

## THEORETICAL BASIS OF ESTIMATION OF MOISTURE CONTENT BY CAPACITANCE METHOD

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A theoretical expression for capacitance exerted by hygroscopic granular material has been derived. This expression was found to relate capacitance with bulk density and moisture content. The derived expression was verified using four grades of tea, BOP, BOPF, Dust I and BM. There was close agreement between the theoretical expression and the measured data. It is concluded that for the accurate estimation of moisture content by this method both bulk density and capacitance must be known.

### INTRODUCTION

Measurement of moisture content of made tea is an important practice carried out in tea processing factories to ensure that the quality of the finished product does not deteriorate. At the end of the drying process tea should have a moisture level of about 3% (wet basis), whereas at the time of packing of tea in chests or bags for delivery, the moisture level is expected to be less than 6%.

There is no international standard method for measurement of moisture in black tea, but the determination of loss of mass at 103°C (ISO 1573 — 1980 (E)) is usually taken to be the moisture estimation method. This method or similar oven-based methods are not practicable in routine factory use.

Moisture determination by Infra Red Bulb method is very popular in tea processing factories, but this method is subject to a large number of inaccuracies.

Several manufacturers of equipment have developed moisture meters based on the capacitance method. However, in the models tested at the Tea Research Institute of Sri Lanka, it was not possible to obtain any reproducibility.

The aim of the present investigation was to establish a theoretical basis of moisture measurement by the capacitance method. The theory was then verified using four grades of made tea.

### MATERIALS AND METHODS

The theory was verified using a capacitance meter specially constructed for the purpose. It contained a parallel electrode type capacitor and a RCL bridge. Two parallel plates of the capacitor were constructed by neatly pasting thin aluminium

foil onto the inside of two parallel faces of the perspex sheet body. The effective gap between the plates was 0.888 cm. The capacitor had a depth of 7.925 cm and a length of 9.945 cm, thus the volume was 70.0 cc. The calculated net cell capacitance of this capacitor was 7.85 pF.

The RCL bridge — model PM 6302 (Phillips) was used for the measurement of capacitances. The range used was 5 to 100 pF. The gross cell capacitance, i.e. including wires, of the test arrangement was 11.00 pF.

Four grades of made black tea, namely BOP, BOPF, Dust 1 and BM, from St. Coombs factory were taken for this verification. These samples, numbering 17-20 per grade covered the range 0.7 to 7.6% moisture content on a wet basis.

For measurement of capacitance, the sample was filled into the capacitor using a specially constructed hopper while tapping the body of the capacitor five times. The hopper was then removed thus levelling the contents inside the capacitor. The capacitance was then measured in the RCL bridge and the sample was then removed, weighed and the bulk density calculated. A portion of the sample was then tested in duplicate for moisture content by the standard oven method, i.e. loss of mass at 103° C in 4 h.

## THEORY

Consider, for the sake of simplicity, a parallel plate capacitor with plate area  $A$  and distance between the plates  $D$ .

When hygroscopic, granular matter is filled into this capacitor and then the total capacitance exerted can be expected to depend on individual capacitances exerted by dry material, moisture in that material and air gaps due to porous nature of the bulk sample. As moisture is available only in a bound form its effect cannot be isolated.

Therefore, we assume the composite capacitance to depend on (i) dry matter layer, (t); (ii) wet matter layer, (w), whose moisture level is in equilibrium with (iii) an air layer (a).

### Notation

$d_i$  = imaginary thickness

$k_i$  = dielectric constant

$\rho_i$  = density

$c_i$  = capacitance

$z_i$  = moisture content (wet basis)

### Suffixes

$i$  = layers t, w, a or sample s

By continuity,

$$d_t + d_w + d_a = D \quad (1)$$

From mass balance, per unit area

$$p_t d_t + p_w d_w + p_a d_a = p_s D \quad (2)$$

But, weight of moisture, per unit area =  $Z_s p_s D$

∴ (2) can be rearranged as

$$p_t d_t + (p_t d_w + Z_s p_s D) + p_a d_a = p_s D$$

For simplicity, take  $p_a \ll p_t, p_s$

$$\therefore p_t (d_t + d_w) = (1 - Z_s) p_s D \quad (3)$$

Effective moisture content of tea in the wet layer "w" is

$$Z_w = \frac{Z_s p_s D}{Z_s p_s D + p_t d_w}$$

$$\therefore d_w = Z_s \left( \frac{p_s}{p_t} \right) D \left( \frac{1 - Z_w}{Z_w} \right) \quad (4)$$

Note : Here  $Z_w$  is the moisture level of the layer "w", which is in equilibrium with layer "a". The thickness of the layer  $d_w$  is taken so as to satisfy the above criteria.

