## CHRONICLES

# ABSTRACTS OF PAPERS AT THE INTERNATIONAL SYMPOSIUM ON HEAT AND MASS TRANSFER PROBLEMS IN FOOD ENGINEERING

This symposium was held on October 24-27, 1972 at Wageringen in the Netherlands; 48 papers from 14 countries were presented.

The subjects of the papers varied greatly, as is clear from the contents of the two volumes of papers, which were nearly all in English (three were in French), and which were reproduced by offset for circulation.

The abstracts or summaries are reproduced below.

A1. W. J. Beek and P. B. Kwant (Netherlands). Non-Newtonian Heat Transfer in Round Pipes

A1-A1.16

Simple relationships exist between non-Newtonian heat transfer with constant liquid properties and Newtonian heat transfer with temperature dependent properties.

Consequently, all that is known about Nu-numbers for these two general cases can be presented in a unique way, basing relationships either on the dimensionless velocity gradient at the wall or on the dimensionless local pressure drop.

This unique relationship is demonstrated for the case of pipe flow.

A3. G. Forrest and W. L. Wilkinson (UK). A Theoretical Study of Heat Transfer to Temperature-Dependent Non-Newtonian Fluids in Laminar Flow

A3-A3.28

This paper presents a theoretical treatment of laminar flow heat transfer in circular tubes for a temperature dependent non-Newtonian fluid for which the relationship between the shear stress, $\tau$, and the shear rate, $\gamma$, can be described by an equation of the form:

$$\tau = \tau_y + K(T)\,\gamma^n,$$

where $\tau_y$ is a yield stress, n is a constant, and K(T) is a function of temperature. This model can therefore cater for both power-law and Bingham plastic behavior. The two boundary conditions of constant wall temperature and constant wall heat flux are covered for both heating and cooling situations. The computed results are presented by plotting a Nusselt number as a function of the Graetz number with dimensionless groups specifying the temperature dependence effect, the rheological properties and the wall conditions as parameters. This method of presentation is convenient for engineering design purposes. Temperature profiles, velocity profiles, and the pressure drop can also be determined.

A4. G. S. Cattell (UK). Heat Transfer in Plate Heat Exchangers with Laminar Flow

A4-A4.27

Laminar flow theory is applied to the plate heat exchanger and the problems involved in the analysis of the complicated flow patterns generated in a plate heat exchanger are discussed. Existing correlations for Newtonian flow are presented and an example of their use shown. Non-Newtonian flow is considered and the implications of the correction factors currently used to account for non-Newtonian behavior are examined. Finally, trends in the design of plate heat exchangers produced specifically to handle viscous fluids are discussed.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 25, No. 5, pp. 928-939, November, 1973.

A6. H. G. S. Edney and M. F. Edwards (UK). Heat Transfer in Agitated Vessels

A6-A6.21

In the food industry many processes are carried out in agitated vessels and in many cases heat addition or removal is an important part of the operation. A brief review is given of the equipment for mixing and heat transfer in such processes.

A large amount of data is at present available in the published literature for the prediction of rates of heat transfer in agitated vessels. The correlations available for jacketted vessels and those fitted with heating or cooling coils with agitation provided by paddles, turbines, propellers, and anchors are critically discussed. Data for both Newtonian and non-Newtonian liquids are considered.

In addition, experimental data obtained from a 1.22 m diameter tank equipped with helical cooling coils are presented. In this study, results have been obtained for the Newtonian and non-Newtonian liquids agitated by a six flat-bladed turbine.

Finally, consideration is given to the design of agitated vessel systems which could be used for batch, continuous, or semi-batch operation.

A7. A. E. Hawkins (UK). Heat Transfer from Mashed Potatoes in Laminar Flow

A7-A7.19

Thermal calculations are used to show that the cooling of potato in circular and rectangular equipments is fairly slow. Theoretical and experimental studies have been performed on the cooling of mashed potato in a highly efficient cooler with an annular working section formed by two concentric tubes. A description is given of the apparatus, with the optimum conditions for operation. Experimental results are presented as tables and graphs.

A8. F. G. De Saulles (UK). Factors Influencing Heat Transfer in Scraped Surface Heat Exchangers

A8-A8.7

Scraped surface heat exchangers are employed in a relatively specialized field of heat exchange involving the processing of products of high viscosity, often involving a change of state, as in the chilling and plasticizing of edible fats. Crystallization and a tendency to deposit a static layer on the heat exchange wall are other considerations which this type of heat exchanger is designed to overcome and which bring special problems not normally encountered in other types of continuous heat exchange equipment.

