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DRYING OF A POROUS MEDIUM WITH INTERNAL HEAT GENERATION

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Abstract—An experimental investigation is presented for the drying of absorbent materials (such as cotton) with the aid of microwave heating. Data is presented for the transient temperature, pressure, and moisture distributions for axial, radial and combined axial and radial drying. It is shown that there is only a very small mass concentration gradient under these conditions. Temperature gradients also are small. Mass transfer occurs due to pressure gradients caused by the rapid vapor generation throughout the sample. The drying cycle is divided into four regions: the initial adjustment period during which the temperature throughout the product rises steadily and very little drying occurs; a liquid movement period during which liquid is forced out of the sample with a high initial moisture content (over 200 per cent); a constant rate period when water is vaporized in the sample; and a falling rate period when final drying occurs.

INTRODUCTION

SOLUTIONS to coupled heat- and mass-transfer problems in porous media with heat generation are difficult to obtain due to the shortage of fundamental experimental data. This work is concerned with the measurement of temperature, mass concentration, and pressure at specific locations within a cotton sample which is being dried with the assistance of microwave heating. Although this study is restricted to drying cotton, the techniques and general observations should be useful for studies of the drying of paper, foods, and other textiles.

Luikov [1] presented a discussion of the development of the coupled heat and mass transfer equations and presented a set of solutions for several geometries and boundary conditions [2]. These solutions do not apply to problems involving distributed heat sources. Approximate solutions for problems without heat generation were reported in [3] and [4]. There appears to be little information available on the important problem of coupled heat and mass transfer in porous media with internal heat generation. An important step in understanding the process is the availability of experimental data on the internal heat and mass transfer characteristics.

EXPERIMENTAL INVESTIGATION

The drying of cotton samples took place in an aluminum oven (18 × 17·5 × 15 in.) which used a 2450 MHz Raytheon model QK 390 magnetron as a source of microwave energy (see Fig. 1). The sample was suspended above a plexiglas rod on which a strain gage was attached for weight measurements. The strain gage was positioned outside of the oven to prevent erroneous readings that might result from the microwave radiation. Temperature measurements in the microwave field were accomplished with small ($\frac{1}{8}$ in. dia. by 6 in. long) alcohol filled glass thermometers. They remained unaffected by the microwave field and were calibrated prior to each experiment. A gamma ray attenuation technique [5] was used to de-

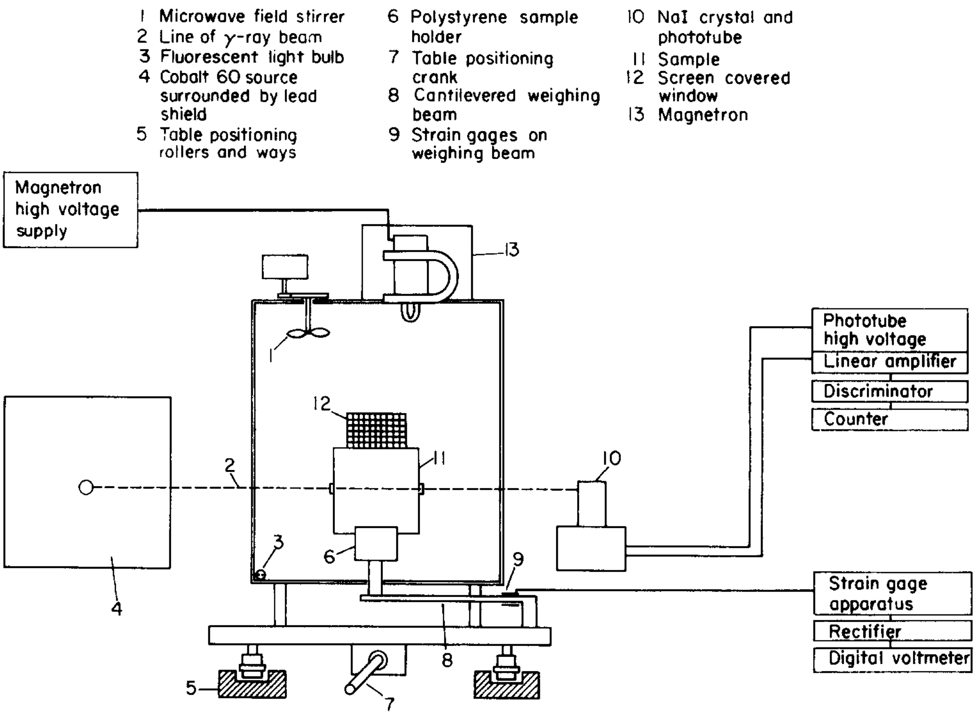

FIG. 1. Schematic of experimental apparatus.