From (1), (3) and (4)

$$d_a = D \left[ 1 - \left( \frac{p_s}{p_t} \right) (1 - Z_s) \right] \quad (5a)$$

$$d_w = D \left( \frac{p_s}{p_t} \right) Z_s q \quad (5b)$$

$$\text{and } d_t = D \left( \frac{p_s}{p_t} \right) (1 - Z_s - Z_s q) \quad (5c)$$

$$\text{Where } q = \frac{1 - Z_w}{Z_w} \quad (6)$$

Now the three layers "t", "w" and "a" are in series.

$$\therefore \frac{l}{C_s} = \frac{l}{C_t} + \frac{l}{C_w} + \frac{l}{C_a}$$

$$\frac{l}{C_s} = \frac{\propto d_t}{K_t A} + \frac{\propto d_w}{K_w A} + \frac{\propto d_a}{K_a A} \quad (7)$$

Within the "w" layer capacitances of moisture (m) and dry matter are considered to be in parallel.

$$\therefore K_w = K_t + K_m \quad (8)$$

and cell capacitance

$$\bar{C} = \frac{A}{\propto D} \quad (9)$$

Where  $\propto$  is a constant.

$\therefore$  (7) can be rearranged as

$$\frac{\bar{C}}{C_s} = \left(\frac{-}{p_t}\right)' \frac{l}{K_t} (1 - Z_s - Z_s q) + \left(\frac{-}{p_t}\right) \frac{l}{(K_t + K_m)} (Z_s q)$$

$$+ \frac{l}{K_a} \left[ 1 - \left(\frac{p_s}{p_t}\right) (1 - Z_s) \right]$$

Now  $K_m > K_t > K_a$

$$\therefore \frac{\bar{C}}{C_s} = \frac{l}{K_a} - p_s \left[ \frac{l}{p_t} \left( \frac{1}{K_a} - \frac{1}{K_t} \right) \right] - p_s Z_s \left[ \frac{l}{p_t} \left( \frac{1}{K_t} + \frac{q}{K_t} - \frac{q}{(K_m + K_t)} - \frac{1}{K_a} \right) \right] \quad (10)$$

This can be expressed as,

$$\frac{l}{C_s} = A_0 - A_1 p_s - A_2 p_s Z_s \quad (11)$$

Where  $A_0$ ,  $A_1$  and  $A_2$  are constants given by

$$A_0 = \frac{l}{\bar{C} K_a} \quad (12 a)$$

$$A_1 = \frac{l}{\bar{C} p_t} \left( \frac{1}{K_a} - \frac{1}{K_t} \right) \quad (12 b) \text{ and}$$

$$A_2 = \frac{l}{\bar{C} p_t} \left[ \frac{(1+q)}{K_t} - \frac{q}{(K_m + K_t)} - \frac{1}{K_a} \right] \quad (12 c)$$

Equation (11) is a curvilinear relationship between  $p_s$ ,  $Z_s$  and  $\frac{l}{C_s}$ .

## RESULTS AND DISCUSSION

Measured values of capacitances ( $C_s$ ), bulk densities ( $p_s$ ) and moisture contents ( $Z_s$ ) of samples of tea grades BOP, BOPF, Dust I and BM are presented in Table I (a) to (d). Multiple linear correlation between variables ( $1/C_s$ ), ( $p$ ) and ( $p_s Z_s$ ) in the form given in Equation (11) was established. The coefficients of Equation (11) and correlation coefficients are given in Table 2.

TABLE I — Measured Values of capacitances, bulk densities and moisture contents for four different grades of tea, (a) BOP, (b) BOPF, (c) DUST, (d) BM.

(a) Grade = BOP			(b) Grade = BOPF		
Capacitance $C_s$ , $p^F$	Bulk density $P_s$ $g\ cm^{-3}$	Moisture content $Z_s$ (Wet basis) %	Capacitance $C_s$ , $p^F$	Bulk density $P_s$ $g\ cm^{-3}$	Moisture content $Z_s$ (Wet basis) %
16.0	0.3457	3.2	17.0	0.3930	4.3
16.5	0.3510	3.2	18.0	0.4041	4.8
15.8	0.3297	2.1	16.6	0.3931	1.9
17.7	0.3578	5.8	16.8	0.3940	2.4
19.0	0.3643	6.8	17.7	0.3831	5.0
17.5	0.3707	4.7	17.0	0.3650	4.4
17.0	0.3581	3.6	18.0	0.3998	4.6
16.9	0.3718	3.1	16.8	0.3668	3.1
16.0	0.3677	2.0	17.1	0.3941	3.0
15.9	0.3562	1.6	16.1	0.3667	1.9
15.7	0.3617	1.4	16.4	0.3871	2.2
15.4	0.3480	1.3	15.7	0.3630	1.4
15.0	0.3604	1.2	16.0	0.3836	1.4
15.5	0.3516	1.2	16.1	0.3924	1.4
15.7	0.3611	1.2	15.7	0.3537	1.0
15.3	0.3528	0.8	16.0	0.3957	1.0
15.5	0.3628	0.9	15.8	0.3687	0.8
—	—	—	16.0	0.3943	0.7
—	—	—	—	—	—

  