Because of the nature of the fluids normally processed, their non-Newtonian properties, or the change of state which often occurs, it is not practicable to arrive at realistic formulae on which heat exchange coefficients may be calculated. Nevertheless there are several factors which must be given careful consideration in designing a heat exchanger for any given application.

In this short paper the operating principle of this type of unit is briefly outlined and its field of application, then we consider in more detail those factors which can substantially influence heat transfer rate and performance. This will include consideration of the effect of: a) shaft speed, b) mechanical power requirements, c) product pressure, d) material of construction of the cylinder, and e) material of construction of the scraper blades.

Tests on a laboratory system have indicated the effects of these factors on the heat-transfer rate in exchangers with mechanically scraped surfaces, as intended for cooling liquid food products.

A9. W. A. Beverloo, W. F. Hermans, and A. K. Muntjewerf (Netherlands). Heat Transfer and Pressure Drop in Plate Heat Exchangers

A9-A9.14

Experimental and literature searching work on the influence of plate profilations on the heat transfer rate in plate heat exchangers is described. The work was performed at the Food Engineering Division of the Agricultural University and at Stork Amsterdam N. V. as an extension of earlier described work.

Study of flow phenomena indicated appreciable disturbances of stationary laminar flow for Re > 100. A device was developed to measure directly the average wall temperature over some longitudinal length in the equipment described by Muntjewerf in his thesis. From the measured wall temperatures local Nu numbers can be derived. From a limited number of measurements and rather scarce data in literature

it appears that disturbance of the laminar flow profile can promote heat transfer. For very viscous products the application of the heat transfer promoting effect of profilations can be limited by the moderate pressure tightness of plate heat exchangers.

B1. H. Spreng (Switzerland). Pilot Plant Studies of Microwave Heat Sterilization for Heterogeneous Food Products

B1-B1.18

The adaptability of three applicator types to heat sterilization of heterogeneous food products has been tested (multimode cavity, rectangular $TE_{10}$ waveguide and cylindrical cavity with $TM_{01}$ dominant mode). The working frequency lies within the S band (2.45 GHz). The difficulties encountered in each case are briefly discussed. The "$TM_{01}$ applicator" was found the most promising system and some data using it has been collected and summarized. A detailed cost analysis gives an average of the estimated costs – both investment and running.

B2. J. Deltour and F. Flaubert (Belgium). Exact Temperature and Lethality Calculation for Sterilizing Process

B2-B2.7

The exact analytical solution of the heat conduction equation is used to describe the time evolution of the temperature at the geometrical center of a cylindrical can heating by conduction. The solution is shown to depend on 6 variables in the heating phase and on 8 variables in the cooling phase. Dimensional analysis allows to reduce these numbers to 3 and 5 dimensionless products and the invariance properties of the phenomenon are discussed.

These results are then used to compute the so-called "lethality" of the entire process. The impractical integrals which always occur in such evaluation are simplified and only depend on 3 and 4 dimensionless products (heating on cooling phase). The integrals are tabulated as functions of these quite significant parameters and an exact lethality evaluation results from two readings in these tables.

Invariance properties of this solution are discussed and a comparison with Ball's approximation is performed. It shows that Ball's method fails, in some cases, by as far as 25%. The reason of which appears to be the fact that the temperature rise at the center of the can, which is supposed to stop with the heating phase in Ball's method, actually continues after the cooling is started.

B3. S. N. Thorne and R. Jowitt (UK). Fluidized Bed Heating of Canned Foods; the Influence of the Outside Heat Transfer Coefficient on the Sterilizing Value of the Process

B3-B3.16

The rate of heating of a can of a hypothetical foodstuff in surroundings at 250°F was calculated for values of heat transfer coefficient h to its surface of 5 $BTU.ft^{-2}.hr^{-1}.°F^{-1}$ to $\infty$. Except at low values ($< 50$), the heat transfer coefficient had little effect on the rate of heating of the can.

