DRYING OF SOLIDS

Recent International Developments

EDITOR
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A HALSTED PRESS BOOK

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PREFACE

Truly global recognition of drying of solids as an important unit operation worthy of serious academic and industrial R & D has come rather late. It was possibly triggered by the so-called "energy crisis" of the early 70's. The highly successful Biennial International Drying Symposia and the resulting series of publications provided a further impetus to the science, technology, engineering and even art of drying. Today drying R & D continues worldwide at a pace unmatched in any earlier period.

The objective of this book is to provide a compilation of papers coveirng a wide variety of contemporary topics in solids drying. Since the ultimate objective of any industrial drying operation is to reduce the product moisture to desired level, the unit operation of nonthermal dewatering is just as crucial in governing the overall economics. To this end one review article on a new dewatering technique was specially commissioned for this volume.

I have made a deliberate attempt to provide wide geographic coverage and also to provide a reasonable balance betwen theory and practice. The papers are reproduced as submitted by the authors.

I want to thank the authors for their efforts and enthusiasm without which this book could not have materialized. I would also like to record with thanks the generosity and vision of Mr. H. Bana of MacNeill and Magor Ltd., Bombay, India, for a grant-in-aid to cover the editorial and related expenses. I hope this will make the book more readily accessible even in the developing countries of the world. Finally my gratitude to Purnima Mujumdar who served as the Editorial Assistant throughout this project.

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ACKNOWLEDGEMENTS

It is indeed with great pleasure that I acknowledge the sponsorship of the Kilburn Division of Macneill & Magor Ltd.,Bombay, India, which enabled the initiation and completion of this book project. As a leading specialist in a wide spectrum of DRYING SYSTEMS available internationally and the sponsor of Industrial Drying Systems Seminars in India, Macneill and Magor have displayed a strong commitment to development of the science and technology of drying in India as well as internationally. Such a commitment is of course backed by innovative designs to meet the special requirements of the process applications and furthermore by excellent fabrication facilities for a timely execution of the project.

In particular, I would like to thank Mr. Homi Bana and Dr. Rohit M. Shah of Macneill and Magor for their encouragement and suppport throughout the duration of the project. This project owes its success to their thoughtfulness and vision.

As the Editor it is my pleasant duty to thank all the authors for their time and effort. Dealing with over 80 authors from 17 countries was not an easy task. Nonetheless it was professionally rewarding and I hope the authors share this feeling. Also, I must record with deep gratitude the assistance provided by Purnima Mujumdar and Mainul Hasan in the long drawn out editorial process. Finally, I must express my sincerest appreciation to Mr. A. Machwe of Wiley Eastern Ltd. for his efficient handling of the publication process.

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CONTENTS

COMPUTER CONTROL OF A HIGH TEMPERATURE ALFALFA DRYER-INSTRUMENTATION AND PERFORMANCE

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ABSTRACT

The operation of an alfalfa dehydrating plant has been outlined. A high temperature wet bulb sensor was developed to monitor the instantaneous evaporative load of the system. Based upon the operational responses of process components a control system was developed to regulate feed flow. The control system will be tested at the plant in the 1984 alfalfa production season.

1. INTRODUCTION

Pelleted alfalfa is rich in protein (about 18 %), vitamin A, and coloring substances and is used as poultry and animal feed. Western Canada produces about 200000 tonnes (t) of pellets annually most of which is exported oversees. Significant effort is underway to expand domestic consumption in the form of livestock ration supplements.

In the first step of the pelleting process, green chopped alfalfa is dehydrated in rotary drum dryers. A typical dryer can evaporate about 10 t of moisture per hour; a capacity that represents the amount of water to be removed from 16.4 t of green alfalfa with a moisture content of 65 % to produce 6.4 t of 10 % dehydrated product. The present dryers use about 200 cubic meters of natural gas to produce one tonne of product, or about 3250 kJ per kg of evaporated water. Maintaining a uniform moisture content of 9 to 10 percent in the final product is essential. Undried product is susceptible to spoilage during storage and transportation while overdrying is extremely costly in terms of energy input, weight loss and brittleness of the pellets. Good control of the process is therefore important.

