Effect of Ambient Temperature on the Calibration of Thermal Conductivity Suction Sensors

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ABSTRACT
Soil suction is one of the stress state variables for describing unsaturated soil behavior. Unsaturated soil properties are a function of soil suction and as a consequence, the measurement of soil suction becomes extremely important to the implementation of unsaturated soil mechanics into geotechnical engineering practice. Thermal conductivity (TC) suction sensors can be used for the *in situ* and laboratory measurement of soil suction. The indirect measurement of soil suction uses the thermal conductivity measurement on a specially designed porous ceramic to provide a measure of soil suction. Soil suction values can be obtained by calibrating the sensors in the laboratory prior to installation in the field. A question has arisen regarding the sensitivity of the calibration curves to the ambient temperature. The present research study focuses on determining a calibration procedure that compensates for ambient temperature. Experimental calibration studies were undertaken at the Golder Unsaturated Soils Laboratory in Saskatoon, using a new custom built calibration cell placed in a controlled temperature environment. Three sets of calibration curves were measured on the TC suction sensors corresponding to three different but constant temperatures. The temperatures selected for the calibration study were 10°C, 21°C and 35°C. The calibrations consisted of measuring the thermal conductivities of the sensors at 10 different applied suctions ranging from completely saturated to completely dry states. The results of the experimental measurements were analyzed to provide an improved calibration procedure that takes into account the affect of ambient temperature.

RÉSUMÉ
La succion des sols est l'une des variables de l'état de stress servant à décrire le comportement des sols non saturés. Les propriétés des sols non saturés sont une des fonctions de la succion du sol. Par conséquent, la mesure de la succion du sol devient extrêmement importante dans l'exécution de la mécanique des sols non saturés dans la pratique de la géotechnique. Les capteurs de la succion de la conductivité thermique (CT) peuvent être utilisés in situ ainsi qu'en laboratoire afin de mesurer la succion du sol. La mesure indirecte de la succion du sol utilise la mesure de la conductivité thermique d'une céramique poreuse spécialement conçue afin de fournir une mesure de la succion du sol. Les valeurs de succion du sol peuvent être obtenues en effectuant un étalonnage des capteurs en laboratoire avant l'installation sur le terrain. Une interrogation a surgi concernant la sensibilité des courbes de calibration de la température ambiante. L'étude met l'accent sur la détermination d'une procédure de calibration compensant pour la température ambiante. Des études expérimentales d'étalonnage ont été menées au Laboratoire des sols non saturés de Golder, Saskatoon, en utilisant une nouvelle cellule de mesure d'étalonnage crée sur mesure et placé dans un environnement à température contrôlée. Trois séries de courbes d'étalonnage ont été mesurées sur les capteurs de succion TC correspondants à trois températures différentes, mais constantes. Les températures sélectionnées pour l'étude d'étalonnage ont été 10°C, 21°C, et 35°C. Les étalonnages consistaient à mesurer la conductivité thermique des capteurs à 10 différentes succions appliquées, allant de complètement saturé à complètement sec. Les résultats des mesures expérimentales ont été analysés afin de fournir une procédure de calibration améliorée qui tient compte de l'effet de la température ambiante.

1 INTRODUCTION

The verification of unsaturated soil theories in engineering practice is generally accomplished through the *in situ* measurement of soil suction and water content. Thermal conductivity (TC) soil suction sensors constitute a promising technique for the measurement of soil suction. Being an indirect soil suction measurement system, they utilize the thermal conductivity measurement of a specially designed porous ceramic to provide a measurement of soil suction. The *in situ* soil suction is obtained through the use of a calibration curve that is measured in the laboratory prior to installation in the field.

Thermal conductivity sensors have been used in the laboratory as well as in the field (Wong et al. 1989; Nichol et al. 2003; Nguyen et al. 2010). Currently, thermal conductivity sensors are available commercially (e.g., GCTS and Campbell Scientific, Inc.). The GCTS Fredlund Thermal Conductivity (FTC) sensor and Campbell Scientific Inc. thermal conductivity sensor (CSI 229) have a matric suction measurement range from 10 to 1,500 kPa.

This study focuses on determining an accurate calibration procedure for FTC suction sensors that compensates for the ambient temperature at which the *in situ* measurements are made.

2 LITERATURE REVIEW

There are a number of research studies that have been undertaken to assess the influence of temperature on the

measurements of soil suction when using TC suction sensors. The effect of ambient temperature on the sensor readings has been observed since the 1970's (Phene et al. 1971; Wong et al. 1989). Concern over temperature changes has been expressed when using both the FTC and CSI 229 sensors. The following literature review briefly summarizes the findings published on the GCTS FTC suction sensors.

