Automatic Moisture Content Control for Grain Driers

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A description is given of the development of apparatus for automatically controlling the moisture content of the output of a continuous-flow drier by adjusting the grain throughput rate in response to the signal from a capacitance-type moisture monitor.

Experimental work to determine the relationship between permittivity and grain m.c. and temperature is reported.

Emphasis has been given to the optimization of the control action suitable for a relatively simple controller and the performance of this unit, when encountering wide variations in the input m.c., is examined.

1. Introduction

In continuous-flow driers it is usual to set the temperature of the drying air at or near the recommended maximum for the crop being dried and to control the amount of moisture removal from the grain by adjusting the rate at which the grain passes through the drying plant and hence the time of drying. The extent of this adjustment may be limited, of course, by conveyor capacity and by the rate of grain arrival from the combine.

The necessity of throughput adjustment to maintain the required output moisture content is normally determined by periodic m.c. determinations on grain from the drier output, using a sample-type moisture meter. In practice these measurements appear to be most usually carried out at approximately hourly intervals. However, in general, drier manufacturers are unable to specify the degree of adjustment necessary to correct a particular error in output m.c. because of the effect on drying rate of air temperature and possibly of grain characteristics. As a result of previous experience, a drier operator is able to establish the approximate adjustment required, but observations made on the performance of a typical continuous-flow farm drying installation have demonstrated that control can be relatively inefficient.

Provided that the continuous sensing of grain m.c. can be made sufficiently accurate and control action is optimized, there is obviously every likelihood that automatic control can be made more effective than manual operation, since moisture monitoring is continuous instead of periodic, and corrective action may be designed for minimum practicable m.c. error when encountering typical variations in wetness of the harvested material.

The development of m.c. control equipment may thus be resolved into two main investigations:—

(a) The practicability of continuously sensing the moisture level of the dried grain, either within or on discharge from the drier.

(b) The evolution of a control action for the adjustment of the grain throughput control in response to the signal from the sensing unit.

For continuous sensing of moisture content the more practical measurement methods would appear to be those utilizing the electrical properties of the grain; more specifically conductivity or permittivity.

The former is sensitive to the surface condition of the grains, which during drying is likely to be a misleading indication of the overall m.c. In contrast, the permittivity of a grain bulk is very little affected by the distribution of moisture within the seeds. To render the conductivity measurement insensitive to surface conditions it would be necessary to grind and mix the material on which measurements are made, which would severely limit the size of the monitor sample and also greatly complicate the monitoring apparatus.

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Permittivity measurement was considered preferable and from previous experience,[1, 2] a measurement frequency of 1 Mc/s or greater was considered necessary to satisfactorily eliminate surface effects.

2. Variation of permittivity with grain m.c. and temperature

2.1. *General*

Existing published information[3] on the dependence of the permittivity of grain on m.c. and temperature appears to be limited to isolated values quoted for particular grains at a few levels of m.c. Calibration data for existing commercial moisture meters provides some picture of the relationship. However, such data include any non-linearities of the instrument and electrical circuit and are restricted to grain temperatures in the expected ambient range. For optimum control performance, the sensing of grain m.c. should ideally be carried out immediately after drying, even before passing through the cooling zone of the drier. It was thus decided to investigate the variation of the permittivity of one variety of grain over the ranges of m.c. and temperature likely to be encountered within the drier at this point (10–18 % m.c. and 100–160 °F).

Initial attempts to obtain the required grain conditions within an enclosed heated container were discarded in view of the excessive sweating of the higher m.c. grains when hot. It was then considered preferable to make the measurements during the actual drying process. Both freshly-harvested and artificially-wetted grains were used to investigate the implications of using the latter in out-of-season development trials.

2.2. *Experimental apparatus*

An experimental counterflow drier was available[4] and the flexibility of operation made it a suitable vehicle for these experiments.

The drier has a drying chamber in the form of a 4 × 2 ft cross-section tower containing two horizontal rows of air vents, the rows being approximately 18 in. apart vertically; heated air is forced through the grain from the lower vents and escapes through the upper openings. Cold air is blown into the hopper bottom below the grain bed, from where it is forced to pass upwards through the lower layers of dried grain which it cools, at the same time becoming heated itself, and eventually mixing with the main drying air with which it escapes through the upper system of vents.

The gravity grain flow through the tower is controlled by an oscillating grid on the floor of the tower. Dried material is discharged from the drier by an auger and a paddle valve, which is sealed against continuous escape of the cooling air.

For this experiment dividing partitions were fitted within the tower to limit the available cross-section and thus reduce the grain throughput. This was necessary to simplify the grain handling problems during the experimental work and to economize in moist material, particularly necessary when artificial moistening was employed.

The grain flow was divided into two parallel paths (*Fig. 1*) near the end of the drying zone due to the presence of the inlet ducts (A). Geometrically these paths are identical, and the grain flowing through each of them has previously encountered similar drying conditions.

Within one channel was mounted an electrode of fringe-field design (B), constructed of brass with epoxy resin insulation (*Fig. 2*). At the corresponding position within the second channel a port (C) was included to enable a suction-sampling spear to be inserted. Further ports (D)