termine the local mass concentration within the sample. This method consisted of directing a collimated beam of gamma rays through the sample in a direction normal to the moisture flow. The attenuation of the gamma rays depended on the mass of the moisture along the path of the beam so that the change in intensity could be measured and related to the change in local moisture content of the sample. The pressure distribution within the sample during the process was measured with teflon pressure probes (0·106 in. i.d.) which were connected to inclined manometers outside the microwave chamber.

The samples were constructed from absorbent and non-absorbent cotton yarn wound on an impervious paper core, $\frac{7}{8}$ in. dia. The samples were 8 in. dia. and $5\frac{3}{8}$ in. long. The non-absorbent cotton yarn was 24 count single ply, and had not been exposed to any bleach treatment. The absorbent cotton yarn was 28 count, two ply, unmercerized and treated with a caustic bleach process to make it absorbent. In some tests, moisture flow was restricted to one direction by coating each end or the circumference of the cylinder with a polyester resin which penetrated into the cotton sample less than $\frac{1}{16}$ in. This resin is essentially transparent to microwave radiation. The samples were brought to uniform temperature and mass concentration prior to each experiment.

EXPERIMENTAL RESULTS

Six different experiments were made for drying absorbent cotton. These experiments are outlined in Table 1.

Typical drying curves showing the mass fraction (weight of water divided by weight of dry cotton) as a function of time are presented in Fig. 2. The curve for Test 1 represents radial drying which is accomplished by sealing the ends of the sample. Test 2 is for simultaneous

Table 1. Table of test samples

Test number	Surfaces sealed	Sample size diameter by length, (in)	Dry weight of cotton (lb)	Mass fraction*	Measurements taken
1	Ends	$7\frac{7}{8} \times 5\frac{3}{8}$	3·24	2·18	*TWM*
2	None	$7\frac{7}{8} \times 5\frac{3}{8}$	3·24	1·67	*TW*
3	Circum.	$7\frac{7}{8} \times 5\frac{3}{8}$	3·25	2·12	*TWM*
4	None	$7\frac{7}{8} \times 5\frac{3}{8}$	3·24	2·24	*TWM*
5	Ends	$7\frac{7}{8} \times 5\frac{3}{8}$	3·42	2·00	*TWP*
6	None	$7\frac{7}{8} \times 5\frac{3}{8}$	3·20	2·23	*TWM*

* Mass fraction is lb_m water per lb_m of dry cotton.
T = Temperature
W = Weight
P = Pressure
M = Mass fraction

radial and axial drying—no surfaces were sealed for this test. The rate of drying during the early stages is very slow for Test 2. During this same period (about 30 min) Test 1 shows a much larger rate of drying due to drainage of liquid from the sample.

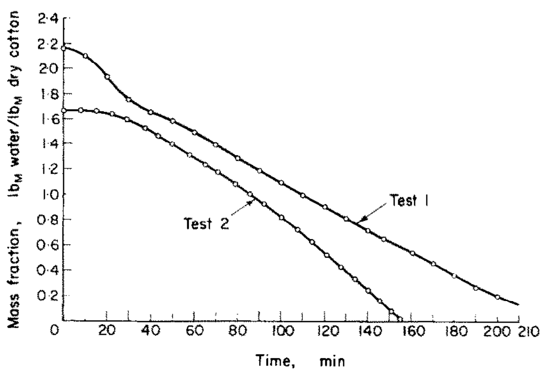

FIG. 2. Mass fraction vs. time with ends of sample sealed. Test 1. and with ends not sealed. Test 2.