High temperature drying of alfalfa has been the subject of research but not to the same extent as research into the area of barn drying or sun curing. Menzies and O'Callaghan studied drying of ryegrass in a thin-layer with temperatures up to 410 C [1]. They noted a constant drying rate above 200 C, and found the leaves to dry at twice the rate for stems. O,Callaghan et al. simulated high temperature alfalfa drying using a semi-empirical equation for material transport within the dryer [2]

A number of reports are available regarding automatic control of this type of dryer. Taylor [3] describes a moisture sensing device for continuously sensing moisture on the feeder apron, and Carlson et al. [4] describe an adaptive control system using the exhaust temperature.

In this paper progress on the development of a data acquisition and control system for a rotary alfalfa dryer is described. The project is in progress and a final report will be published upon its completion.

2. DRYER DESCRIPTION

The alfalfa dehy plant studied is located in Tisdale, Saskatchewan. Figure 1 shows the overall process flow of the plant. The drying plant can be functionally divided into three sections: 1) feeding section, 2) drying section, and 3) pelleting and storing section. We are concerned with the operation of the feeding and drying sections. These sections are described in detail.

2.1. Feed Section

Field chopped alfalfa is transported to the plant site by trucks and dumped on the concrete yard close to the feeders. The material is then loaded gradually onto the feeder apron with a front-end loader. The green alfalfa moves on the feeder apron at a slow speed while a leveling roller with short pyramid spikes maintains a uniform depth of material. The leveling roller rotates at about 30 rpm in a direction opposite to the direction of the feeder. The material past the leveling roller is thrown on a horizontal belt conveyor by a high speed spiked roller. The material is then transported with an inclined belt conveyor to the top of the furnace. Feed rate is regulated by adjusting the speed of a DC motor driving the feed apron and the rollers.

2.2. Drying Section

The drying section consists of a stationary furnace and a rotary drum dryer. The circular furnace is 1.5 m diameter and 2.5 m long, lined with refractory bricks. A gang of five burners mounted on a circular plate injects natural gas

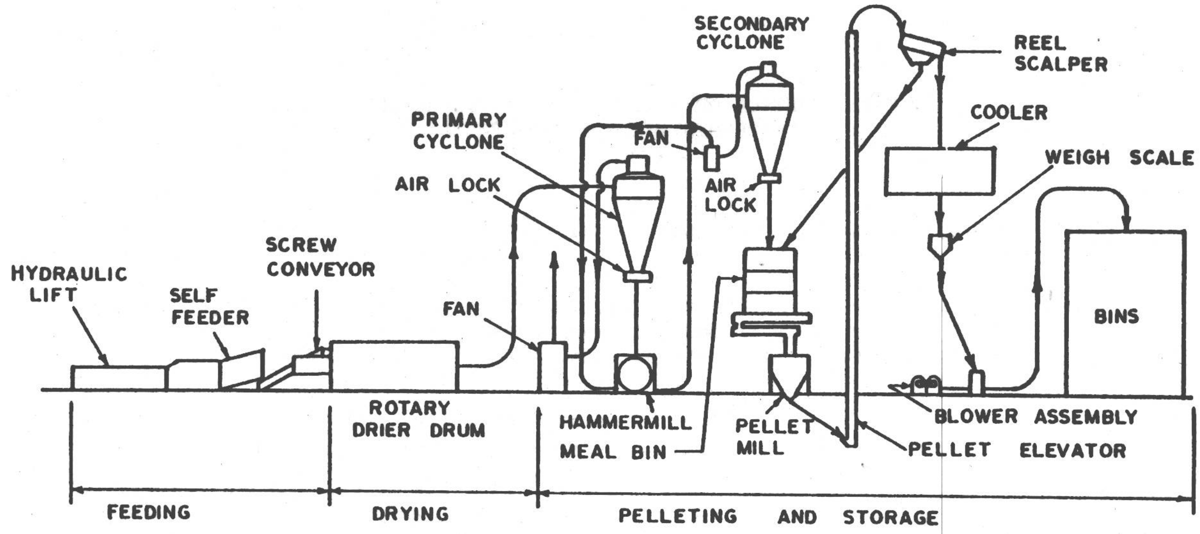

Fig. 1. Process flow of the alfalfa dehydrating plant.

for combustion. Air is drawn into the combustion zone from outside. Feed is introduced into the dryer at the rear part of the furnace. An inclined chute directs the feed into the dryer. A shielded thermocouple located just beside the chute senses the drying air temperature before it mixes with the wet material.

Drying takes place in three concentric rotating drums. The drums are 2.5 m, 1.5 m, and 1 m in diameter. The length of the drum is about 12 m, so the total drying path is about 36 m. Baffles on the inside wall are configured such that the material is transported toward the exit by the drum rotation . The air movement also assists in transporting the drying material.