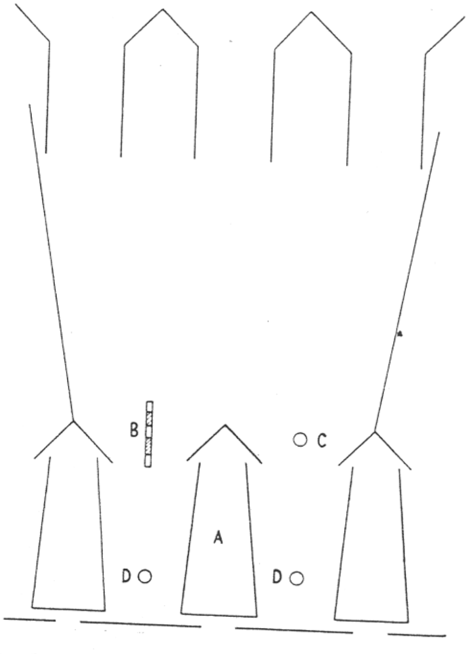

Fig. 1. Drying bed for permittivity measurements

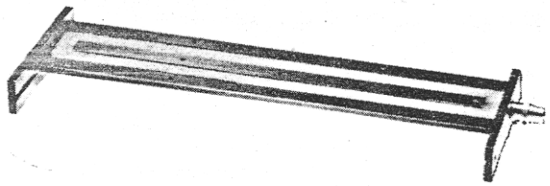

Fig. 2. Fringe-field electrode

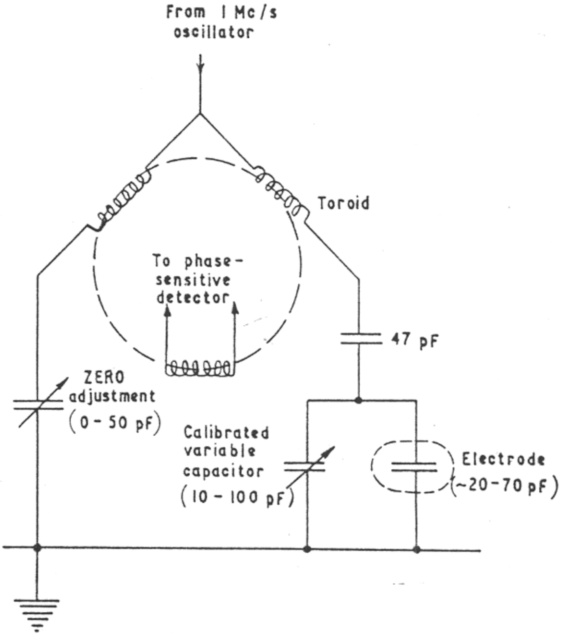

Fig. 3. Capacitance bridge for permittivity measurements

at a lower level in each grain path enabled a direct comparison of m.c. to be regularly made between the two channels.

The electrode was connected in a capacitance-inductance bridge circuit (*Fig. 3*) powered by a 1 Mc/s transistorized oscillator. Bridge balance was indicated by the d.c. output of an inductively coupled phase-sensitive detector, and the electrode capacitance measured by rebalancing the bridge with a calibrated variable capacitor.

For the measurement of grain temperature a thermistor-probe thermometer, having a low thermal capacity, was used.

2.3. *Experimental procedure*

The experiments were carried out during and after the 1960 harvest period. Initially the measurements were made during drying of freshly harvested Dominator wheat (~ 21% m.c. at harvest).

The same material (then at 13·5% mean m.c.) was artificially rewetted and the experimental work repeated. It was necessary to use tap water for rewetting in view of the quantity of grain needed (3 t). The procedure for wetting was to run about 20 cwt of grain into a rotating mixing drum, and to spray on the calculated quantity of water to raise the grain m.c. to 21%, whilst continuously mixing. Water addition generally occupied about 1 h and was followed by intermittent mixing over a period of three days.

To cover the required ranges of moisture content and grain temperature, six separate drying runs were carried out for each material (natural and rewetted). Through each run the drying air temperature was maintained at a constant level; the temperatures used for the six runs being 100, 120, 140 (twice), 160 and 180 °F. The throughput rate was, however, periodically adjusted, starting at approximately 100 lb/h and being decreased in steps to about 20 lb/h. In this way a range of m.c. levels in the dried grain was obtained. The total time taken by each run varied between 5 and 15 h.

After sufficient time for the drying pattern to become stable, grain sampling and electrode capacitance measurements were carried out at half-hourly intervals. The procedure at the time of sampling involved taking in rapid succession an electrode capacitance reading, a grain sample for subsequent m.c. measurement, and a grain temperature measurement. The sample and temperature measurement were taken at the port equivalent to the electrode position (*Fig. 1*, C), the latter measurement necessitating shutting off the drying air for 1 min to enable the inserted thermistor probe to read accurately the temperture of the grains.

In this way grain m.c. and temperature in one channel were related to electrode capacitance, and hence permittivity, in the other. To compare the grain condition in the two channels, samples were taken from the lower ports at hourly intervals. These showed the grain to have generally reached the same dryness at the two positions, and it is thus reasonable to assume the grain temperatures to be approximately the same. Throughout the experiment the mean m.c. at the lower port in the channel containing the electrode was less than that in the other channel, though by 0·2% only. An adjustment of this amount was made to the comparative data at the electrode level on the assumption that no significant change in the relative m.c. values occurred between these two sampling levels.

The six drying runs at different temperatures provided a total of approximately 80 individual relationships between electrode capacitance and grain m.c. and temperature, these being well distributed over the m.c. and temperature range.

Moisture content was determined by measuring the weight loss of 10-g samples of whole grains after oven drying for 16 h at 130 °C. All results are expressed as wet basis.

2.4. *Results*

2.4.1. Naturally moist Dominator wheat

Inspection of the plot of the individual relationships showed the capacitance to be generally a linear function of both grain m.c. and grain temperature. It was therefore decided to derive statistically the plane of best fit for these data, and to judge subsequently the validity of the assumed linearity by the residual variability, and by comparison of randomly selected measured data with those calculated from the plane equation.

The equation to the plane was calculated to be

$$C = 2{\cdot}58\,M + 0{\cdot}129\,T - 21{\cdot}2 \qquad \ldots(1)$$

where C = increase in electrode capacitance due to the presence of the grain, pF
M = m.c. of the grain, %
T = grain temperature, °F

It will be noted that the temperature coefficient of capacitance (or permittivity) in terms of equivalent m.c. variation has been derived as 0·050% per °F. This appears to confirm the value most generally in use for measurements on wheat with commercial capacitance-type moisture meters.

The calculated residual standard deviation for the measured data about the derived plane was 1·4 pF, this being equivalent to a m.c. deviation of 0·5%. Table I gives a comparison between sixteen points randomly selected from the experimental data and the equivalent capacitance calculated from the equation to the plane. There is little evidence of any systematic variation from the plane relationship, except perhaps at the extremely low moisture content values where the calculated capacitance values are generally lower.

In an auxiliary experiment the fringe field electrode was immersed in wheat of known permittivity, the resulting measurement of electrode capacitance enabling a calculation to be made of the inherent (air dielectric) capacitance of the electrode. This known permittivity, determined previously by measurement in a cell of calculable inherent capacitance, was 5·22 and the measured change in capacitance of the fringe-field electrode on immersion in this material 29·0 pF.