Figure 3 shows the mass change rate vs. mass fraction. It should be noted that the right end of the curve represents the initial state and drying proceeds as one follows the curve to the left. The initial period is designated the "initial adjustment period". During this time, the temperature throughout the sample rises. The temperature distributions as a function of time at several locations along the axial direction are shown in Fig. 4 for Test 3, where the circumference of the sample is sealed in order to obtain axial drying. The radial temperature variation for Test 1 is shown in Fig. 5 where it may be observed that the temperature throughout the sample rises rapidly during the initial adjustment period. After about 30 min the temperature throughout the sample approaches 210°F (the local boiling point of water). As the temperature approaches 210°F, a rapid increase in the mass

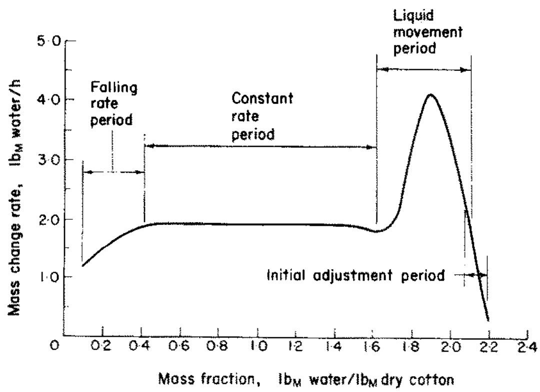

FIG. 3. Mass change rate vs. mass fraction with ends of sample sealed, Test 1.

change rate was observed for samples with a very high initial moisture content. Liquid may be observed to flow from the sample during this time due to the rapid rate of vapor generation which causes a pressure gradient within the

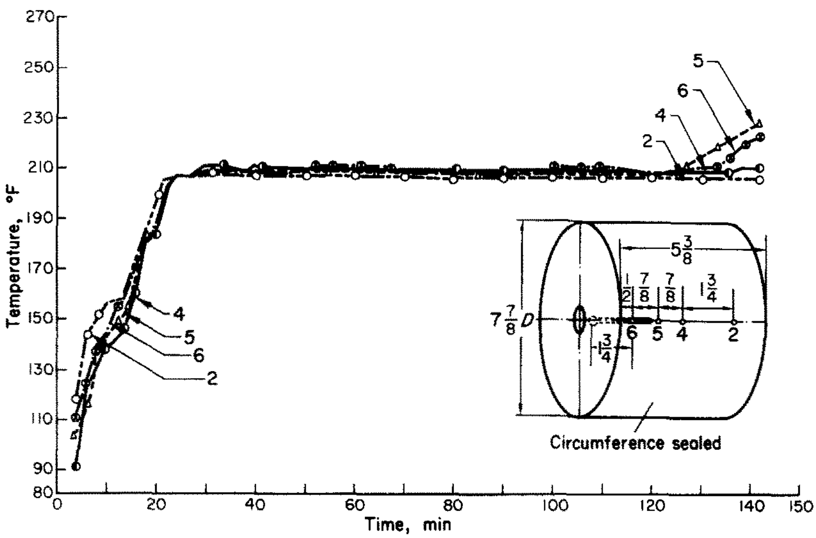

FIG. 4. Temperature variation along the axial direction, circumference of sample sealed, Test 3.

sample. This period is designated as the "liquid movement period". Such a period is observed only in samples with high initial moisture contents. Drier samples do not exhibit a liquid movement period. The distinction between the initial adjustment and the liquid movement periods is arbitrary as can be seen in Fig. 3; however, the later period starts before the temperatures in the sample reach the boiling point.

As the drying proceeds, the observable transport of liquid ceases and the mass transport becomes primarily a movement of vapor. The temperature throughout the sample becomes and remains at the local boiling temperature. Since the moisture is vaporized before leaving the sample, the drying rate is proportional to the vaporization rate and is, therefore, proportional to the energy input to the sample. The

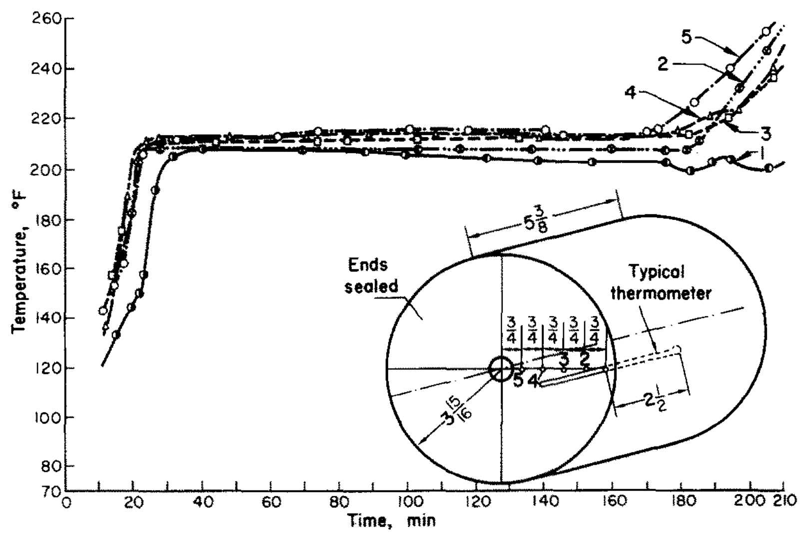

FIG. 5. Temperature variation along radial dimensions, ends of sample sealed, Test 1.

energy output of the oven remained constant throughout the process; therefore, the mass change rate during this period remains constant. This period is designated as the "constant rate period".