Cans of six foodstuffs were heated in a fluidized bed ($h \approx 100$) and in saturated steam ($h \approx 1000$) at the same temperature. The thermal diffusivities of these foods were determined, and their theoretical rates of heating at infinite heat transfer coefficient were calculated. The lethality/time curves for the two observed processes and the theoretical process were compared with each other. For conduction-heating packs, little difference between the curves was found.

B4. H. Burton and A. G. Perkin (UK). Control of the Water Content of Milk during Processing by Steam Injection and Flash Cooling

B4-B4.11

A theoretical and practical examination has been made of the problem of ensuring that there has been no concentration or dilution of milk as a result of a sterilization process comprising steam injection followed by expansion cooling. It is shown that suitable control of temperature should maintain the milk composition to limits closer than can be checked by available chemical analytical methods.

B5. A. Rabich (Germany). Steam and Liquid Injection

B5-B5.16

Some aspects are discussed for the main trends in the hydrodynamics and heat and mass transfer on injecting steam and liquid into a liquid.

B6. H. F. Th. Meffert and J. W. Rudolphij (Netherlands). The Cooling Process of Heat Generating Bodies

B6-B6.20

The cooling process of heat generating bodies can be described in analogy to the cooling process without heat generation, after a slight adjustment of the definitions of temperature difference and intercept value. Information on both is given in figures for the three basic bodies slab, cylinder, sphere.

The cooling rate has to be defined in terms of the possible temperature drop. The definition of the intercept value serves at the same time as a criterion for the possibility of cooling.

Application to composite bodies is demonstrated on the basis of experimental results.

Theory is based on a negligible variation of heat generation with temperature for agricultural produce in unit loads under practical conditions.

B7. F. W. Bakker-Arkema (USA). Heat and Mass Transfer during Bulk Storage for Granular Biological Products

B7-B7.42

The heat and mass transfer processes occurring during the bulk storage of biological products, in particular of root and tree crops, and grains, have been simulated. Optimization techniques have been applied to the simulation models to establish the optimum conditions for processing such products.

B8. A. Ohm and N. W. F. Kossen (Netherlands). Oxygen Concentration Distribution in an Unventilated Food Store during Self-Heating

B8-B8.12

A model is described for the distribution under stationary conditions; the heating occurs most rapidly in the outer layers, where there is a reasonably rapid influx of oxygen by diffusion.

B9. A. Gac (France). Analysis of Mass Loss in a Refrigerating System

B9-B9.11

A system of equations is presented for estimating the water loss from frozen and cooled products under storage in relation to the storage conditions; the system can be solved by introducing appropriate relationships between the various factors, namely temperature of the location, evaporator temperature, relative humidity, flow rate of circulating air, mass of stored products, evaporator characteristics, and so on.

The equations are examined to reveal the main trends and to give practical recommendations on reducing the loss of food products under these conditions. The basic criterion for storage is not the relative humidity of the air but the difference in temperature between the building and the evaporator. Deterioration in products can be reduced by filling stores properly, reducing the air transfer, and minimizing the heat loss from the location. Frozen products should be stored in saturated air; cooled ones should be kept only in moist air.

C1. M. Le Maguer (France). Sorption of Volatiles on Solids of Varying Water Contents

C1-C1.19

Frontal analysis and elution chromatography have been used to derive sorption isotherms for volatiles on dried microcrystalline cellulose. The absorption capacity of the cellulose has been examined in relation to temperature and water content. The materials absorbed have been water, ethanol, acetone, and carbon tetrachloride.

The results indicate that water has a definite effect on the retentivity for the volatiles. This is explained in terms of hydrogen bonds between the adsorbent and the volatiles if water is present on the adsorbent. Heats of sorption and specific adsorption surfaces are calculated for cellulose from the results.

It is pointed out that the results can be used for various practical purposes in retaining aromatic and taste properties in food products.

C2. P. J. A. M. Kerkhof, W. H. Rulkens, and J. van der Lijn (Netherlands). Calculation of Aroma Losses from Drying Liquid Foods

C2-C2.38

The liquid food containing the volatiles can be considered as a multicomponent system consisting of water, dissolved solids, and volatiles. This means that in principle the diffusion flux of any one of the compounds in such a system is affected by the fluxes and concentrations of all other components. However, owing to the low concentrations of the volatiles, the transport of a specific volatile component will be independent of the presence of the other volatiles and is only influenced by the fluxes and concentrations of the nonvolatile dissolved solids and water. The fluxes of the dissolved solids and water are not influenced by the volatile components. Taking the dissolved solids as one component, the diffusional transport in a liquid food containing volatiles can therefore be treated as a binary system when considering the transport of water and dissolved solids, and as a ternary system concerning the transport of the volatiles.