In 2002, Shuai et al. conducted a series of tests in an attempt to quantify the effect of ambient temperature on the measurement of soil suction when using the GCTS type of TC suction sensor. These tests were performed on sensors manufactured at the University of Saskatchewan, Canada, but were of the same design as those used in the current GCTS FTC sensors. The experimental procedure adopted by Shuai et al. (2002) involved varying the temperature over a narrow range for constant suction values. Based on their experimental results, a correction equation was proposed of the following form:

$$\Delta V_{23} = \frac{0.0014T + 0.5743}{0.6065} \Delta V_T \qquad [1]$$

where T is the soil temperature, ΔV_{23} is the output voltage at 23°C and ΔV_T is the output voltage at temperature T. It should be noted that the equation was based on the assumption that the change in suction reading with changing temperature was due solely to changes in the thermal conductivity of water. However, the temperature corrections are also applied in the high suction range (i.e., when there is little or no water in the sensors). The proposed correction had some theoretical justification when the ceramic is filled with water but has no justification when the sensors are dry. Figure 1 shows the Shuai et al. (2002) correction applied to a typical GCTS TC sensor calibration curve measured at 23°C. If the thermal conductivity of water was primarily responsible for the temperature effects it would be more reasonable to have all temperature correction curves converge to a single point at suction of about 100,000 kPa. Figure 1 clearly indicates that this is not the case.

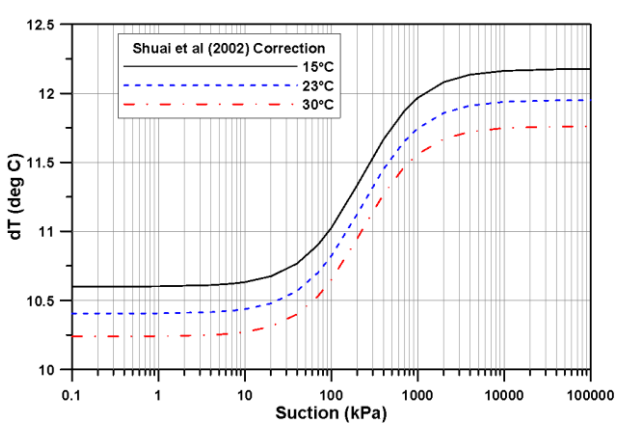

Figure 1. The Shuai et al. (2002) temperature correction applied to a typical GCTS TC sensor calibration curve.

Nichol et al. (2003) also studied the effect of ambient temperatures on the TC suction sensors. Their study also involved the use of TC suction sensors from the University of Saskatchewan. Based on their findings, a more rigorous temperature correction model was proposed to take into account the effect of ambient temperature for different suction regimes. The proposed correction factor was expressed as:

$$\Delta T_{23oC} = \Delta T(s_1 + s_2 T + s_3 T^2) \qquad [2]$$

where ΔT is the change in temperature measured by the suction sensor, ΔT_{23oC} is the corrected temperature change that can be applied to the 23°C calibration curve, T is the ambient temperature, and s_1, s_2, and s_3 are constants that depend on the range of suction being measured. The details of these constants can be found in Nichol et al. (2003).

Figure 2 shows a plot of the Nichol et al. (2003) temperature corrections for the range from zero degrees to plus 40°C. The plot clearly indicates that the largest corrections are applied when the soil suctions are the lowest (i.e., 0 to 10 kPa). The Nichol et al. (2003) correction factor appears to be justifiable in the sense that the main corrections are applied when the TC suction sensor is wet. Figure 3 shows the effect of the Nichol et al. (2003) temperature correction when the ambient temperature is changed over the temperature range from 15°C to 30°C.

Hu et al. (2007) undertook a study in which the Shuai et al. (2002) and the Nichol et al. (2003) correction techniques were applied. The two correction procedures produced quite similar results. A study was also undertaken by Tan et al. (2004) where both the Shuai et al. (2002) and Nichol et al. (2003) corrections were applied to 7 years of field measurement data. The temperature corrections were reported to be quite similar using both procedures.

3 CALIBRATION OF THERMAL CONDUCTIVITY SUCTION SENSORS

Thermal conductivity suction sensors are usually subjected to limited calibration prior to shipment from the factory. One calibration reading is usually taken with the sensors placed in water (i.e., zero matric suction), and a second reading is taken when the sensors are completely dry. Other calibration points at various applied suctions can be obtained but may not be measured on each sensor prior to their shipment from the factory. The two-point factory calibration procedure may be adequate for some applications; however, it has been suggested that a more rigorous calibration procedure is necessary when the sensors are used for geotechnical engineering applications (Wong et al. 1989).

3.1 Equation for the Calibration Curve for the FTC Suction Sensor

A number of equations have been used to best-fit the

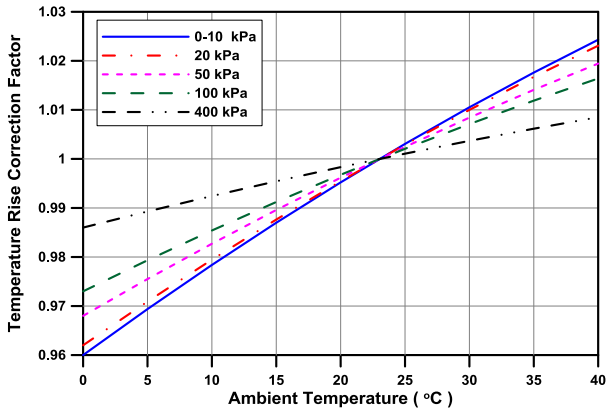

Figure 2. Graphical representation of the Nichol et al. (2003) temperature corrections.