Near the end of the process some portions of the sample became dry, while others remained slightly wet. The mass change rate decreases in this period and is designated as the "falling rate period".

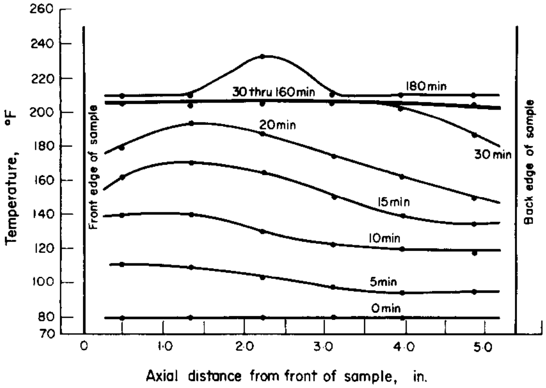

FIG. 6. Temperature profiles along the axial dimension at a radius of $2\frac{1}{4}$ in., sample unsealed, Test 4.

Typical temperature profiles within the samples at selected times are shown in Figs. 6 and 7. Figure 6 shows the temperature variation along the axial direction and Fig. 7 shows the temperature distribution in the radial direction.

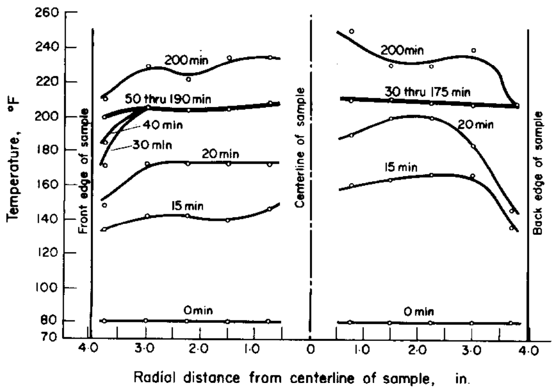

FIG. 7. Temperature profiles along the radial dimension, ends of sample sealed, Test 1.

These figures show that the temperature distribution is nearly constant during most of the process. During the initial warm up period, some temperature variation exists, but once the sample reaches 210°F, the temperature distribution throughout the sample remains uniform.

It is significant to note the lack of large temperature gradients within the sample. Measurements of the sample surface temperature revealed a considerable temperature gradient near the surface. The depth beneath the surface at which the temperature remained substantially less than the sample center temperature (210°F) was affected by movements of the surrounding air. In all cases the region affected by the temperature gradient extended less than $\frac{1}{4}$ in. below the surface.

The pressure variation within the sample during test 5 is presented in Fig. 8. This represents the pressure variation at several different radial locations for a sample with the ends sealed (i.e. radial mass flow). The pressure throughout the sample remains essentially unchanged throughout the initial adjustment period. At the end of the initial adjustment period, as the temperature of the sample approaches 210°F, a sharp rise in the pressure is observed. This period corresponds in time to the start of the liquid movement period. The pressures become large and then start to decrease as the process continues. As the moisture content of the sample decreases the permeability increases and the pressure at all locations within the sample decreases.

A plot of the pressure profiles in the radial direction, shown in Fig. 9, shows as one would expect, that the highest pressure within the sample occurs at the center of the sample.