The purpose of this study is to give more insight into the quantitative effect of process variables in water and volatile losses during drying. Numerical calculations of the drying of a slab containing volatiles were performed. Water concentration dependences of the diffusivities and of the activity coefficients were used, which are representative of those of liquid foods. The results of the theoretical calculations will be compared with experimental results and with data presented in literature.

C3. M. Karel (USA). Calculation of Storage Stability of Foods on the Basis of Analysis of Kinetics of Deteriorative Reactions of Foods and of Mass Transfer Rates through Packaging Materials

C3-C3.30

Techniques are being developed by which laboratory tests on foods and on packaging materials may be used to predict shelf life of a particular food-package combination, or conversely by which protective packaging requirements for a given food may be calculated if the needed shelf life is known. These techniques are based on a combination of kinetic parameters of deterioration reactions with mass transfer properties of packaging materials, and result in analytical or numerical solutions useful for prediction of the desired quantities either with or without computer assistance.

Confirmation of usefulness of the above approach has been obtained by tests on foods representing the following types of food storage problems:

1) Dehydrated foods in which the shelf life is limited by water absorption.

2) Dehydrated foods limited in shelf life by nonenzymatic browning, accelerated by water absorption.

3) Dehydrated foods limited in shelf life by either water absorption or by oxidative reactions depending on environmental conditions.

C4. K. Frankowski and F. Herrern (West Germany). Mass Transport through Packaging Materials and Packages

C4-C4.6

A description is given of a method of determining the air and water-vapor permeabilities of packaging materials for food products; practical applications are discussed.

C5. P. Marcellin (France). Preservation of Vegetable Products by Packing with Selective Permeability

C5-C5.17

Methods are considered for storing fruit and vegetables in controlled atmospheres produced within organic packaging materials with selective permeability.

The possible gas composition and main trends in the pressure change within the packaging are considered, and the permeability characteristics are discussed.

Several types of packaging used in industry are described.

C6. C. Peri, P. Battisti, and D. Setti (Italy). Solute Transport and Permeability Characteristics of Reverse Osmosis Membranes

C6-C6.25

The paper summarizes the results of reverse osmosis experiments carried out on model solutions of organic acids, phenolics and alcohols in simple solution or in mixture.

Cellulose acetate anisotropic membranes have been tested at various operating pressures, constant concentration and temperature in a stirred reverse osmosis cell. Long-term operation under pressure causes irreversible changes of the porous membrane layer, that results in product rate and retention changes. When operated with pure water, membranes undergo uniform compaction effects, while in the presence of some organics they become typically heterogeneous in structure, with porous spots located near compact ones. The retention is a function of both molecular weight and functional groups with a very marked increase for increased number of –OH groups.

When two solutes are mixed in solution their retentions tend to approach each other, lowering the separation ability of the membrane. Two hypotheses are presented to explain this phenomenon, based on the possibility of association of molecules and/or intermolecular bonding of solutes and membrane active sites.

Ethanol may play a 'second-solvent' role in solutions containing higher alcohols having low water solubility, such as butanol and amyl alcohol.

The behavior of solutes in all experiments suggests that the main transport mechanism involved is pore flow.

C7. C. Peri and C. Pompei (Italy). Concentration and Purification of Milk and Whey Proteins by Ultrafiltration

C7-C7.23

Protein concentrates may be obtained from milk and whey by ultrafiltration and/or diafiltration.

The choice of a particular combination of the two techniques is a key factor in determining the economy of the process.

An experimental approach is suggested and mass-balance equations are developed that allow a reliable definition of the optimum process.

C8. F. A. Glover (UK). Concentration of Milk by Ultrafiltration and Reverse Osmosis

C8-C8.9

The aim of the work is to concentrate milk in the cold to avoid changes in flavor. Rates of permeation and levels of retention have been studied in laboratory scale apparatus for both ultrafiltration and reverse osmosis in order to investigate the possibilities of a two-stage process. Concentration factors for milk of $\times 3$ have been achieved.