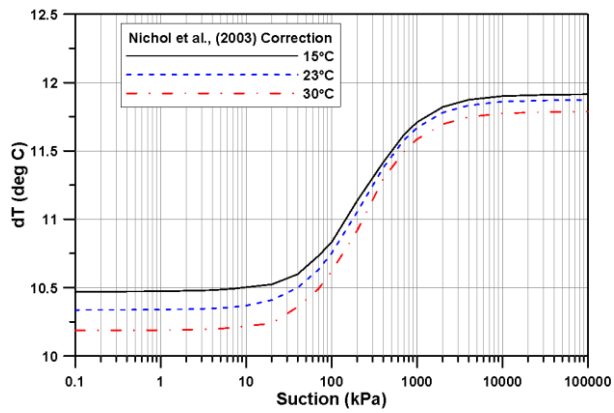

Figure 3. The Nichol et al. (2002) temperature correction applied to a typical TC sensor calibration curve.

calibration data for the FTC suction sensors. Details of these equations can be found in Feng and Fredlund (1999), Feng and Fredlund (2003) and Hu et al. (2007). The details pertaining to recently proposed calibration equations by Hu et al. (2007) are as follows.

Hu et al. (2007) proposed a modification to the equation by Feng and Fredlund (1999), in an attempt to provide a more significant physical meaning to each of the fitting parameters. The modified equation is illustrated in Figure 4 and the equation can be written as follows:

$$\psi = b_1 \left[\frac{\Delta T - a_1}{c_1 - \Delta T} \right]^{d_2} \qquad [3]$$

where:

$$d_2 = d_1 \left[\frac{c_1 - a_1}{4 b_1} \right] \qquad [4]$$

where ψ is the suction, and a_1, b_1, c_1 and d_1 are fitting parameters.

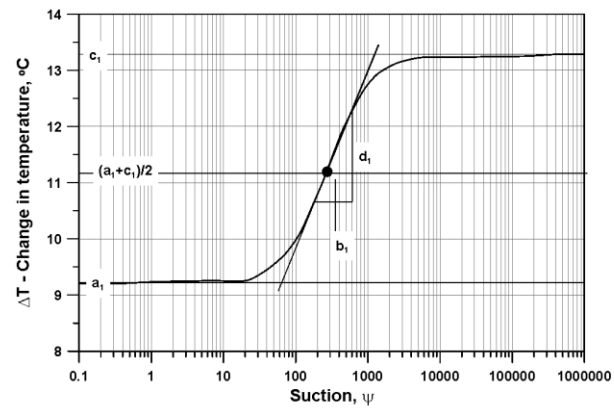

Figure 4. Illustration of the modified Feng and Fredlund (1999) TC suction sensor calibration equation.

From the illustration of the calibration equation, it is quite expedient to obtain two, "anchor-type" points on the calibration curve. The first calibration point represents the reading from the sensor when the ceramic stone is completely dry. This point is referred as c_1 in the calibration equation and is representative of the thermal conductivity of the ceramic stone with air filling the voids. It should be noted that it is important to define what is meant by a dry ceramic stone. It is possible for the "dry ceramic stone" to be initially air dried, initially oven-dried, or initially placed above salts that create an extremely high total suction environment (i.e., total suction ranging from 10,000 to 1,000,000 kPa). A recommendation is made regarding the definition of a "dry ceramic stone" in the conclusion section of this paper.

The second calibration point represents the reading from the sensor when the ceramic stone is saturated with water. In this case, the measured thermal conductivity represents the thermal conductivity of the ceramic stone with water filling the voids. This point is referred as a_1 in the above-mentioned calibration equation. Similar to the completely dry state of the sensor, it is again important to precisely define how the ceramic stone should be saturated with water. It is possible for the "wet" or "saturated ceramic stone" to be immersed in water for a period of time. It is also possible to attempt to thoroughly saturate the ceramic through the use of an applied backpressure or applied vacuum to withdraw air bubbles from the ceramic. Previous research studies (Feng and Fredlund, 1999; 2003) have clearly shown that simply immersing the ceramic stones in water for a period of time does not fully saturate the sensors. Occluded air bubbles appear to remain entrapped in some of the voids in the ceramic. It was found that back-pressuring the ceramic resulted in higher degrees of saturation and a change in the thermal conductivity measurement. A recommendation is made regarding the procedure advocated to obtain the water saturated thermal conductivity measurement of the sensors in the conclusion section of this paper.

The parameter b_1 is the suction at the inflection point along the calibration curve. In other words, it is mid-way between the "dry" and "saturated" sensor readings. Stated another way, b_1 designates the suction when ΔT is

equal to $(a_1 + c_1)/2$. The parameter d_1 is the arithmetic slope of the curve at point b_1 (See Figure 4).

Equation 3 is used to interpret the results from the present study on the temperature effects on the calibration curve. The proposed four fitting parameters have physical meaning and as such have the most meaningful parameters for the assessment of the influence of the ambient temperature.