The local mass variation within the sample as measured by the gamma ray technique of [5] is shown in Fig. 10. The local mass content curves demonstrate the same drying characteristics as the mass fraction curve for the entire sample, Fig. 2. It is significant that only small mass concentration gradients exist with internal heat generation. The local mass concentration

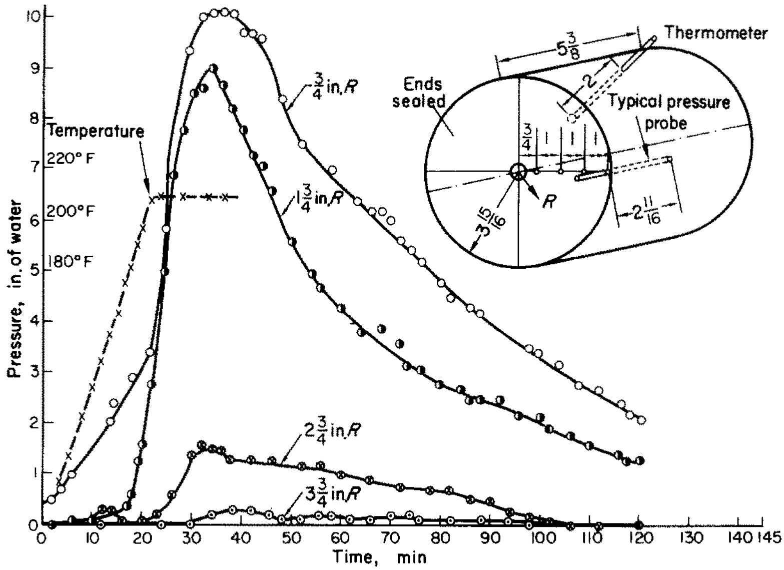

FIG. 8. Pressure variation with radial flow, ends sealed, Test 5.

along the axial direction of an unsealed sample is presented in Fig. 11 and in the radial direction in Fig. 12. The sample used in both Figs. 11 and 12 was unsealed allowing mass diffusion in all directions. These data reveal the lack of large mass concentration gradients existing during the process.

The data reported here were obtained for samples of absorbent cotton. Experiments also

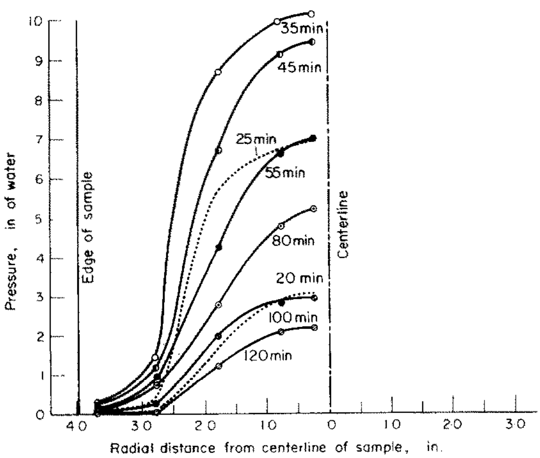

FIG. 9. Pressure profiles in radial dimension with radial flow, sample ends sealed, Test 5.

obtained for non-absorbent samples showed characteristics that are similar to the results presented.

CONCLUSIONS

External characteristics

The characteristics of heat and mass transfer in a drying porous media may be greatly influenced by internal heat generation. Drying occurs during a liquid movement period which does not occur during more conventional drying processes. The constant rate period continues until the moisture content is very low. The rate of heat dissipation corresponds directly to the latent heat required for evaporation of the water. A brief falling rate period occurs only near the end of the drying process when the moisture content is very low. Much faster drying is possible by using internal heat generation than by using surface heating.

Internal characteristics

Perhaps one of the unexpected results of using internal heat generation to accelerate drying processes is the lack of a significant mass concentration gradient during the entire process. For

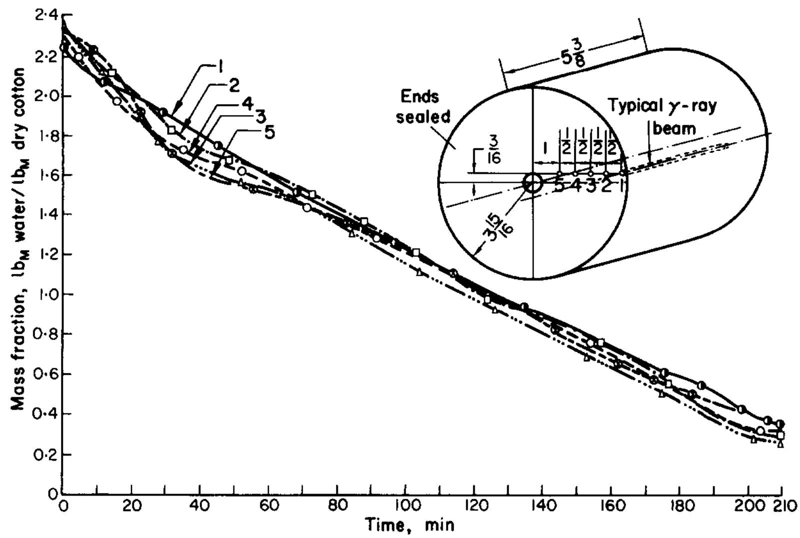

FIG. 10. Mass fraction variation with radial flow, sample ends sealed, Test 1.

example when a sample with non-uniform mass concentration was placed in the oven, the mass concentration became uniform and remained uniform throughout the process.