D1. A. Gac and A. Pont (France). Freezing in a Dense Fluidized Bed

D1-D1.12

A study has been made of the effects of air speed and grain-size composition on the heat-transfer rate in freezing food products in fluidized beds.

The methods used in the experiments are described; the results are presented as graphs.

D2. M. A. Slatter and M. C. Jones (UK). Development of an Accurate Method of Predicting Freezing Rates in Watery Solids

D2-D2.27

The paper describes a theoretical and experimental study to examine and improve existing methods of calculating freezing rates in a watery solid. The study includes the effect on the freezing rate of a thermal resistance between the coolant and freezing phases. This resistance was represented as a heat transfer coefficient, h.

Comparison of four methods of prediction showed that they gave significantly different results, so that experimental measurements of freezing rates became important in choosing an accurate predictive method.

Experiments performed in an apparatus that allowed accurate measurements of the rate of increase of ice thickness over a range of known h values showed that none of the predictive methods agreed closely with experiment for all h values. The best agreement resulted from computations of a finite-difference approximation to the conduction equation. This best method showed discrepancies with experiment of up to 50%.

The work described does not allow us to recommend a universally reliable method for predicting freezing rates, and further studies are in progress.

D3. J. M. Cordell and D. C. Webb (UK). The Freezing of Ice Cream

D3-D3.31

A nonlinear differential equation for thermal conduction is solved by finite-difference methods to obtain an analytical solution describing the nonstationary temperature distribution in an ice-cream briquette on the basis of the phase changes during solidification. The treatment incorporates the observed relationship between the thermophysical properties (specific heat and thermal conductivity), and also the density, on temperature. The analytical calculations agree well with experiment. It is considered that the freezing model can be used to determine optimum cooling parameters in existing commercial equipments such as those of tunnel type.

D4. M. A. G. Vorstman and H. A. C. Thijssen (Netherlands). Stability of Displacement of Viscous Aqueous Solutions by Water in a Packed Bed of Ice Crystals

D4-D4.22

The separation of ice crystals from viscous aqueous solutions is a part of freeze concentration processes. This separation can be performed in wash columns. In wash columns mother liquid is displaced from a bed of ice crystals by water. Solute losses with the ice and dilution of mother liquid by wash water are negligible when the displacement is stable.

The observed high stability of displacement, even at high displacement velocities, is explained by a decrease of the permeability of the ice bed on washing. This is confirmed by the measurements of permeability, porosity, and solute concentration as a function of height in the bed of a continuous wash column. A lowering of permeability at the wash front is caused by refreezing in the form of dendrites and a compression of the ice. The low solute losses with the ice are ascribed to the reflux which refreezes at the wash front.

D5. W. K. Beek and K. M. K. Muttzall (Netherlands). Extraction of Oil Seeds

D5-D5.14

A countercurrently operated cascade for oil seed extraction has been analyzed in order to optimize the dimensions and the operational conditions of the unit.

The influence and importance of the choice of a number of physical parameters is illustrated, such as: extraction medium, extraction factor, number of stages, particle size, drainage time, true extraction time, filling height, and extraction temperature.

D6. E. Balmaceda and S. K. Rha (USA). Diffusion Mechanisms in the Coagulation of Single-Cell Protein Coagulate

D6-D6.12

The overall rate of coagulation of single-cell protein dope was determined experimentally. Alkali dope (pH 9) was prepared at various concentrations and brought into contact with a coagulating medium containing 14% $Na_2SO_4$, 10% $H_2SO_4$, and 8% $Al_2(SO_4)_3$. The rate of advance of the sharp boundary between coagulated and uncoagulated portion was measured. The data were analyzed according to a mechanism of diffusion-limited chemical reaction at a moving boundary and values of the diffusion velocity were obtained at the different dope concentrations and bath temperatures. From the temperature dependency, a value of the activation energy for this particular coagulation process was obtained.

D7. M. Jamil and J. Lamb (UK). Heat Transfer in Low Rate Evaporation from Thin Films

D7-D7.16

Heat transfer coefficients and evaporation rates under small temperature differences between heating fluid and evaporating liquid have received little attention. Although large surface areas may be

required to obtain adequate evaporation there are advantages in evaporating heat sensitive liquids under these conditions. This paper reports on our investigations in this area.