Thus the inherent capacitance of the fringe-field electrode (C_E) is given by

$$C_E = \frac{29{\cdot}0}{5{\cdot}22 - 1{\cdot}00} = 6{\cdot}9\ \text{pF} \qquad \ldots(2)$$

From Eqns (1) and (2), the permittivity of the Dominator wheat (K_W) may be expressed by

$$\begin{aligned} K_W &= 1{\cdot}0 + \frac{2{\cdot}58\,M + 0{\cdot}129\,T - 21{\cdot}2}{6{\cdot}9} \\ &= 0{\cdot}375\,M + 0{\cdot}019\,T - 2{\cdot}1 \qquad \ldots(3) \end{aligned}$$

TABLE I

Comparison between data calculated from plane of best fit and measured data (naturally moist grain)

Moisture content, M, %	*Grain temperature, T, °F*	*Measured electrode capacitance, pF*	*Calculated electrode capacitance, C, pF*	*Error in calculated capacitance, pF*
10·0	162	26·9	25·5	− 1·4
11·4	118	24·7	23·4	− 1·3
11·6	161	29·9	29·5	− 0·4
12·3	120	26·2	26·0	− 0·2
13·3	96	26·6	25·6	− 1·0
13·8	155	32·7	34·4	+ 1·7
14·0	127	31·8	31·3	− 0·5
14·0	141	32·0	33·1	+ 1·1
15·5	99	30·3	31·5	+ 1·2
15·8	138	37·1	37·4	+ 0·3
16·3	126	36·2	37·0	+ 0·8
17·1	123	41·5	38·9	− 2·6
17·3	146	41·8	42·2	+ 0·4
17·7	97	35·7	36·9	+ 1·2
18·2	106	40·0	39·5	− 0·5
18·2	131	44·4	42·7	− 1·7

A known source of error is the effect of the resistive component of the electrode/grain impedance on the capacitance measurement. This was investigated through two additional drying runs, during which measurements of the effective parallel resistance of the electrode impedance were made at half-hourly intervals, using a Q-meter, and related to the values of m.c. and grain temperature obtained from corresponding samples. The values obtained by these Q-meter readings varied from approximately 60 kΩ for grain having both low m.c. (∼ 12%) and temperature (∼ 120 °F) to 20 kΩ for 18% m.c. grain at 150 °F. These values were shown by separate experiment to affect the capacitance determination by an amount ranging from 2 pF at 60 kΩ to 3·5 pF at 20 kΩ, the effect being independent of electrode capacitance within the encountered range. The error on an electrode incremental capacitance varying from approximately 25 pF (low m.c. and temperature) to 45 pF (high m.c. and temperature) is about 8%.

This error must of course be taken into account when considering the absolute values of permittivity calculable from these results. Such data would be needed to predict the performance of a moisture content sensing device having a response purely to the capacitive component of the electrode impedance. However, in practice some small dependance on the resistive component is generally present, either resulting from the actual material resistivity or from the dielectric loss. The sensing equipment used was of lower frequency than that incorporated in the prototype control system, so that the relationship applicable to the control equipment is somewhat modified from the above, although the difference is probably small.

2.4.2. ARTIFICIALLY WETTED DOMINATOR WHEAT

From these data, again by inspection apparently linearly related, the equation to the plane of best fit was calculated as

$$C' = 2{\cdot}19\,M' + 0{\cdot}108\,T' - 12{\cdot}6 \qquad \ldots(4)$$

The residual standard deviation was calculated as 1·0 pF, a lower value than that for naturally wet grain and equivalent to a m.c. deviation of 0·4%.

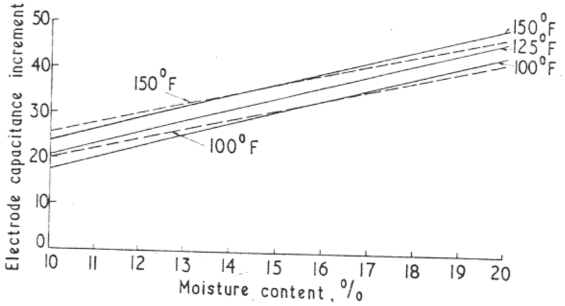

Fig. 4. Variation of electrode capacitance with grain m.c. and temperature

(Full line) Naturally moist; (Dotted line) Artificially wetted

Eqns (1) and (4) differ in that, although at about 15% m.c. the electrode capacitance is approximately equal, its variation with both m.c. and temperature is less for the artificially-wet than for the naturally-wet wheat. The temperature coefficient of capacitance in terms of equivalent m.c. is however again close to 0·05%/°F.

In *Fig. 4* a direct comparison between the m.c.-capacitance relationship for the two materials is shown at a range of temperatures to be found in drying grain.

Again, points calculated from the equation to the plane of best fit have been compared with experimental measurements (Table II).

TABLE II

Comparison between data calculated from plane of best fit and measured data (artificially moistened grain)

Moisture content, M, %	*Grain temperature, T, °F*	*Measured electrode capacitance, pF*	*Calculated electrode capacitance, C, pF*	*Error in calculated capacitance, pF*
9·6	162	26·4	25·9	− 0·5
10·0	161	26·1	26·7	+ 0·6
11·1	99	23·0	22·4	− 0·6
12·9	119	28·8	28·5	− 0·3
12·9	99	25·9	26·3	+ 0·4
14·2	117	30·8	31·1	+ 0·3
14·2	152	33·7	34·9	+ 1·2
14·6	162	36·9	35·5	− 1·4
14·8	127	33·5	33·5	0
15·3	142	36·1	36·3	+ 0·2
15·8	100	30·5	32·8	+ 2·3
16·1	95	31·0	32·9	+ 1·9
16·9	136	40·0	39·1	− 0·9
16·9	113	38·2	36·6	− 1·6
17·3	133	38·8	39·7	+ 0·9
18·0	108	41·4	38·5	− 2·9

There is no evidence of consistent departure of measured data from the calculated plane over either the m.c. or the temperature range.

The considerations of possible error in the capacitance values due to the resistive component of impedance also apply to the artificially wetted wheat.

2.4.3. SUMMARY OF PERMITTIVITY MEASUREMENTS

It is evident from the reported data that the m.c. of this particular variety of wheat may be deduced from permittivity measurement even at the elevated temperatures present during drying, provided that a linear correction for temperature variation can be incorporated. Furthermore, the m.c. deviation from a desired level at which the capacitance bridge is balanced, will be linearly related to the unbalance of the bridge or to the output signal from the detector unit.

The effect of different grain variety and possibly of different growing or ripening conditions, will be relevant to the calibration of the m.c. controlling apparatus, and is discussed more fully below. However, it is not unreasonable to assume the effect on permittivity of grain m.c. and temperature to be similar for at least all varieties of wheat, the principal difference being one of absolute permittivity value.