Upon exit from the dryer the air/alfalfa mixture is ducted to a cyclone where the solids are separated from the air. The solids move on for grinding, steaming, pelletting, cooling and storing. The air is drawn from the cyclone by a centrifugal fan and exhausted to the atmosphere. The exhausted air carries moisture, small particles and approximately 90 % of the input energy.

2.3. Dryer Control

The dryer operation is controlled both automatically and manually. An automatic control maintains a constant exhaust temperature by adjusting the flow rate of natural gas. The rationale for this control is that the exhaust air temperature is an indicator of the product dryness. The operator sets the exhaust temperature manually on a Honeywell controller. The set temperature is maintained by sensing the present exhaust temperature with a thermocouple, throttling the amount of fuel gas to the burners. The choice of the exhaust temperature for the set point is the operator's responsibility. His judgement is based on feeling the feed material and occasionally measuring the moisture content of the pellets with a moisture meter in his control room. Once in a while he also checks the condition of chops under the cyclone for scorching.

Depending on the set point temperature, the operator also manually adjusts the speed of the feeder apron; trying to maintain the exhaust temperature without large excursion of the gas flow rate. Sometimes the material is extremely wet and a wide open gas setting is not capable of maintaining the exhaust temperature. In such cases the operator increases the gas pressure manually by adjusting the pressure regulator on the gas line.

3. THE PROBLEM

The main problem with the present system is that it does not stay stable. The operator constantly changes the feed rate, the set point for the exhaust temperature and the gas pressure. Yet the moisture content of the pellet does not remain uniform, and the gas consumption of the system is rather high. The operator is also faced with occasional fires, and/or plugging of the hammer mills which results in down time and loss of material. The inefficiency is evident from the average energy requirement of 3250 kJ/kg of water evaporated, while a theoretical value of 2300 kJ/kg may be expected.

4. PROCEDURE

After studying the operation of the system, we hypothesized that the temperature feed back control with its inherent thermal delay coupled with instantaneous changes in the feed rate to the dryer are the main causes of the unstable operation. As a first step in the solution we decided to instrument the dryer and monitor the system under normal operating conditions.

The data collection, analysis and control functions have been implemented with a small personal microcomputer. In the analysis phase of the project, signals from many points in the system were obtained, converted to digital values, and stored. The primary signal processing instrument was a Fluke 2240 data logger. The Fluke performed signal processing, conditioning, digitization, and hard copy recording. The timing and magnetic tape storage functions, as well data conversion and calculation of dependent variables were performed by a Commodore PET microcomputer. The signals collected are given in Table 1, and a block diagram of the data collection and the instrumentation are shown in Fig. 2.

TABLE 1 Channel number designation and range of values for a data logger.

Channel	Variable	Range
1	ambient air temperature	5 - 30 °C
2	stack dry bulb temperature	100 - 120 °C
3	stack wet bulb temperature	70 - 85 °C
5	dryer exhaust temp. (edge)	100 - 125 °C
5	dryer exhaust temp. (center)	100 - 125 °C
6	calculated relative humidity	20% - 80%
7	calculated evaporative load	5 - 12 t/h
8	hammer mill current	50 - 250 A
9	gas valve position	0 - 100%
10	dryer inlet temperature	150 - 1000 °C
11	feeder conveyor load cell	0 - 100
12	dry chops temperature	40 - 120 °C
13	product moisture content	5% - 12%

In addition to the data obtained by Fluke, a number of experimental data were obtained manually in order to confirm readings by the instruments. In the following section methods of obtaining various data are described.

Two or three trucks arriving from field were weighed and their contents were piled separately on the concrete yard. The dryer which had already been operating was cleared of any old material and the loader fed the new material to the feed apron. The green chopped material was sampled every five minutes and the samples were cumulated for 20 minutes in plastic bags for moisture measurement.

The flow of gas and the line pressure were recorded manually every five minutes. The inputs to the gas valve position indicator in the control panel were tapped and connected to the data logger. This enabled us to record the instantaneous position of the gas valve. The temperature of the drying air immediately after the burner was read from the furnace thermocouple. The exhaust gas temperature immediately after the dryer was sensed by a pair of thermocouples located adjacent to the thermocouple that sends signal to the Honeywell temperature controller. The dry bulb and wet bulb temperatures of the exhaust air down stream from the fan were also sensed. The wet bulb sensor consisted of a constant level water reservoir, and a long wick which was inserted into the air stream. A thermocouple was installed within the wick to sense the wet bulb temperature; dry bulb temperature was sensed by an adjacent thermocouple in the air stream. All thermocouples were secured in copper tubing to prevent physical damage.