(c) Grade = Dust I			(d) Grade = BM		
Capacitance $C_s$ , $p^F$	Bulk density $P_s$ $g\ cm^{-3}$	Moisture content $Z_s$ (Wet Basis) %	Capacitance $C_s$ , $p^F$	Bulk density $P_s$ $g\ cm^{-3}$	Moisture content $Z_s$ (Wet basis) %
18.8	0.4733	4.5	17.0	0.3643	3.8
19.5	0.4748	4.5	16.2	0.3661	2.6
17.2	0.4690	1.2	16.0	0.3557	1.5
23.5	0.4843	7.2	16.9	0.3563	4.1
19.0	0.4800	4.4	15.9	0.3486	1.6
19.5	0.4720	5.4	20.0	0.3753	7.2
17.9	0.4168	4.3	21.0	0.3898	7.6
21.0	0.5193	4.5	18.8	0.3781	5.2
17.8	0.4318	3.2	17.5	0.3908	3.5
19.2	0.5124	2.8	17.1	0.3787	3.6
17.1	0.4314	2.0	16.6	0.3958	2.0
18.1	0.4836	2.5	17.0	0.3786	3.6
17.7	0.4856	1.8	15.9	0.3676	1.8
16.6	0.4264	1.3	16.0	0.3885	1.4
17.2	0.4780	1.5	16.0	0.3740	1.6
17.1	0.4807	1.3	16.0	0.3780	1.5
16.7	0.4227	1.2	15.9	0.3844	1.2
17.3	0.4800	1.0	16.0	0.3773	1.3
16.4	0.4287	0.8	16.0	0.3916	0.9
—	—	—	15.9	0.3781	0.9

TABLE 2 — Coefficients of the equation  $1/C_s = A_0 - A_1 p_s - A_2 p_s Z_s$  and multiple linear correlation coefficients for individual grades and in combination.

Grade	$A_0$	$A_1$	$A_2$	$r$
BOP	0.0797	0.0363	0.5394	0.9735
BOPF	0.0795	0.0399	0.3989	0.9735
Dust I	0.0816	0.0440	0.4429	0.9776
BM	0.0829	0.0457	0.5745	0.9887
All four grades	0.0790	0.0372	0.4901	0.9511

Averages of measured bulk densities of the four grades of tea are given in Table 3.

TABLE 3 — Average measured bulk densities,  $g\ cm^{-3}$  and their standard deviations.

Grade	Average bulk density $p_s$	Standard deviation
BOP	0.3571	0.0103
BOPF	0.3832	0.0150
Dust I	0.4658	0.0303
BM	0.3759	0.0120
All four grades	0.3965	0.0460

If Equation (11) is to be used for estimation of moisture content ( $Z_s$ ) of a sample, it necessitates measurement of capacitance ( $C_s$ ) and bulk density ( $P_s$ ). Since variation of bulk density within a grade is somewhat small (as seen in Table 3, it may be possible to use simplified versions of Equation (11) i.e.  $1/C_s$  and  $Z_s$  relationships, in  $Z_s$  estimations of a known grade of tea.

This simplification is now examined by taking as an example, the BOP grade where, average  $p_s = 0.3571$  and 95% confidence limits of  $p_s$  are 0.3468 and 0.3674 and comparing the following equations :

- (i) Best fit Equation (II) for the grade,  
 $1/C_s = 0.0797 - 0.0363 p_s - 0.5394 p_s Z_s$
- (ii) Best fit Equation (II) for all grades together,  
 $1/C_s = 0.0790 - 0.0372 p_s - 0.4901 p_s Z_s$
- (iii) Simplified form of (i), with  $p_s =$  average bulk density for the grade,  
 $1/C_s = 0.0667 - 0.1926 Z_s$  and
- (iv) Best fit relationship between  $1/C_s$  and  $Z_s$  for the grade (from data),  
 $1/C_s = 0.0669 - 0.2012 Z_s$ .

Within the 95% confidence limits of  $p_s$  variation, for given value of  $1/C_s$  and an average moisture level of 3.0%, the predicted values of  $Z_s$  using Equations (i) to (iv) are as follows :

TABLE 4 — Predicted values of moisture contents (%).

Predicted $Z_s$	$p_s = 0.3468$	$p_s = 0.3571$	$p_s = 0.3674$
From (i)	3.3	3.0	2.7
From (ii)	3.0	2.7	2.4
From (iii)	3.0	3.0	3.0
From (iv)	3.0	3.0	3.0

In comparison to predictions from Equation (i),

- (a) predictions from Equation (ii) (best fit curve for all grades) have constant error through the whole range of  $p_s$ , and
- (b) predictions from Equations (iii) and (iv) (being  $1/C_s$  vs.  $Z_s$  relationships) are Insensitive to  $p_s$  variations.

### CONCLUSIONS

- I. A theoretical relationship between capacitance, bulk density and moisture content has been established using four grades of tea. This relationship should be valid for all hygroscopic granular materials.

2. For accurate estimation of moisture content by the capacitance method a knowledge of bulk density of the sample is essential.
3. One single equation can represent all four grades of tea with a known constant error for each grade of tea. This error however varies with the moisture level.
4. The derived equation can be simplified to  $I/C_s$  vs  $Z_s$  relationships. Predictions from these equations are insensitive to variations in bulk density. The error in each reading is therefore not predictable.

#### **REFERENCES**

ISO 1573 - 1980 (E) - TEA - Determination of loss of mass at 103°C.  
International Standard Organisation.