When samples are heated externally, the potential of energy transfer is a temperature gradient resulting in heat conduction to the interior of the sample. Similarly, the potential of mass transfer is the mass concentration gradient which exists between the wet interior portion and the drier surface. With internal heat generation the mechanism of energy transfer is primarily internal heat generation and the mass transfer is primarily through a total pressure gradient established due to the rapid vapor generation inside the sample.

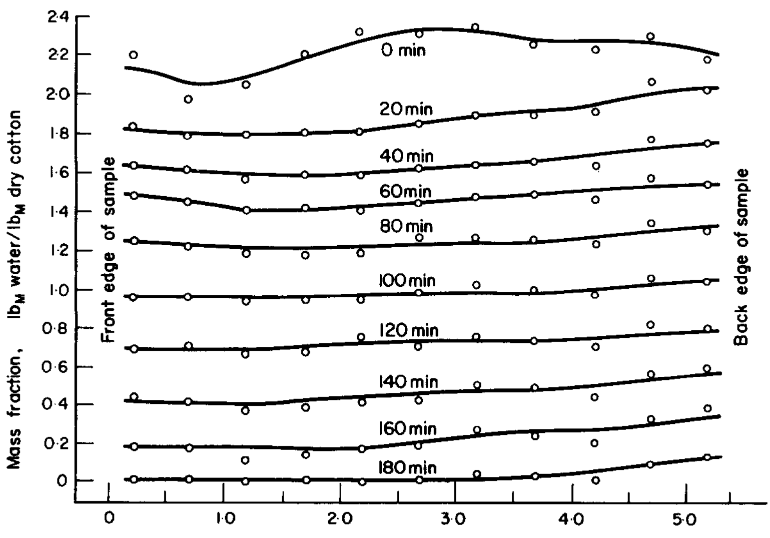

FIG. 11. Mass fraction profiles along the axial dimension, unsealed sample, Test 4.

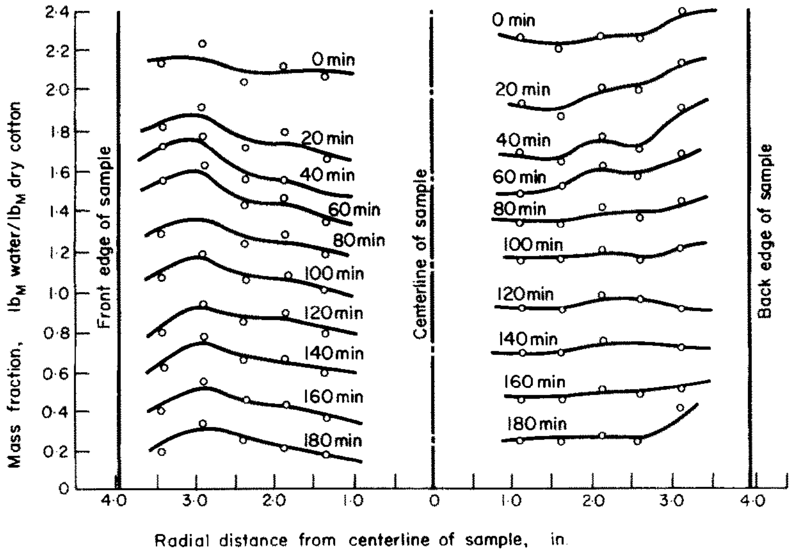

FIG. 12. Mass fraction profiles along the radial dimension, unsealed sample, Test 6.

With the internal heat generation, most of the moisture is vaporized before leaving the sample. However, when the sample is initially very wet and the pressure inside the sample rises rapidly, liquid may be removed from the sample under the influence of a total pressure gradient. The higher the initial moisture, the more influence this pressure gradient has on total mass removal.

It is hoped that this study will provide a basis for approximate solutions to be obtained for coupled heat and mass transfer in a porous media with internal heat generation.