3. Arrangement of control apparatus

3.1. *Permittivity sensing electrode*

Superficially, m.c. sensing may be of either the dried or the undried grain, and therefore this electrode may be sited within the drier or in a column of grain either feeding to or being removed from the drying plant. It is considered, however, to be advantageous to sense the moisture content after most of the drying has taken place, since a measurement before or during drying, although equally useful with constant drying conditions and perhaps having advantages in permitting anticipatory control, may not be used when drying conditions (ambient r.h. or ease of drying of grain) are likely to affect the drying rate. The electrode should thus be incorporated either at or near the end of the drying zone of the drier, within the grain cooling zone or in a drier outlet duct, which must be constructed to include a sufficiently large volume of fairly slowly moving grain.

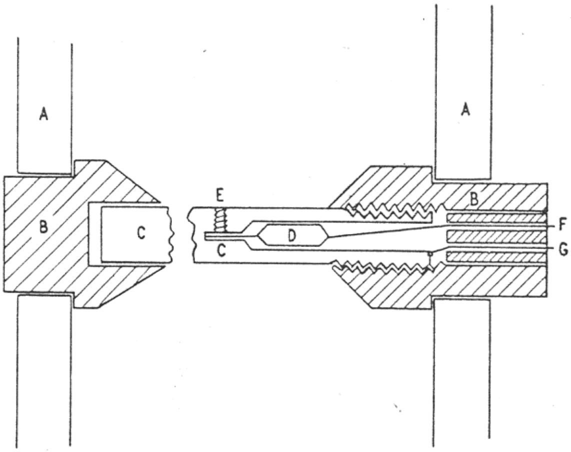

Fig. 5. Rod electrode

(A) End walls of drying bed; (B) Insulating bushes; (C) Electrode; (D) Temperature-sensitive capacitor (T.S.C.); (E) Grub screw connection to T.S.C.; (F) Connection to T.S.C.; (G) Connection to electrode

Electrodes suitable for this application may be either of the fringe-field type as shown in *Fig. 2* or in the form of a simple rod if intended for mounting within a plane drying bed (*Fig. 5*) in which case the perforated metal walls of the bed act as the "earth" plate. Alternatively the electrode may consist of parallel "live" and "earth" plates perhaps mounted flush with either drying bed or duct walls, with the grain flowing between the plates.

Fringe-field electrodes have also been constructed of copper-clad resin laminate, and of laminate with the conducting elements sprayed onto the surface.

An adaption of the rod type of electrode has been constructed for use with a drier having a vertical annular grain bed (*Fig. 6*, left). A further feature of this electrode is its fixing to existing plant through a 4 × 6 in. hole cut in the outer wall of perforated metal, the main arc-shaped section of the electrode being fixed to a plate mounted in this hole by two pillars.

The parallel-plate configuration has the advantage of not introducing obstructions to the moving grain, liable to collect straws, etc., with the subsequent possibility of partial blockages. However, within the drying bed such an arrangement is difficult without considerable disturbance to the flow of drying air.

3.2. *Temperature compensation*

Capacitors are available in the picofarad range, having high negative temperature coefficients

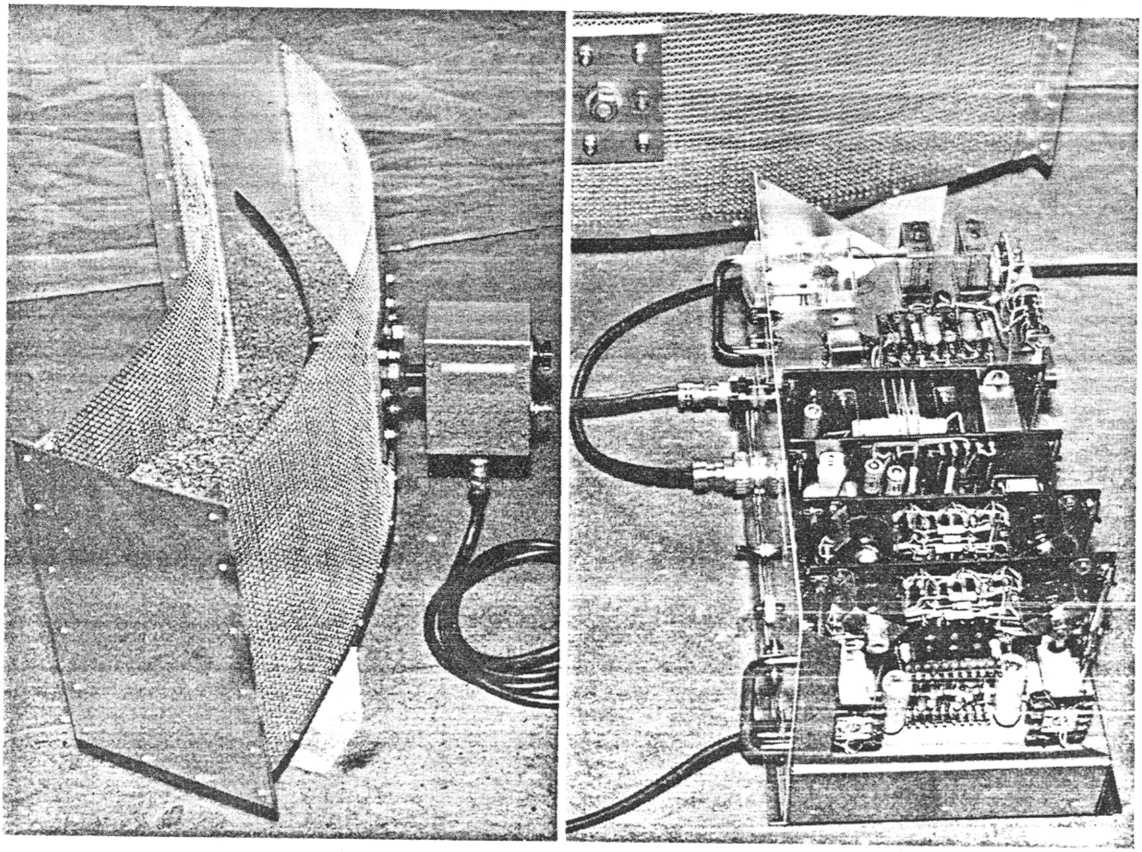

Fig. 6. Sensing electrode for annular bed (left) and prototype control unit

of capacitance within quoted ranges. These components may be of simple tubular or disc moulded ceramic construction, or they may be of parallel-plate, air-spaced type in which case the movable plates are controlled by a bimetallic strip.