Local film coefficients were measured by a point-by-point analysis during the climbing-film evaporation of water in a 1.5 m tube. Data was obtained at temperature differences of 7°, 14°, and 25°C, giving single pass vapor qualities at the tube exit of 2-22%.

The local film coefficients to the climbing-film were found to increase with increasing vapor quality, typically from a value of 1,000 $W/m^2°K$ to a peak value of 7000 $W/m^2°K$ or greater and then to decline to a value of 5000-6000 $W/m^2°K$. These results are compared with previous workers' findings on the existence of a two-phase forced convection regime in film evaporation.

D8. I. J. Kopelman and S. Mizrahi (Israel). Dimensional Analysis of the Temperature Response Parameter f

D8-D8.11

The authors discuss the nonstationary heating of bodies of classical shape; experiments in various ranges of the Biot number enable one to relate $f\alpha/R^2$ to Bi for a body of any arbitrary shape.

E1. A. V. Lykov and P. S. Kuts (USSR). Some Trends in the Drying of Moist Materials

E1-E1.48

The paper deals with numerous aspects of the theory, technology, and general drying of food and agricultural products, as well as other thermosensitive materials. Results are presented on new methods of drying developed at the Institute of Heat and Mass Transfer of the Academy of Sciences of the Belorussian SSR.

Details are considered for the main trends in highly efficient drying of dispersed thermally labile materials in fluidized beds using oscillating states.

Much attention is given to the form of binding of the water to the material, and a study has been made of the hygroscopic behavior and the thermodynamic parameters of the mass transport, together with the diffusion coefficients applicable to drying of food products and agricultural materials. Systematic results are presented on the equilibrium water contents and thermodynamic parameters for some agricultural products.

The theoretical examination shows that there is a relationship between the drying rate, the Nusselt number, and the Rebinder number during the period of falling drying rate.

Processing of numerous results on convective drying for colloidal materials shows that there is a single-value relationship between the ratio of the Nusselt numbers in the periods of falling and constant drying rate and the dimensionless drying rate itself.

Considerable theoretical and practical interest attaches to the resulting relationship for the surface temperature of the material.

E2. P. M. Bluestein and T. P. Labuza (USA). Mass Transfer Properties of Porous Materials: Effect of Pore Structure

E2-E2.22

During air dehydration of foods, the rate of drying falls drastically in the final stages of drying. Measured vapor diffusivities during this stage fall by an order of magnitude. This phenomenon has been attributed to the fact that vapor diffusivity is related to moisture content but no physical meaning for this has been elucidated. In this study, a system was designed to elucidate vapor flow diffusivity as a function of the mass transport properties in a porous material. Heat transfer limitations were minimized and accounted for. A mathematical model was derived to elucidate the vapor flow permeability as a function of pore size. It has been found that the changeover in vapor flow diffusivity to low values is due to a change in path and mechanism of flow. Initially the major flow of water vapor occurs as bulk flow in pores of about 10 $\mu$ in radius with a permeability of about $10^{-3}$ moles/atm-cm-sec. When moisture content goes below 10 g-$H_2O$ per 100 g solids, 40 to 50% of the water left is in pores of less than 100 Å in size due to the very large surface area of foods. These pores have a permeability of about $10^{-7}$ mole/atm-cm-sec and flow occurs by Knudsen diffusion. Thus, the overall lowering of vapor diffusivity is due to a change in flow path and mechanism and not per se a change in moisture content.

E3. J. Valchar (Czechoslovakia). Theoretical Analysis of Nonstationary Water and Temperature Distributions in Capillary Materials

E3-E3.20

A theoretical analysis is presented for transport processes in capillary materials, incorporating the binding energy of water.

The discussion concerns the choice of optimal working modes from the basic trends for internal heat and mass transfer. Particular attention is given to stresses arising in the material as a result of the nonuniform water distribution.

E4. J. J. Bimbenet (France). Heat and Mass Transfer during the First Steps of Drying

E4-E4.23

Heat and water transfer in a semiinfinite solid during the first steps of drying are studied on a theoretical basis. Analytical solutions for coupled heat and mass transfer equations are developed and an analogy has been found for heat transfer with and without drying. A finite-difference method gives a more flexible solution of the same equations. A comparison is made between these solutions and experimental results. Solutes movement is studied experimentally, with its consequences on the temperature of the solid and the rate of drying. The influence of these phenomena on the quality of the dried product is studied, the Maillard reactions being taken as a model of heat-sensitive biochemical alteration.