A thermocouple was placed under the main cyclone to measure the temperature of the dried chops. In addition, the temperature of the dried chops at the same location was determined manually in a thermos bottle equipped with a thermometer. The same samples were saved and cumulated every five minutes and placed in a plastic bag for moisture determination. All moistures were determined using the oven method as recommended in ASAE Standard S 358.1 [5].

Airflow was measured by traversing a pitot tube across the stack gas pipe.

The load on the hammer mill was sensed by monitoring the motor AC current. The speed of the feeder apron was recoreded by tapping the output of the tachometer on the DC drive motor.

The above data were scanned continuously and were recorded on the tape every minute for the duration of the test.

5. ANALYSIS

The air flow rate was measured in two occasions, and the velocity was read directly from the manometer. The velocities of about 12 points across the tube were measured. Table 2 summarizes the readings and the various conversion factors used to obtain the mass flow rate of the air. The diameter of the exhaust duct in which the velocity was measured was .914 m, and used an average mass flow rate of about 10.7 kg/s for calculating evaporative load.

Wet bulb readings obtained with a hand held wet bulb thermometer and by the wet bulb sensing device are plotted in Fig. 3. The data were obtained immediately following the installation of a new wick on the wet bulb sensing device. Figure 4 shows that the manual readings were consistently

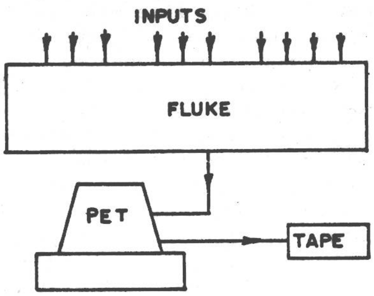

Fig. 2. Data acquisition, processing and storage components.

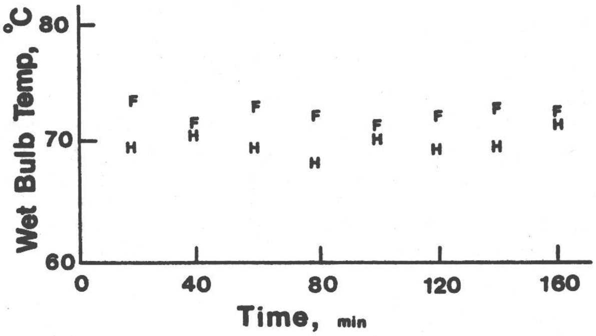

Fig. 4. Wet bulb temperature reading with FLUKE data logger (F) and with a wetted wick glass thermometer (H).

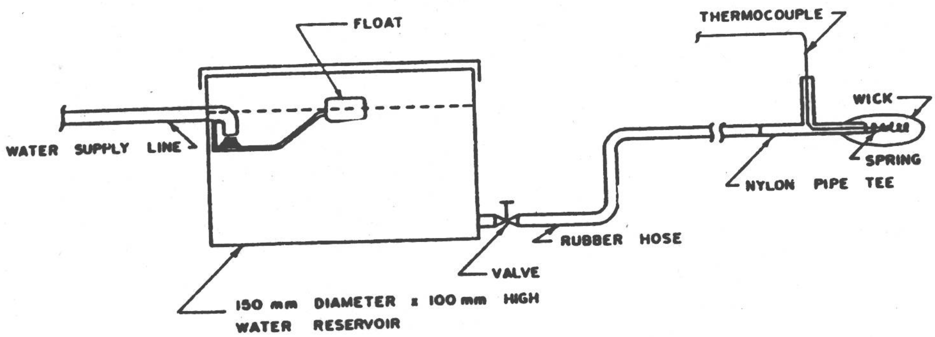

Fig. 3. Diagram of wet bulb temperature sensor.

lower than those registered by the Fluke by about 2-3 degrees°C. The manual readings were performed by wetting the wick of the thermometer and inserting the bulb into the stack for about 180 s. This duration might not have been sufficient to increase the wet bulb temperature of the wick.

