaporation rate is sufficient to stabilize the humidity at a higher level than observed for dry tests.

While further testing is required to establish a comprehensive working knowledge of RH and temperature for saturated samples; the reduction observed in the water level clearly demonstrates that if drying and evaporation effects are not fully considered they could have a detrimental impact to scientific tests. For example, an intended saturation specimen could quickly become partially-saturated in the upper region if no or insufficient fluid is present at the surface, thus affecting the observed test performance such as a shallow footing bearing capacity problem.

4 CONCLUSIONS AND FURTHER WORK

An environmental health monitoring system has been installed in the University of Sheffield Centre for Energy, Infrastructure and Ground research 50gTon centrifuge facility. The system is used to monitor variations in atmospheric conditions during centrifuge tests and over seasonal variations. Preliminary tests have been conducted with both dry and liquid samples, where g-level and test duration was varied. The rotation of the centrifuge acts to increase the internal chamber and model temperatures with increasing g-level. Changes in humidity are inversely proportional to temperature in relatively static ambient conditions. Humidity levels were observed to be higher and to stabilize when testing wet samples (where surface water evaporation plays a role) than those observed with dry samples. Over long durations, the responses tend to a steady-state; in 50*g* tests conducted with equivalent initial conditions the internal temperature rise settles at ≈4ºC, relative humidity levels generally decrease at rate of twice the temperature change, but are somewhat dependent on sample conditions (wet or dry), initial relative humidity and changes to ambient conditions occurring during the test.

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6 REFERENCES

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