For this development work the tubular form has generally been used, the capacitor being mounted, in the case of the rod electrode, within the rod itself, and with the curved electrode, within one of the supporting pillars. In this way the temperature of the compensating capacitor is equal to that of the electrode, which is in turn similar to that of the surrounding grain. The component is connected in series with the actual electrode capacitance; further parallel capacitance being added to either until the compensation afforded by the temperature-sensitive element balances the electrode capacitance deviation due to the prevailing grain temperature.

3.3. *Capacitance bridge*

In view of the slight but significant dependence of the capacitance-bridge output on grain resistance at 1 Mc/s (Section 2.4.1), an increase in frequency was considered worthwhile. A value of 2 Mc/s was chosen, being near the upper frequency limit of the transistorized capacitance-sensitive bridge circuit chosen for the control equipment.[5] Previous usage at the N.I.A.E. had shown this unit to have excellent stability and good sensitivity at the low values of capacitance associated with practicable sensing electrodes. With such low capacitance values, it is necessary to reduce the length of connections within the arms of the bridge to the absolute minimum. However, the complete capacitance-sensitive circuit, including oscillator, inductance-capacitance bridge and phase-sensitive detector (P.S.D.) is sufficiently small to be mounted on the side of the drier or duct adjacent to the electrode, so eliminating any flexible connection (*Fig. 6*). The necessary four conductors between this unit and the main controller unit all carry d.c. signals of milliampere proportions (8-V d.c. supply and P.S.D. output) and are thus unrestricted in length.

4. Choice of optimum control action

4.1. *General*

The object in optimizing the action of the controller is to minimize the duration and extent of the moisture content error when input m.c. variations are encountered. Such variations may be sudden changes or slow drifts in moisture level over a considerable period. Measurements on a typical farm plant have shown both to occur, although drifts were more common than step changes. A typical value of the rate of drift was found to be $\frac{1}{2}\%$ m.c. per h, possibly sustained for up to 8 h. Maximum step changes were 3% m.c., generally as a result of a change in plot or a change in day of harvesting.

In the development of control equipment, various forms of possible control action were considered, beginning with the simplest.

4.2. *Experimental cross-flow drier for control experiments*

For practical reasons the counterflow drier[4] did not easily lend itself to automatic control. Thus, to enable control performance trials to be carried out throughout the year, using artificially-damped wheat out of the normal harvest season, a special low-capacity, cross-flow drier was constructed (*Fig. 7*). This was designed to have a throughput rate of 2–3 cwt/h at 150 °F and 6% moisture removal, so enabling drying runs of 8–10 h to be carried out on about 25 cwt of moist material.

A 6-in. drying bed was incorporated, the low throughput being achieved mainly as a result of the small bed width (30 in.), so maintaining the similarity between the drying process in this experimental drier and in the normal farm driers.

A large range of controlled drying air temperatures was made available in the drier to allow the effect of this variable and of grain temperature on the controlled m.c. to be investigated. Flow of grain through the drier was controlled by an oscillating grid, displacing a fixed amount of material from the floor of the vertical grain bed on each cycle. The oscillatory drive was through a magnetic coupling whose output speed was continuously adjustable, being either manually set or arranged to be proportional to an applied voltage signal.

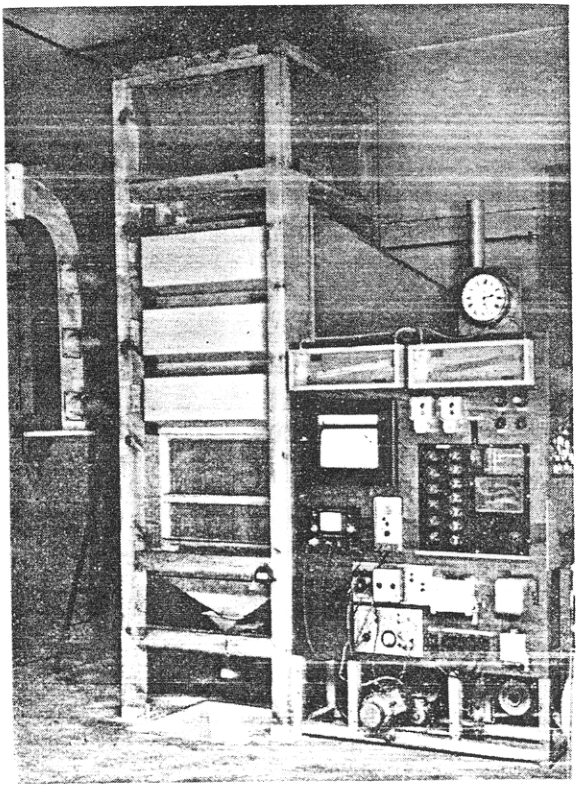

Fig. 7. Experimental cross-flow drier

Other features included were adequate sampling ports to enable the progress of drying to be traced down the bed and particularly to examine gradients around the electrode, and instrumentation to record air and grain temperatures, to indicate drying and cooling airflow rates, and to count the number of oscillations of the grain discharge grid.

4.3. *On/off control action*

The output of the m.c. sensing circuit was arranged, after amplification, to operate a relay when the monitored m.c. was at or below the desired level, the relay switching on the drive of the grain discharge grid. The sensing electrode was mounted 3 in. above the end of the drying zone, so that drying was able to continue on the monitored grain, but very little further drying occurred below the electrode.

Unsatisfactory operation of this form of control was caused by variation in the packing of the grain around the sensing electrode. The packing density became greater during periods of zero output, thus increasing the apparent permittivity of this material which therefore appeared wetter than was the case. Once the discharge of grain had started, the reverse process took place, and discharge continued for longer than desirable. This instability sometimes developed to the point where the equipment operated as an automatic batch drier, the complete drying bed material being changed at each period of discharge operation.

4.4. *Proportional control*

In this form of control action, the error moisture content (E, %) at the monitoring position is caused to adjust the grain throughput rate in such a way that the potential change in drying (D, % m.c.) is proportional to this error, i.e. $D = P.E$, where P is the proportional control factor.

It is necessary, of course, to decide on an optimum throughput to which the drier is set when the m.c. error at the sensing electrode is zero.

The optimum value of P for a process depends on the process time and also on the amount of sustained m.c. deviation which can be tolerated, since this latter feature is implicit in this form of control.