Figure 5 shows the dry matter content of alfalfa before and after drying. It is of interest to note the variations in the dry matter (or moisture content) of chopped alfalfa arriving from field. The dry matter content of the dried alfalfa seems dependent upon the initial moisture content of the feed. In spite of the apparent consistency in the temperature of the exhaust air (Fig. 6), the present control system fails to maintain a constant moisture in the product. It becomes clear that the dryness of the product does not depend on the exhaust air temperature.

Figure 6 shows the temperature of the exhaust air, and the evaporative load as calculated from wet bulb/dry bulb measurements. There is no doubt that the Honeywell controller is capable of maintaining rather uniform temperature; however other variations in the system cause substantial changes in the evaporative load.

Figure 7 shows humidity ratio in the exhaust and the moisture difference between the undried and dried alfalfa. The value of the moisture difference was scaled down by 10 times in order to show it on the same scale as the humidity ratio. There is a time lag between the two sets of data as is evident from the Figure; nevertheless the humidity and moisture difference have the same trends. This indicates, firstly that the wet bulb sensor reflects the moisture in the air, and secondly it suggests that if the humidity ratio is to be used to adjust feed rate then it should be possible to obtain a uniform moisture of the product. We should note that the speed of the apron during this particular test was maintained constant.

6. PROPOSED CONTROL SYSTEM

Upon further analysis of the data, the important variables for system control were identified, and a simplified data collection, conversion, analysis, and control system was designed and built. The elements of this system have been individually tested, but the entire system will not be installed and operated until the summer of 1984 when the dryer will be in operation. The object will be to control the feedrate, in addition to the existing gas control system.

The system is designed around a Commodore VIC, a readily available, inexpensive, and suitable machine. The operators are not afraid of this popular machine, and readily accept its

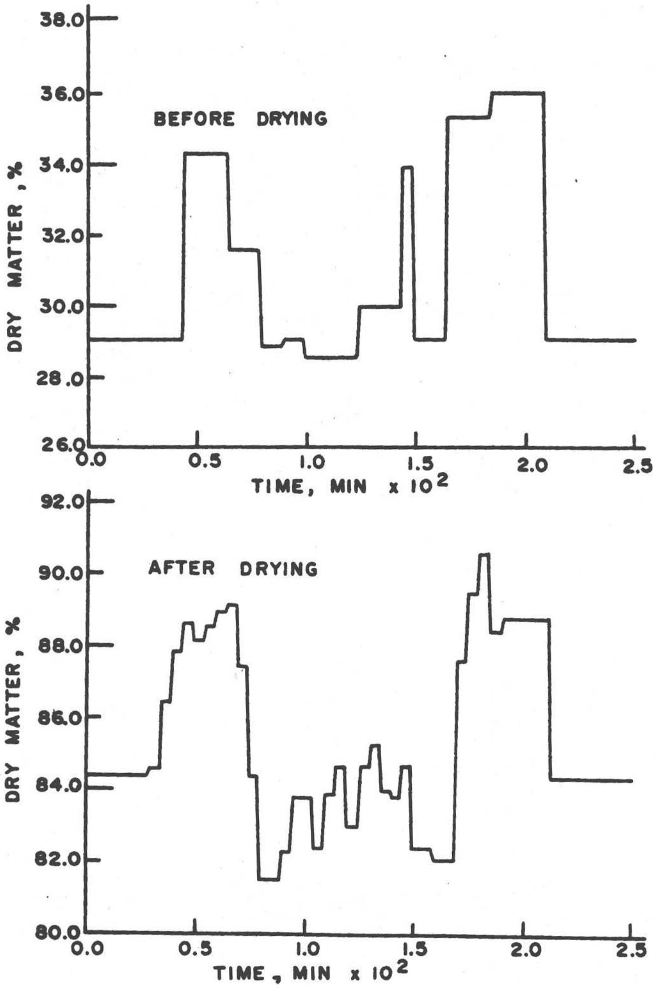

Fig. 5. Percent dry matter content of the undried chopped alfala (top) and that of the dried alfalfa (bottom).