E5. J. Middlehurst and N. S. Parker (Australia). Analog Solutions to Some Heat and Mass Transfer Problems

E5-E5.32

It is shown that analog methods have substantial advantages in solving heat and mass transfer problems; no restrictions are imposed on the boundary conditions, and in essence there is no need to employ any simplifying assumptions in order to obtain an acceptable solution. If the actual boundary conditions are known, they can be used directly in the equations.

As an illustration, the authors consider problems concerned with heat conduction in an unbounded plate and a parallelepiped; they also consider freeze-drying under oscillatory conditions, and the mean values for the thermophysical characteristics of food products. In conclusion they discuss topics related to analog methods applied to transport processes with moving phase boundaries.

E6. D. R. Heldman and G. A. Hohner (USA). Atmospheric Freeze-Drying Processes for Food

E6-E6.52

A mathematical model which simulates the atmospheric freeze-drying of food and allows the evaluation of appropriate heat and mass transfer parameters has been developed. The model includes the numerical solution of appropriate partial differential equations for heat and vapor transport in a semi-dry, porous product layer.

The model has been verified by experimental measurement of moisture content during atmospheric freeze-drying. The results indicate that heat transfer is primarily by conduction through the matrix of product solids.

Simulation of product drying in three-dimensions indicates that the rate of atmospheric freeze-drying can be increased most effectively by reducing tube size and increasing the surface mass transfer coefficient. A dimensionless number which represents the ratio of external to internal mass transfer incorporates the influence of the primary contributions to atmospheric freeze-drying rate.

E8. J. D. Mellor and P. F. Greenfield (Australia). Heat and Vapor Transfer Problems in Cyclic-Pressure Freeze-Drying

E8-E8.23

In cyclic-pressure freeze-drying, the heat and mass transfer rates vary periodically with the imposed pressure fluctuations. The principal transport processes are: heat transfer through the dry, porous solid to the interface where sublimation takes place, vapor transfer from this interface to the surface of the material, countercurrent to the heat transfer, and vapor removal from the freeze-drying chamber, usually by a refrigerated condenser.

The first three sections of this paper report on recent work in each of these areas: i) an approximate analytical method of determining the times for the low and high pressure parts of the cycle is described, ii) an effective permeability, which may be used to describe vapor flow through a freeze-dried material is measured using a technique which simulates the actual flow conditions experienced during cyclic-pressure freeze-drying, and iii) a special condenser has been designed to cope with the high intermittent heat load of cyclic-pressure freeze-drying.

The final section reports briefly on a numerical method of analyzing the heat and mass flow processes within a partially dried material, so that cyclic-pressure freeze-drying might be effectively simulated.

E9. C. R. Lerici (Italy). Heat Transfer Problems during Freeze-Drying of Model Food Gels

E9-E9.25

The results of a group of experiments made to measure the influence of thermal conductivities of dried layers of some model food gels during freeze-drying at standard conditions, are reported.

The samples examined were prepared at different initial solid content, and with different rates of freezing, in order to evaluate the differences of behavior in the freeze-drying process as a function of apparent thermal conductivity.

The value of the apparent thermal conductivity was found to be higher for more concentrated samples and for the ones slowly frozen.

The low apparent thermal conductivities and the limitation placed upon the thermal driving force by the process, are then resulted the primary reasons for the slow rates encounted for freeze-drying in practice.

F1. J. Flink (USA) and P. Fosbøl (Denmark). Simulation of Continuous Freeze-Drying of Whole Egg Concentrate

F1-F1.39

Adoption of a continuous freeze-drying process means that some of the process parameters which were variable in batch type freeze-dryers can no longer be varied independently. The interaction of factors concerning economic freeze-dryer construction, freeze-dryer capacity, and final product quality, in particular, results in constraints on the heating platen temperature–time program. Optimization of the heating program within these constraints is of importance regarding the economic operation of the continuous freeze-dryer.

Engineering and biochemical factors which influence the development of the heating platen programs are discussed. The importance of accounting for particular aspects of the physical properties of the raw material is demonstrated in an analysis of experimentally determined heating programs for whole egg concentrate.