In the grain drying process, the process time is of such long duration (perhaps up to 2 h when drying by 10–12%) that, to avoid serious hunting in the controlled m.c., a very low value of proportional control factor would be necessary. In fact, empirical calculations indicate a value of near unity to be optimum. This unfortunately leads to very large sustained deviations (offset) when the throughput is adjusted as a result of changes in the input m.c. In fact with $P = 1$ and a 2% change in input m.c. level an output deviation of 1% is allowed.

4.5. *Integral control*

With integral control action the applied correction to the magnitude of drying is proportional to the time integral of the error. In other words, during any period of deviation from the desired m.c. a continuous adjustment to the throughput is applied at a rate proportional to the error. In this way the achieved adjustment to throughput is always proportional to the error integrated over the duration of deviation.

No permanently sustained errors are implicit to this form of control, but again, to avoid m.c. hunting, an extremely low rate of adjustment is necessary and deviations are maintained for long periods before the effect of correction is fully experienced.

4.6. *Proportional control with automatic reset*

To remove the inherent offset of the proportional control action, an appropriate continuous adjustment of the throughput rate during periods of significant m.c. error is added. Thus this form of control takes advantage of both the immediate corrective action of proportional control and the lack of sustained offset associated with integral control. When associated with a proportional action, it is permissible, for simplicity, to make the reset rate independent of the magnitude of the error, although this form of correction alone would lead to sustained hunting. In this way the action differs from a true proportional-integral system.

To arrive at optimum values for the proportional control factor (P) and reset rate (R), it is normal to either consider the mathematical model of the process, and to derive these parameters from an analysis of the frequency response of the system, or to compare the performances of different parameter combinations experimentally. However, in this instance, the mathematical representation of the drying process with continuous grain flow is not adequately established. For subsequent performance measurements, using the low-capacity, cross-flow drier, the control constants have been chosen partly as a result of a qualitative assessment of a limited number of previous performance runs using either proportional or normal integral control, and partly from empirical calculations of performance using greatly simplified drying assumptions. In these calculations the moisture content decrease was assumed to be proportional to the time for which the grain is within the drying zone of the plant. Conditions at the sensing electrode were calculated at 15-min intervals, and the throughput rate adjusted in accordance with the m.c. deviations and the postulated control parameters. The performance so calculated for various control actions is summarized in Table III. In all these calculations, the sensing electrode was assumed to be sited between drying and cooling zones of the experimental drier.

From these data, a value of 1–2 for P combined with a reset rate equivalent to about 0·5% change in drying per hour appears to be optimum. Comparison with earlier performance runs suggested the performance calculated in this manner to be slightly more prone to sustained oscillation than is likely in practice, indicating a slight increase in P or R to be permissible. In fact, good performance was later shown with $P = 1$ and $R = 1$%/h.

Due to the non-linear and varying relationship between the m.c. decrease and the grain throughput, the control parameters quoted may only be applied approximately. In subsequent work, they have been calculated for 6% m.c. decrease from 21 to 15% and 150 °F drying air temperature.

TABLE III

Summary of control performance forecast by empirical calculations

Control action	*Control constants*		*Predicted performance*
	P	*R, % m.c./h*	
Proportional	4·0	—	Oscillation sustained
Proportional	2·0	—	Large ultimate deviation
Proportional with reset (single speed)	1·0	2	Oscillation sustained
Proportional with reset (single speed)	1·0	½	Satisfactory (near optimum)
Proportional with reset (single speed)	2·0	1	Oscillation sustained
Proportional with reset (single speed)	2·0	½	Satisfactory
Proportional plus integral	1·0	1½ (at 3% error)*	Satisfactory

* Rate of potential correction proportional to instantaneous error

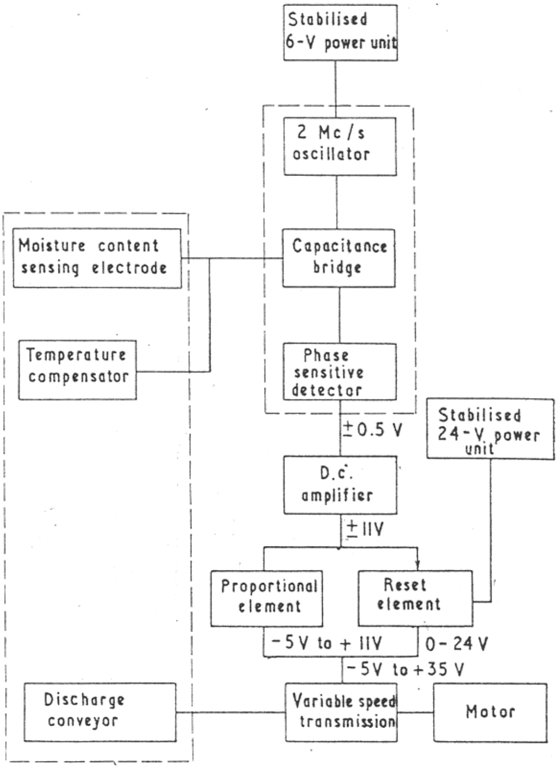

Fig. 8. Block diagram of control unit

5. Prototype control equipment

5.1. *General arrangement of equipment*

A schematic diagram of the prototype control system is shown in *Fig. 8* and the sensing bridge unit and controller unit with the electrode in *Fig. 6*. A voltage output signal from the controller unit is applied to a commercial variable-speed magnetic drive, modified to operate from a − 5 to + 35 V signal, thus allowing transistor circuitry to be employed in the controller.

5.2. *Controller unit*

This unit (*Fig. 9*) consists essentially of a 6·8-V d.c. stabilized power supply for the bridge circuit oscillator, a d.c. amplifier stage to raise the level of the bridge detector output signal to the range ± 11 V, a proportional control element, reset element and means of manually adjusting the drier throughput. This latter facility would be used to set an approximate rate at the start of drying and might be adjusted with advantage if the input m.c. was known to have