REFERENCES

1. A. V. LUIKOV and YU. A. KIKHAILOV, *Theory of Energy and Mass Transfer*. Pergamon Press, Oxford (1965).
2. A. V. LUIKOV, *Heat and Mass Transfer in Capillary-Porous Bodies*. Pergamon Press, Oxford (1966).
3. E. V. TOLUBINSKIY, An integral method of solution of the general heat and mass transfer problem, *Int. J. Heat Mass Transfer* **9**, 1471–1488 (1966).
4. I. J. KUMAR and H. N. NARANG, A boundary-layer method in porous body heat and mass transfer, *Int. J. Heat Mass Transfer* **10**, 1095–1107 (1967).
5. J. D. HATCHER, D. W. LYONS and J. E. SUNDERLAND, An experimental study of moisture and temperature distributions during freeze-drying, *J. Food Sci.* **36**, 33–35 (1971).

SÉCHAGE D'UN MILIEU POREUX AVEC GÉNÉRATION INTERNE DE CHALEUR

Résumé—On présente une recherche expérimentale pour le séchage de matériaux absorbants (comme le coton) à l'aide d'un chauffage à haute fréquence. Des résultats sont présentés concernant les distributions de température, de pression et d'humidité pour des séchages axiaux radiaux et combinés. On montre qu'il n'y a dans ces conditions qu'un très petit gradient de concentration de masse. Les gradients de température sont petits eux aussi. Le transfert massique observé est dû aux gradients de pression provoqués par la génération rapide de vapeur à travers l'échantillon. Le cycle de séchage est divisé en quatre parties: la période d'ajustement initiale durant laquelle la température à travers le produit s'élève lentement et durant laquelle le chauffage est très faible; une période de mise en mouvement du liquide qui est chassé hors de l'échantillon avec un grand taux d'humidité initial (supérieur à 200%); une période de flux constant lorsque l'eau est vaporisée dans le modèle; et une période de flux décroissant correspondant au séchage final.

TROCKNUNG VON PORÖSEN MEDIEN MIT WÄRMEERZEUGUNG IM INNERN

Zusammenfassung—Eine experimentelle Untersuchung für die Trocknung von absorbierenden Materialien (z.B. Baumwolle) mit Hilfe einer Mikrowellenheizung wird vorgestellt. Für zeitlich veränderliche Temperatur, Druck und Feuchtigkeitsverteilungen, für axiale, radiale und kombinierte axiale und radiale Trocknung werden Daten angegeben. Es wird gezeigt, dass es nur einen sehr kleinen Massenkonzentrationsgradienten unter diesen Bedingungen gibt. Die Temperaturgradienten sind ebenfalls klein. Stoffübertragung tritt gemäss dem Druckgradienten auf, verursacht durch die rasche Dampferzeugung im ganzen Probekörper. Der Trocknungszyklus ist in vier Bereiche eingeteilt: die Nulleinstellungsperiode, während der die Temperatur im Produkt gleichmässig ansteigt und sehr geringfügige Trocknung eintritt; eine Flüssigkeits-Bewegungsperiode während der aus dem Probekörper mit einem hohen Anfangsfeuchtigkeitsgehalt (über 200%) Flüssigkeit herausgepresst wird; eine Periode, in der das Wasser im Probekörper mit gleichmässiger Geschwindigkeit verdampft; und eine Periode abnehmender Geschwindigkeit, in der die Schlusstrocknung erfolgt.

ВЫСОКОЧАСТОТНАЯ СУШКА ПОРИСТОГО МАТЕРИАЛА

Аннотация—Проведено экспериментальное исследование сушки гигроскопических материалов (например, хлопка) с помощью высокочастотного микроволнового нагрева. Приведены данные по нестационарному распределению температуры, давления и влажности при аксиальной, радиальной и смешанной сушке. Показано, что при таких условиях существует лишь небольшой градиент концентрации массы. Градиенты температуры также очень малы. Массообмен происходит благодаря градинетам давления, вызванным быстрым парообразованием в образце. Цикл сушки можно разделить на четыре режима: начальный период, во время которого температура материала постепенно повышается, а удаление влаги почти полностью отсутствует; период движения жидкости, во время которого жидкость выталкивается из образца при значительном начальном влагосодержании (свыше 200%); период постоянной скорости сушки, когда вода испаряется в образце; и период падающей скорости сушки, когда процесс сушки заканчивается.