4 EXPERIMENTAL PROGRAM

The experimental program consisted of calibrating eight TC suction sensors at three different but constant temperatures. The FTC sensors used in this study are the commercial version of the previously tested prototype models developed at the University of Saskatchewan (Shuai et al. 2002; Feng and Fredlund 2003; Nichol et al. 2003; Shuai et al. 2002 Tan et al. 2004). The selected temperatures were 10°C, 21°C and 35°C. The calibration program consisted of measuring the thermal conductivity of the sensors at the following suctions; namely, completely dry conditions, saturated conditions, 7 kPa, 15 kPa, 30 kPa, 50 kPa, 100 kPa, 200 kPa, 300 kPa, and 450 kPa. The details of the calibration equipment, temperature control system, and test protocols are provided in the following sections.

4.1 Description of Calibration Cells

Special calibration cells were designed for the purpose of this testing. Each sensor was placed within an individual calibration cell. Figure 5 shows the three primary components of the calibration cell; namely, the top cap, the main calibration chamber, and the lower base with a 500 kPa air-entry value ceramic disk. The ceramic disk is fixed in-place using epoxy. A series of small diameter holes are drilled through the metal portion below the ceramic stone to allow for the drainage of water during calibration. An air pressure can be applied to the main chamber, and O-rings provide air tight seals between the sensor cap and the inside of the calibration chamber. The electrical lines from the sensors pass through the cap of the individual calibration cells.

4.2 Temperature Control System

The soil laboratory is maintained at a temperature near 21°C. No other attempt was made to ensure that the temperature remained at precisely 21°C for the first set of calibration measurements. An insulated chamber with a temperature control unit was used to keep the ambient temperature at a constant value while calibrating the sensors at 10°C. The chamber consisted of a hydraulically operated “hood” that could be placed over-top of all the calibration cells. A refrigerator system allowed the temperature to be kept at a temperature of 10°C. A slightly different system was used to maintain high temperatures. In this case, light bulbs were used to raise the temperature in the chamber to around 35°C. A relay switch was used to turn the light bulbs on and off in order that the temperature could be maintained at a constant value.

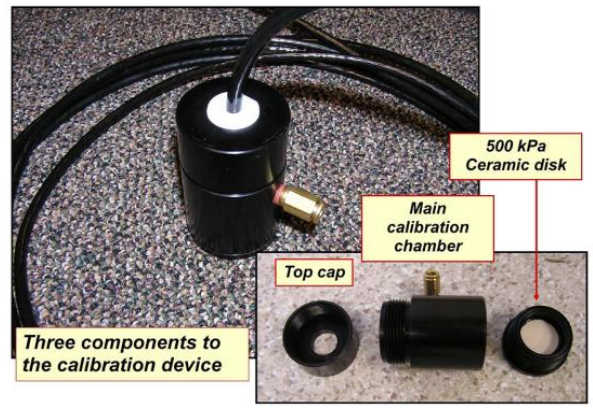

Figure 5. Components of the individual calibration cell

4.3 Test Protocol

The first sets of measurements were made at 21°C. In general, the sensors were first allowed to come to equilibrium with the air in the room. The laboratory temperature was approximately 21°C and the relative humidity was about 30%. The sensors were then immersed in water and readings were taken as the sensors took on water. The sensors were then placed into the calibration cells and allowed to come to equilibrium under an applied suction of 7 kPa. Approximately 2 days were allowed for the sensors to come to equilibrium with each applied suction. The same procedure was repeated for suctions of 15, 30, 50, 100, 200, 300, and 450 kPa. The sensors were then removed from the calibration cells and allowed to dry in the air at room temperature.

After performing the calibrations under room temperature conditions, the sensors were then placed into a controlled temperature environment held at 10°C. The calibration procedure started with saturating the suction sensors and then applying the same range of suction values as previously used in the 21°C environment. It should be noted that the suction sensors were not first tested in their air-dried state prior to commencing the calibration under applied suctions. The air-dried readings were measured at a later date.

After calibration testing was completed at 10°C, the sensors were then placed into a controlled temperature environment maintained at 35°C. The calibration procedure started with the sensors fully saturated. The same range of suctions as previously used was then applied to the calibration cells. Once again, the sensors were not first tested in their air-dried state prior to commencing the calibration under applied suctions. The air-dried readings were measured at a later date. This is not the procedure that is recommended for future calibration protocols.

Near the end of the calibration program it became apparent that significant care needed to be taken when making the measurements on the completely “dry” and completely “wet” sensors. The completely “dry” and “wet” sensor measurements become the “anchor points” on the calibration curves and care needs to be taken in detailing the exact procedure that should be used for their determination.

5 EXPERIMENTAL RESULTS

The calibration data for measurements made at temperatures of 10, 21, and 35°C is shown in Figures 6 to 8. The results indicate that there is a general downward movement of the calibration data as the ambient temperature is increased. The movement is more pronounced at higher temperatures (i.e. temperatures greater than 21°C).

Best-fit regression analyses were performed on each set of calibration data. After studying all the data, it was concluded that engineering judgement should also be used in the interpretation of some of the data associated with the completely "dry" and "wet" data. The best-fit lines shown in the above mentioned figures are based on the results of regression analysis and engineering judgement. It can be observed that the best-fit lines provide good representation of the actual measurements.