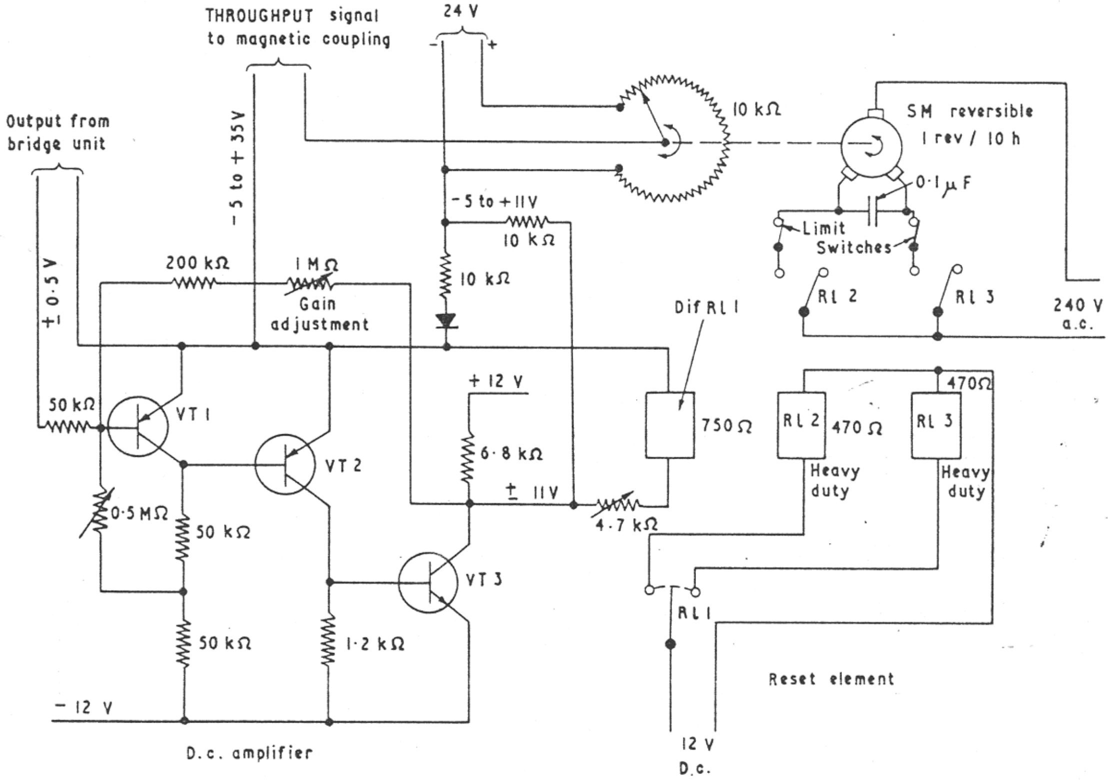

Fig. 9. Simplified circuit diagram of control unit

changed considerably, although the second case would in time be rectified by the automatic control facility.

The proportional control element is a polarity-sensitive attenuator, modifying the ± 11 V amplified signal to one having a range − 5 to + 11 V. When associated with the non-linear relationship between grain throughput and percentage moisture content removal, this produces a more balanced proportional action on either side of the set m.c.

To the output of this unit is added the voltage signal of the reset element which consists essentially of a potentiometer driven by a reversible motor. The operation of this motor is controlled by a sensitive moving-coil relay through slave relays, to aid contact life, and limit switches to prevent overdrive of the potentiometer, the moving-coil relay being arranged to operate the motor only when the moisture content error exceeds ± ¼%.

6. Performance of prototype control equipment

6.1. *General*

Performance tests were made using the cross-flow drier (Section 4.2) with an experimental controller incorporating commercial laboratory instruments for power supplies and for amplification. The comprehensive control equipment (Section 5) was also available at that time, but was fitted to a farm drier (acting only as a monitoring instrument) for endurance testing under farm conditions. In action the two controllers were identical.

6.2. *Temperature compensation*

Tests were carried out to optimize the compensation for the temperature effect on permittivity, the various degrees of compensation being achieved by different values of capacitance in parallel with either the electrode or the temperature-sensitive element of the bridge capacitance.

The tests consisted of a series of five drying runs corresponding to five different values of temperature compensation. During each run the temperature of the drying air was periodically decreased by steps of 5–10 °F from an initial value of 180 °F to a final level of 120–130 °F. In this way the temperature of the monitored grain (sensing electrode between drying and cooling zones) was caused to vary throughout the run. With optimum temperature correction, the controlled level of grain m.c. must be independent of this temperature variation, whilst at other values of correction, examination of the m.c. change with grain temperature indicates the compensation error. Throughout the run, samples of dried grain were collected at 15-min intervals for m.c. determination.

Table IV summarizes the results obtained from the five runs, relating the compensation achieved to the value of corrective temperature coefficient and capacitance in parallel with the electrode.

For optimum compensation (Run E) a temperature coefficient of -1800×10^{-6} pF pF^{-1} °F^{-1} is supplied by the temperature sensitive capacitor. The electrode and its parallel capacitance must therefore be exhibiting a coefficient of $+1800 \times 10^{-6}$ pF pF^{-1} °F^{-1}.

From Eqn (3), electrode capacitance at the grain m.c. and mean temperature at the electrode during this run is approximately 125 pF. With 20 pF added parallel capacitance, the temperature coefficient of this element may also be assessed from Eqn (1) as $+2100 \times 10^{-6}$ pF pF^{-1} °F^{-1}. A number of factors, notably the effect of m.c. and temperature gradients in the electrode region and of capacitor tolerances may account for the 15% discrepancy between these two derived values.

TABLE IV

Summary of performance data from temperature compensation tests

Run	*Temperature coefficient of compensating capacitor, pF pF^{-1}°F^{-1}*	*Capacitance of parallel trimmer to electrode, pF*	*Approximate % temperature compensation achieved*
A	−500	50	50
B	−500	100	60
C	−500	0	10
D	−1800	50	200
E	−1800	20	100

6.3. *Performance of control equipment with varying input moisture content*

Fig. 10 shows the measured response of the control system on the low-capacity drier to variations in the m.c. level of the input grain. These tests were carried out on naturally moist