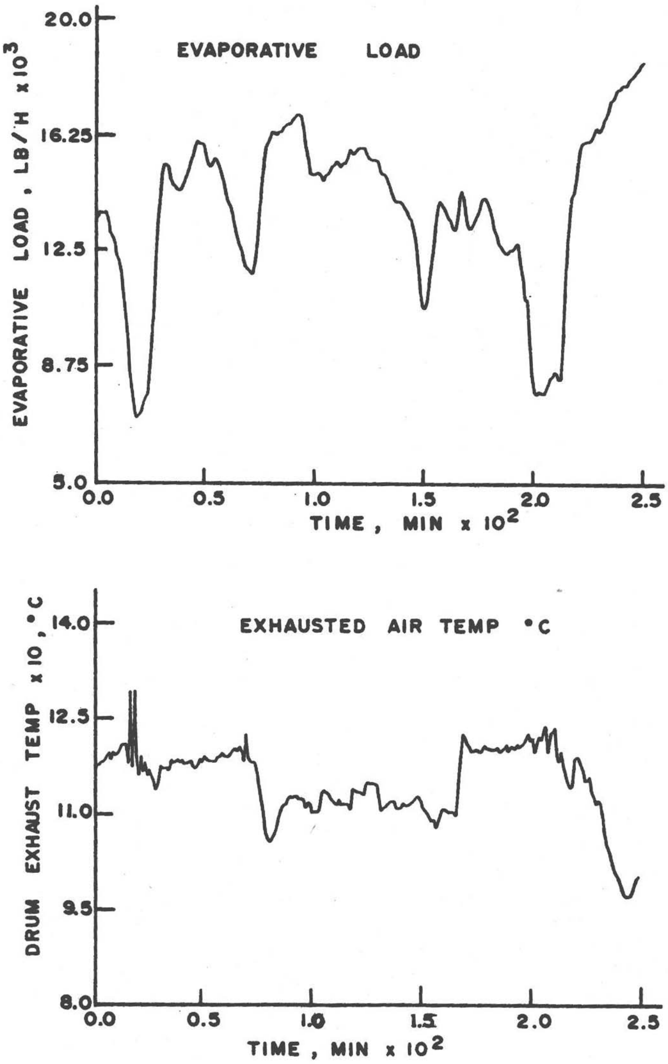

Fig. 6. Evaporative load (top) and the exhausted air temperature (bottom).

presence in the control room. The VIC contains both an expansion port, and a user's port accessing the system through a standard peripheral interface adapter (PIA) 6522. The latter 8 bit parallel port has been used in this case, both to input data to the computer and to transmit control signals to the motor controller for the feed drive.

The primary variables determined from the previous analysis were exhaust gas, wet bulb and dry bulb temperatures. These temperatures were measured with thermistors whose signals are amplified, multiplexed into an 8 bit analog to digital converter then read into the computer on the 8 bit port. The 8 input multiplexer and the converter control lines are also driven from the port, and timed by the computer.

A simplified system diagram is shown in Fig. 8, with input and output sections to the microcomputer identified. The output signals from the computer interface to an existing Ultracon SCR motor speed controller, manufactured by the

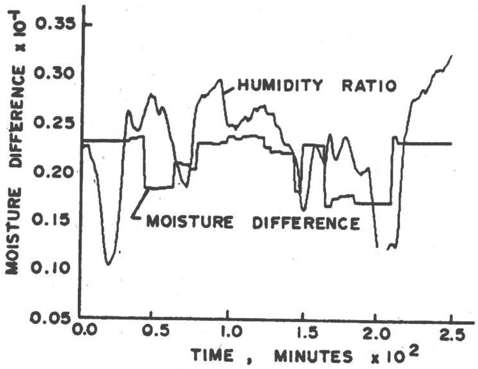

Fig. 7. Humidity ratio in the exhausted air and the difference between initial and final moisture contents.

T. B.Wood's Company. Since this controller operates on independent power supplies, and the control signal could not be referenced to any other system voltage, careful precautions had to be taken to electrically isolate the control signal voltages. Because the isolation required extra electronic components, only one line was used to connect to the computer. A signal was created by the computer, driven through the optical isolation unit, then converted to 8 bit parallel and converted to analog by a D/A converter. The analog voltage was amplified and used to drive the SCR motor controller. The 8 bit system used here provides accurate conversion to within 0.5 %. This parameter is more than adequate for the control required by this system.

TABLE 2. Estimating air mass flowrate.