6 INTERPRETATION OF CALIBRATION RESULTS

Best-fit regression analyses were performed on each of the calibration curves and relevant parameters were determined for each set of measurements. Table 1 shows the best-fit regression parameters from the calibration results conducted at three different temperatures.

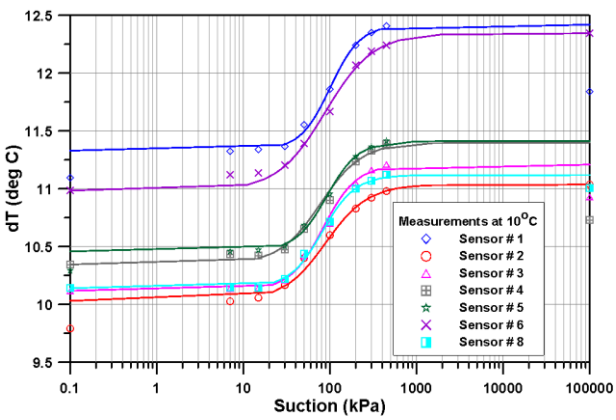

Figure 6. Calibration data for measurements at 10°C.

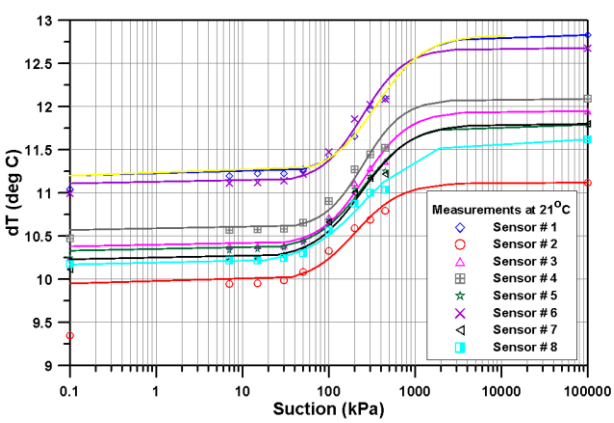

Figure 7. Calibration data for measurements at 21°C.

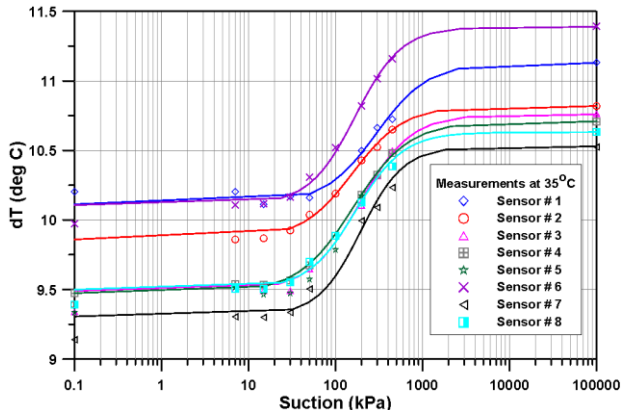

Figure 8. Calibration data for measurements at 35°C.

The a_1 parameter for all suction sensors under three temperature conditions is shown in Figure 9. As described earlier, this parameter is associated with the sensor readings obtained under "wet" or saturated conditions. From Figure 9, it can be observed that for all the sensors tested, the parameter is rather insensitive to temperature conditions between 10°C and 21°C. A decrease in the a_1 parameter can be observed as the calibration temperature is increased to 35°C. A second order polynomial was best-fit through the data and the resulting equation is shown as a solid black line. The R-squared value was estimated to be 0.509. Taking into consideration the 95% confidence interval plots it is suggested that the best-fit equation should not be considered as reliable outside the limiting temperatures of 10°C and 35°C.

The c_1 parameter is associated with the sensor

Table 1. Best-fit regression parameters from the calibration results conducted at three different temperatures.

Sensor #	Temperature (°C)	Parameters			
		a_1 (°C)	b_1 (kPa)	c_1 (kPa/°C)	d_1
1	10	11.3	100.8	12.4	149.3
1	21	11.2	354.6	12.8	560.6
1	35	10.1	294.2	11.1	800.2
2	10	10.0	89.4	10.1	199.9
2	21	10.0	200.2	11.1	425.2
2	35	9.9	158.2	10.8	449.8
3	10	10.1	83.7	11.2	136.9
3	21	10.4	256.1	12.0	391.7
3	35	9.5	191.4	10.8	406.4
4	10	10.4	97.5	11.4	174.8
4	21	10.6	250.5	12.1	353.9
4	35	9.5	191.2	10.7	357.0
5	10	10.5	91.9	11.4	161.3
5	21	10.3	247.0	11.8	443.8
6	10	11.1	111.4	0.0	196.9
6	21	11.1	245.8	12.7	354.2
6	35	10.1	169.6	11.4	324.6
7	21	10.2	240.3	11.8	404.8
7	35	9.3	194.4	10.5	363.7
8	10	10.1	81.8	11.1	146.7
8	21	10.2	255.0	11.6	559.7
8	35	9.5	170.4	10.6	382.0

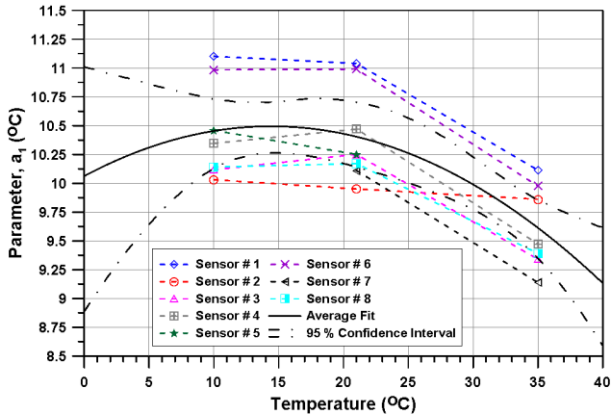

Figure 9. The a_1 curve fitting parameters corresponding to "wet" conditions.