Methods by which the heating programs can be optimized with respect to drying capacity and product quality are presented. Of particular interest are techniques which enable use of an inexpensive laboratory scale batch freeze-dryer together with analytical mathematical procedures, such that the large and expensive continuous layer is used only to verify the optimized heating program prior to production.

F3. J. van der Lijn, W. H. Rulkens, and P. J. A. M. Kerkhof (Netherlands). Droplet Heat and Mass Transfer under Spray-Drying Conditions

F3-F3.23

A physical model is presented for the drying of droplets containing soluble solids. Two extreme cases of airflow pattern in spray-drying are considered. The first case is based on perfectly concurrent spray-drying. Both air and droplets move in plug flow through the dryer. Heat and mass exchange takes place between a droplet and a limited amount of air only. The conditions of this air gradually change during the process. The second case is based on a perfectly mixed vapor phase inside the dryer. Heat and mass exchange takes place between a droplet and air, which is at outlet conditions during the whole process.

The physical model takes into account diffusional resistance both inside and outside the droplet ($0 < Bi < \infty$). Diffusion coefficients may be concentration and temperature dependent. Swelling or shrinking of the droplet may occur.

Characteristic drying histories for droplets of maltose solution were calculated. Temperature and concentration behavior in the droplet as a function of the inlet and outlet temperatures of the drying air are reported. It was found that in concurrent spray-drying the droplet temperature rises well above the outlet temperature. The maximum temperature may be reached, when the droplet is still wet inside.

F4. R. B. Keey (New Zealand). Residence Times of Droplets in a Tall-Form Spray-Dryer

F4-F4.23

Previous work with a 200 mm diameter tall-form spray-drying tower fitted with a hollow-cone swirl-type pressure nozzle had shown that considerable air swirl existed. Some preliminary experiments were undertaken to follow the droplet residence pattern. The feed solution was pulsed with a salt tracer, and the external-age distribution measured. The experiments showed that considerable recirculation was taking place in the ancillary cyclone, but the residence times of the drops within the chamber itself were only 10% greater than times calculated for free fall and the drops were essentially unentrained. This conclusion is consistent with Gauvin's results that only drops below 50 $\mu$m are completely entrained and with the dairy industry's experience of maximum permissible air-inlet temperatures with spray-dryers.

F5. H. Fritze (West Germany). The Use of Drum Dryers in the Human Food Industry

F5-F5.23

The author discusses the optimization of operations and the proper design of roller dryers as widely used in the food industry. Methods are given for heat calibrations on such equipments, and technical schemes and modes of drying are presented for certain food products (mashed potato, partly cooked starch, food yeasts, and so on).

F6. P. J. Fito, F. Pinaga, and V. Aganda (Spain). Heat-Transfer Properties of Freeze-Dried Foods

F6-F6.18

A detailed description is given of an apparatus for determining the thermophysical properties of food products for freeze dryers; the tests were done on coffee and avocado extracts with an equipment operated at room temperature. The thermal diffusivity on reducing the gas pressure occurs in the range $5 < P < 150$ torr, while there is very little variation below 5 torr.

F8. S. G. Il'yasov and V. V. Krasnikov (USSR). Optical Parameters of Food Products and Heat Transfer by Infrared Radiation during Drying

F8-F8.30

A description is given of a method of measuring the spectral and integral characteristics of materials that absorb and scatter radiation; the optical system is given for a two-beam attachment to a spectrometer for simultaneously measuring these characteristics. A theoretical examination is presented for the drying of food products with infrared heat supply, and analytical expressions are derived for the effective, incident, and resultant heat fluxes at the surface, which leads to an examination of the main trends in energy transfer by the integral radiation at the surface. Relationships are also derived for the energy transfer by the integral radiation within the layer, and the basic equation of heat and mass transfer for drying is refined. The treatment incorporates selectivity in the spectral characteristics, thermal radiation response, and emissivity of the material, as well as the analogous characteristics for the infrared source and all bodies participating in the heat transfer.

F9. P. Viaud and J. Aguirre-Puente (France). A Physical Model for the Passage of Ice through a Cell Membrane

F9-F9.17

The structure of a biological material is considered, and a simple capillary model is proposed. The basic microstructural features of freezing are discussed for such objects (cell plasmalysis, ice segregation, and so on). A new interesting feature of this process has been observed, in that there is a mechanical effect within the membrane as a result of the freezing. It is considered that this effect ultimately disrupts the inner layers of the cell membrane.