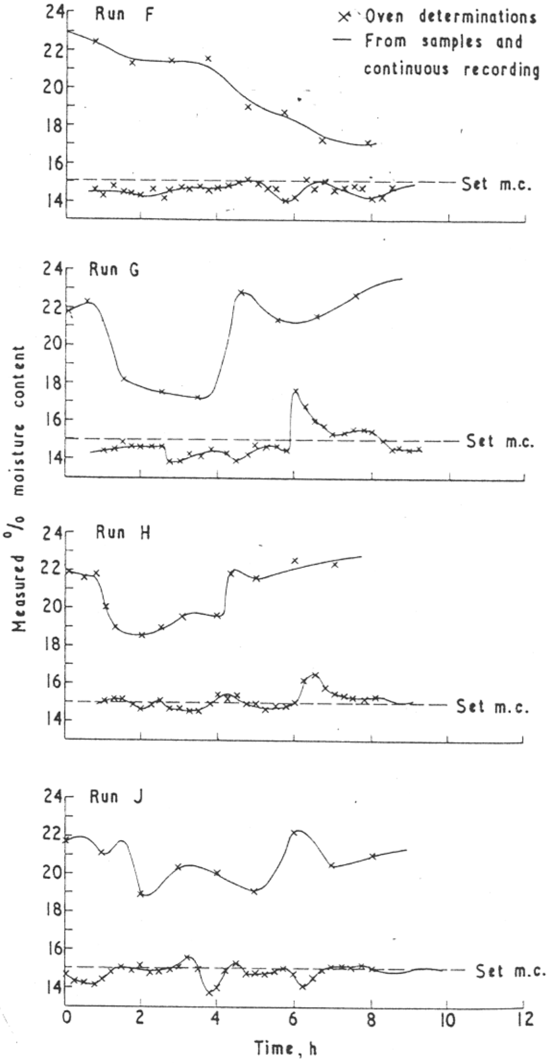

Fig. 10. Measured response of prototype control apparatus to variations in input moisture content

Atle wheat, harvested on successive days to provide material at different m.c. levels. Individual sacks were sampled before the drying runs to enable the input level to be controlled, although sampling limitations led to the considerable, haphazard fluctuations apparent in the recorded data. These data are based on oven determinations on hourly samples taken at the input and 15-min samples at the output, supplemented in both cases by a continuous record of permittivity.

In Run F, a drift in input m.c. level covering the range 22–17% was arranged, the mean rate of drift being about $\frac{3}{4}\%$/h. Control parameters set were $P = 1$ and $R = 1\%$/h.

It is evident that the m.c. of the dried grain was generally within approximately $\pm\frac{1}{2}\%$ of the level at which the bridge was balanced, the principal exception following a large change at the input during which the m.c. decreased by $2\frac{1}{2}\%$ in less than 1 h.

In Runs G and H there were large step changes in input m.c. This is the most stringent requirement met in practice, since the input change is necessarily initially reflected at the output, although somewhat reduced by the non-linearity of the drying process. The frequency of occurrence of such changes is, in practice, low and the steps of up to 4% used in these trials are unlikely to be exceeded. The control parameters were again $P = 1$ and $R = 1\%$/h.

Run J was carried out with $P = 2$ and $R = 1\%$/h. Performance was generally satisfactory, although the step changes were rather less and the test therefore less severe.

From these data, and other similar drying runs, it is generally concluded that the combination of $P = 1$ and $R = 1\%$/h is near optimum for this experimental plant.

6.4. *Calibration of control equipment*

A further drying run was carried out, during which the m.c. setting control was adjusted to three different values. Output samples were collected at 15-min intervals during the run and the deviation from balance of the monitor unit continuously recorded. From previous trials a correlation had been established between the bridge balance deviation and equivalent output m.c. error, enabling the m.c. data on the samples from this run to be individually corrected to the value which would correspond to absolute balance of the bridge. In this way, a number of corrected m.c. values are available for the calibration of each of the settings of the sensing bridge. These data are summarized in Table V, which indicates that the calibration is approximately linear. In addition, the low variability ($\sigma = 0{\cdot}2\%$) of these data shows the validity of such a calibration for a given variety of grain.

TABLE V

Summarized results from drying runs for calibration of prototype control apparatus

Control setting (arbitrary scale)	*Number of samples*	*Mean corrected % m.c. of samples*	*Std Dev. of sample m.c.*
47·0	7	16·4	0·2
43·0	12	15·3	0·2
40·0	11	14·5	0·1

6.5. *Effect of physical properties of grain*

Reported tests in connection with the development of capacitance-type moisture meters[1] have demonstrated the large variation in effective permittivity caused by differences of grain variety and probably also of weather conditions during ripening and harvesting. The need to employ a weighed sample of material for accuracy in all conditions is shown. Such a provision is not, of course, included in this method of m.c. monitoring. At the present state of knowledge, a relative calibration for a given material is practicable, as is the maintenance of a level once established. There are three possibilities for initial setting of the control system:—

(a) A separate sample-type moisture meter may be employed to initially check the controlled level provided that this is reasonably stable and relative adjustments can be made to the control apparatus if necessary.

(b) A capacitance-type sample moisture meter with similar frequency and resistivity characteristics may be employed to measure both fixed weight and fixed volume samples, from which a control setting may be derived.

(c) Measurement of bulk density of the moist grain, related to its measured moisture content, might enable a sufficiently accurate initial setting to be achieved.

The first possibility is now practicable without further tests, whilst the alternatives, although enabling the correct setting to be obtained earlier, require further work.

7. Future work

Satisfactory automatic control of the m.c. of dried grain from an experimental continuous-flow drier has been achieved. It is now intended to incorporate the equipment developed on a typical farm drying plant. A survey of the manual operation and performance of this plant has been completed and should enable a direct comparison between the effectiveness of manual and of automatic control to be made.

The main practical difficulties forecast by this survey seem to be uneven flow of grain within the drier, possibly due to inadequate pre-cleaning, and restricted storage conveyor capacity and storage facilities for undried grain. The possibility of uneven flow within the drying bed may make it preferable to monitor the moisture content at the drier outlet to obtain a reliable m.c. value, although this introduces some delay between the completion of drying and the m.c. sensing with a resultant slight degradation of the control performance. However, this arrangement has the advantage that monitor and throughput control may be combined as a self-contained unit to stand beneath the drier output.

8. Reliability

The reliability of the equipment during its development trials has been good.

In practice, the control system might be either used with periodic supervision, which would probably be more necessary to ensure correct functioning of the grain handling equipment, or left unattended. In the latter case, in addition to supervisory controls to indicate grain blockages or conveyor failures, an alarm might be fitted to the m.c. sensing unit to report serious faults in the drier or m.c. control system.

9. Conclusions

On an experimental scale, the performance of the relatively simple prototype control equipment has been shown to be satisfactory. Proportional control action with automatic reset is suitable for the long process times involved.

Near-optimum values for the control parameters have been established for the experimental plant and these may with reasonable confidence be modified to allow changes in the system such as the resiting of the monitor within the plant.

Some further attention is necessary to the problem of calibrating the equipment, although the control facilities may at present be used with the initial setting obtained by reference to a sample-type moisture meter.

An adaption of this system could allow the completion of drying in a batch drier to be indicated, or possibly followed by automatically switched cooling or emptying and refilling, so providing completely automatic batch drying.

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