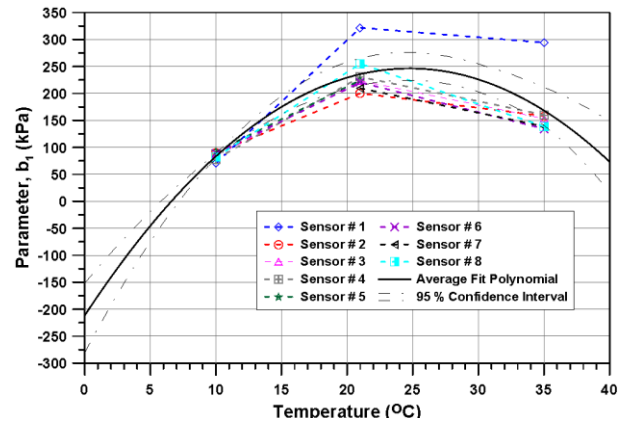

Figure 11. The b_1 curve fitting parameters corresponding to suction at the inflection point.

readings obtained under "dry conditions", corresponding to a high suction reading. When plotted on a logarithmic scale, the c_1 parameters were assumed to correspond to a suction of 100,000 kPa. Figure 10 shows the plot of the c_1 parameter for each sensor under three temperature conditions. All sensors show essentially the same trend; namely, that the highest readings occur at 21°C and there is a reduction in the readings at both an increase and decrease in temperature. A second order polynomial was once again best-fit through the data and the resulting equation is shown as a solid black line with an R-squared value of 0.507. Taking into consideration the 95% confidence interval plots it is suggested that the best-fit equation should not be considered as reliable outside the limiting temperatures of 10°C and 35°C.

The b_1 parameter represents the suction at which the response of the sensor is one-half way between the a_1 and c_1 temperature readings, corresponding to the inflection point on the calibration curve. It also corresponds to the suction at which the sensors are most responsive to suction changes. Figure 11 shows the plot of the b_1 parameter for each suction sensor under three temperature conditions and indicates that the highest change in temperature response occurred at an ambient temperature of 21°C. When the ambient temperature either increased or decreased from 21°C, the b_1 parameter decreased in magnitude. This behaviour was observed for all suction sensors tested. It should also be noted that the b_1 parameter was essentially the same for all sensors tested when the calibration temperature was 10°C (i.e., 83.4 kPa). Once again a second order polynomial was best-fit through the data and the resulting equation is shown as a solid black line. The R-squared value for this fit was estimated to be 0.744. The 95% confidence interval plots suggest that the best-fit equation should not be considered reliable outside the limiting temperatures of 10°C and 35°C.

The d_1 parameter represents the arithmetic slope of the change in temperature response of the suction sensor at a point corresponding to the b_1 parameter. Figure 12 shows the plot of the d_1 parameter for each suction sensor under three temperature conditions, and indicates that the highest change in temperature response of the suction sensors occurred near an ambient temperature of 21°C. When the ambient temperature either increased or decreased from 21°C, the d_1 parameter decreased in magnitude. This behaviour was observed for all suction sensors tested. It should also be noted that the d_1 parameter was essentially the same for all sensors tested when the calibration temperature was 10°C (i.e. 156

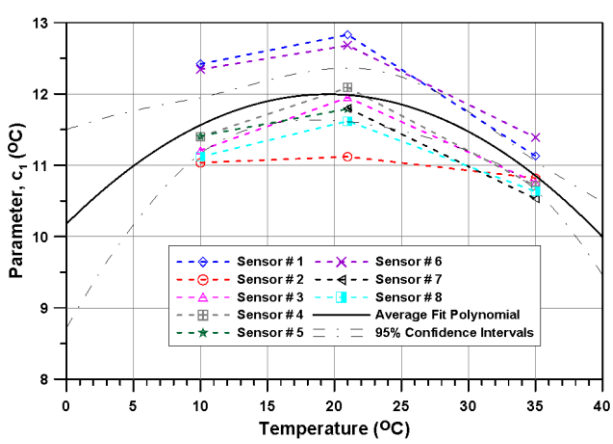

Figure 10. The c_1 curve fitting parameters corresponding to "dry" conditions.