Avg. vel m/s	Temp °C	Hum Ratio kg/kg	Spec. Vol. m3/kg	Flowrate kg/s
23.7	114	0.220	1.47	10.6
24.7	120	0.247	1.50	10.8

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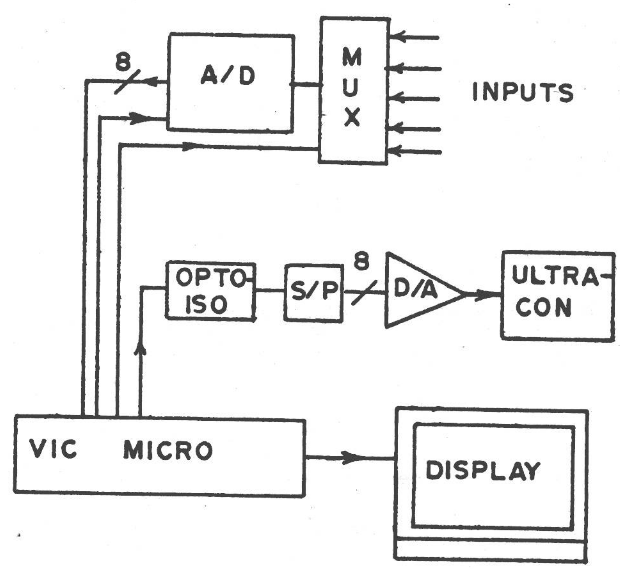

Fig. 8. Block diagram of the controller.

TWO-PHASE FILTRATION EQUATIONS AND SORPTION ISOTHERMS AS APPLIED FOR STUDYING KINETICS AND DYNAMICS OF DRYING PROCESSES

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ABSTRACT

The successive thermodynamic approach is used to obtain the system of the equations for drying, sorption and non-isothermal filtration under incomplete saturation in non-deformed media. To determine the non-isothermal Leverett function, i.e. a capillary liquid pressures as a function of saturation, it is suggested to employ the sorption isotherms and the Kelvin equation. The obtained system of the equations is applied for numerical modelling of vacuum drying of a cylindrical electric-cellulose insulation sample. The effect of the capillary forces on the evaporation zone deepening, moisture content fields and vapour pressure is taken into consideration.

1. INTRODUCTION

There is no unique viewpoint [1-9] in theoretical description of transfer processes in porous media. In the theories of drying, sorption and multi-phase filtration, the divergences are a matter of principle, although all of them must govern the same processes of combined heat and mass transfer in porous media involving phase conversions.

The laws of conservation of mass and energy will be adopted to describe the above processes. The transfer equations stemming from these conservation laws are beyond any doubt. However, these are not closed. To do so, it is necessary to determine the rate of mass transfer between phases I, additional specific heat of sorption (or desorption), r_{sorp}, transfer potentials for liquid and vapour, liquid pressure p_ℓ as a function of moisture content W and temperature T, to elucidate the reason for the effects of thermal moisture conductivity and how these are taken into account in calculations, and to ascertain the physical meaning of diffusion coefficients for vapour and liquid as well as the methods of their determination.

2. THEORETICAL MODEL

2.1. Dynamic Equilibrium Conditions at the Curved Interfaces

In a porous medium, the boundary of two phases is divided into the majority of different-curvature sections. Adopting the mass transfer Fourier analog, it is easy to see that local thermodynamic equilibrium (LTE) develops for the relaxation time, $t_r \approx 10^{-6}$-10^{-8} s, and a pore radius 10^{-7}m. That is why, the LTE hypothesis may always be valid. In case of dynamic equilibrium between the liquid and vapour, the chemical phase potentials must be equal to

$$\mu_\ell(p_\ell,T) = \mu_v(p_v,T) , \qquad (1)$$

and the liquid pressure is determined through that for the vapour by the Kelvin equation

$$p_\ell = p_{sat} + \frac{RT}{v_\ell} \ln \frac{p_v}{p_{sat}} . \qquad (2)$$

Equation (2) is verified experimentally in [3,7,11] specifying its applicability boundaries as well. The case when the liquid film is less than 10 Å, will not be considered here, assuming that a body is "dry".

In practice, we know the sorption (desorption) isotherms $W=f(\phi,T)$. Knowing $p_{sat}(T)$ gives for the isotherm

$$W = f(p_v,T) \qquad (3)$$

where p_v is the pore vapour pressure. From Eq.(3), p_v may be expressed using the inverse function as

$$p_v = F(W,T) . \qquad (4)$$

Hence, with allowance for Eq.(4), Eq.(3) may be written thus

$$p_\ell = p_{sat}(T) + \frac{RT}{v_\ell} \ln \frac{F(W,T)}{p_{sat}(T)} . \qquad (5)$$