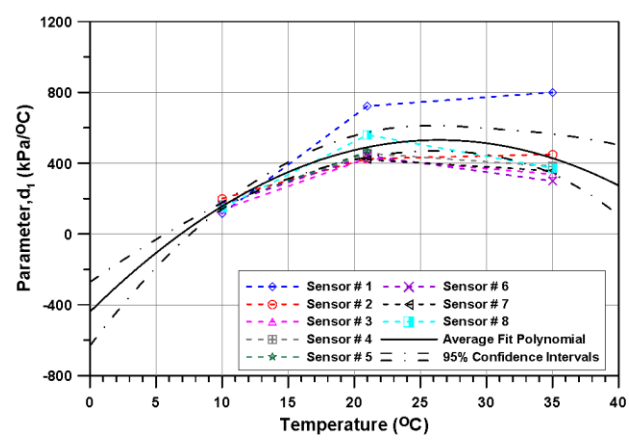

Figure 12. The d_1 curve fitting parameter corresponding to the slope at the inflection point.

kPa/°C). A second order polynomial shown as a solid black line in Figure 12 was fitted to the data with an R-squared value of 0.643. The 95% confidence interval plots suggest that the best-fit equation should not be considered reliable outside the limiting temperatures of 10°C and 35°C.

7 SUGGESTED TEMPERATURE CORRECTIONS

The desired intent of this study is to determine correction factors that could be applied to a TC suction sensor calibrated at 21°C. It was rationalized that all suction sensors showed similar responses to changes in the ambient temperature and as a result it should be possible to apply average empirical temperature corrections to all calibration curves.

Figures 9 to 12 presented the analysis of the four fitting parameters required for the sensor calibration curves corresponding to three different ambient temperatures. Each of the calibration curve parameters versus temperature was best-fit with a 2nd degree polynomial. However, it was felt that there was insufficient justification for the use of a polynomial for practical purposes, particularly when the desired intent is to recommend temperature correction factors that could be applied to any calibration curves that were measured at about 21°C.

The general forms of the corrected fitting parameters to be used in the calibration curve equation can be written as shown in Equations 5 to 8. It is assumed that the calibration equation corresponding to 21°C has either been measured or estimated in some reliable manner. The temperature correction values would be determined through the use of a normalization process applied to the measured results from this study.

The effect of temperature on the fitting parameters would be normalized to the results at 21°C. It was also reasoned that it would be better to use linear relationships between temperature and the correction factors rather than using the results from the best-fit polynomials. The best-fit polynomials tended to exaggerate the results as the temperature exceeded 35°C or went below 10°C.

$$a_1(T) = a_{21} + \Delta a_1(T) \quad [5]$$

$$b_1(T) = b_{21} + \Delta b_1(T) \quad [6]$$

$$c_1(T) = c_{21} + \Delta c_1(T) \quad [7]$$

$$d_1(T) = d_{21} + \Delta d_1(T) \quad [8]$$

The normalized temperature corrections for the parameters a_1 and c_1 are shown in Figure 13. The corrections are normalized to the average parameter values at 21°C and are expressed as a percentage. Corrections corresponding to temperatures lower than 10°C and higher than 35°C were taken to be constant values due to insufficient data. Similarly the normalized temperature corrections for the parameters b_1 and d_1 are shown in Figure 14. From these figures, it can be observed that the a_1 temperature correction is small at

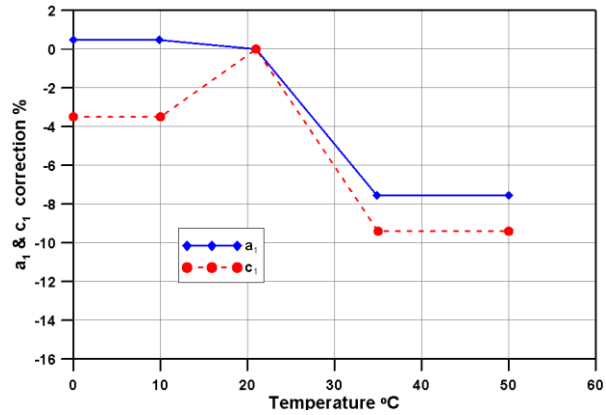

Figure 13. The a_1 and c_1 corrections due to ambient temperature difference from 21°C.

temperatures below 21°C. The b_1 correction is also small for temperatures below 21°C. These observations are in contrast to the temperature corrections for parameters b_1 and d_1, where corrections below 21°C are much larger than corrections at temperatures above 21°C. This suggests that parameters a_1 and c_1, corresponding to the completely dry and wet conditions, are more sensitive to temperatures in excess of 21°C. Similarly, it can also be concluded that the parameters b_1 and d_1, which correspond to the location of the point of inflection and its slope, are more sensitive to temperatures below 21°C. Table 2 provides the values for the correction factors presented in Figures 13 and 14. The correction factors between the 10°C to 21°C and 21°C to 35°C can be linearly interpolated.

Figure 15 shows a series of 4 calibration curves corresponding to ambient temperatures ranging from 15°C to 30°C. The curves are generated by using average parameters from experimental measurements at 21°C and scaling the curves at the other temperatures using the procedure described above. It is clear that the calibration curves vary considerably as the ambient temperature conditions are changed. The primary change in the form of the calibration curve is a vertical shifting of the curves in a downward direction as the temperature is

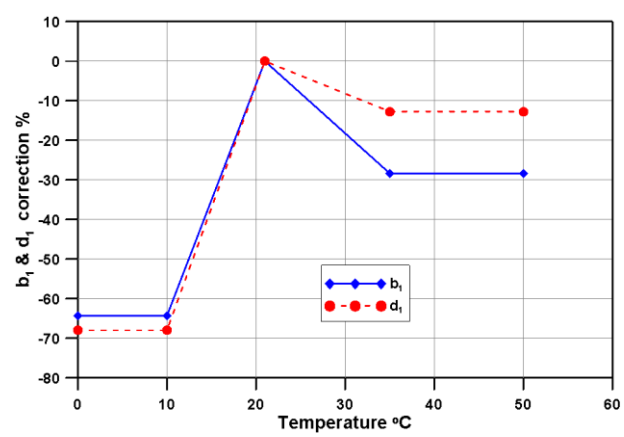

Figure 14. The b_1 and d_1 corrections due to ambient temperature difference from 21°C.

Table 2. Correction factors for ambient temperature correction

Correction factors	Temperature		
	$0^oC \leq 10^oC$	21^oC	$35^oC \leq 10^oC$
Δa_1 (T)	0.048 x 10.48*	0	-0.076 x 10.40*
Δb_1 (T)	-0.646 x 235.7*	0	-0.286 x 235.7*
Δc_1 (T)	-0.035 x 11.99*	0	-0.0944 x 11.99*
Δd_1 (T)	-0.682 x 490*	0	-0.126 x 490*

* Average value of the respective parameter

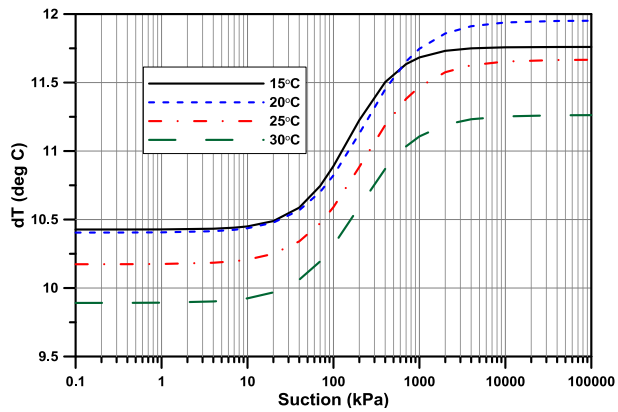

Figure 15. Comparison of the calibration curves corresponding to various temperatures.

increased above 21^oC. It should be noted that the measured temperature corrections are quite different than those proposed by Shuai et al. (2002) and Nichols et al. (2003). While it would be preferable to have more data from the calibration testing of many TC sensors tested at an even wider range of temperatures, it is suggested that the measured temperature corrections are likely the most accurate representation of ambient temperature effects available at this time.

8 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

- All available information suggests that the ambient temperature has an affect on the entire calibration curve of TC suction sensors. There are four fitting parameters that are required to define the TC sensor calibration curve and all four parameters appear to be a function of the ambient temperature.
- The a_1 parameter associated with the reading on a "wet" ceramic shows a decrease in the change in temperature response as the ambient temperature is increased. The temperature influence when the ambient temperature is below 21^oC appears to be quite small.
- It would appear that the ambient temperature influence on the a_1 parameter is affected by other factors than simply the thermal conductivity of water. In other words, the Shuai et al. (2002) and Nichol et al. (2003) corrections may not fully provide a theoretical basis for the influence of ambient temperature changes.
- The c_1 parameter associated with the reading on "dry" ceramic shows a decrease in the change in temperature response as the ambient temperature is increased.
- When the a_1 calibration parameter at 21^oC shows an increased value, the c_1 parameter likewise shows an increased value. It is speculated that the relationship between the "wet" and "dry" readings may be related to the slight porosity differences between various TC sensors.
- There appears to be no sound reason why readings on the "dry" suction sensors are affected by the ambient temperature conditions. Explanations provided to-date regarding the influence of high temperature conditions on the "dry" sensors have not been experimentally verified.
- It is recommended that for future tests the TC suction sensors be first tested in the completely "dry" state. The sensors should NOT be placed into an oven to be dried out. Rather, they should first be left at room temperature for at least one day, then placed inside a container which contains salts that will create an atmosphere with a total suction of approximately 100,000 kPa (e.g., magnesium chloride or lithium chloride). The sensors and salts should be maintained for at least three days at a temperature of 21^oC. The sensors can then be read to obtain the so-called "dry" condition reading. Additionally the sensor readings should be checked every three hours to ensure that the readings remain essentially constant
- For measurements at saturated conditions, it is recommended that sensors be partially immersed in water for one day to allow the ceramic to take on water while allowing air to move out of the ceramic. After one day, the sensors can be completely immersed under water for an additional day. The sensors should then be placed into the calibration cells with a thin paste of kaolin placed on the base of the ceramic to ensure hydraulic contact between the ceramic and the high air entry disk. The assembled calibration cell can be almost filled with water and a vacuum of about 80 kPa (i.e., -80 kPa absolute) should be applied to the cell. The readings on the sensors should be checked every three hours to ensure that the readings remain essentially constant.

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