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By Biological Products in Storage

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ENTROPY PRODUCTION
BY BIOLOGICAL PRODUCTS IN STORAGE

By

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ABSTRACT

ENTROPY PRODUCTION
BY BIOLOGICAL PRODUCTS IN STORAGE

By

Robert Yemoh Ofoli

Non-equilibrium thermodynamics was used to determine entropy production and energy dissipation by biological products in storage subjected to cooling by forced convection. This approach resulted in a procedure that could be used for optimizing the ventilation rate.

A model for the potato storage environment, incorporating heat and mass transport and chemical reaction (respiration) was derived. The resulting equations were solved numerically using the finite difference method.

The optimization procedure is based on an energy dissipation index (EDI) which is defined as the ratio of the total energy dissipated by the system to the input energy required to move the ventilation air. The parameter has an asymmetric profile which displays a minimum value when plotted against the ventilation rate. It predicts a zone of minimum entropy production that may be used for optimizing the ventilation rate.

Robert Yemoh Ofoli

The phenomenon of thermal diffusion has a negligible effect on the product mass loss and the temperature profile in the storage environment. Neglecting thermal diffusion is equivalent to setting the cross-phenomenological coefficient in the entropy production equation to zero. This reduces the rate of entropy production by 9%. However, even though the lower rate of entropy production reduces the magnitude of the EDI, the position of the minimum value of the EDI with respect to the ventilation rate is unaffected. As a result, thermal diffusion can be neglected without affecting the essential results of the study.

TO

My wife Sherry

Our son Robert, Jr. (Bobby)

and my friend always, Jonathan.

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A	affinity of chemical reaction, J/kg
A_{ac}	cross-sectional area open to air flow, m^2
A_c	cross-sectional area, m^2
A_{ct}	potato-to-potato contact area, m^2
A_s	surface area, m^2
c	concentration, kg/m^3
c_k	concentration of species k, $moles/m^3$
c_s	solute concentration, kg/m^3
C	heat capacity, $J/kg\text{-}^oK$
C_p	heat capacity at constant pressure, $J/kg\text{-}^oK$
C_v	heat capacity at constant volume, $J/kg\text{-}^oK$
C_{va}	dry air heat capacity at constant volume, $J/kg\text{-}^oK$
C_{vp}	potato heat capacity at constant volume, $J/kg\text{-}^oK$
C_{vv}	water vapor heat capacity at constant volume, $J/kg\text{-}^oK$
C_{vw}	heat capacity at constant volume of water, $J/kg\text{-}^oK$

D	diameter of storage bin, m
D_{AB}	binary mass diffusivity, m^2/hr
D_G	mass diffusivity, m^2/hr
D_p	diameter of product, m
D_{sp}	diameter of sphere, m
D^T	modified thermal diffusion coefficient, $kg/m\text{-}hr\text{-}^oK$
E	total energy, J
EDI	energy dissipation index, dimensionless
f_p	friction factor, dimensionless
$\bar{g}$	gravitational acceleration, m/sec^2
G	mass velocity, $kg/m^2\text{-}sec$
G^o	standard Gibbs free energy, J/mole
h	heat transfer coefficient, $J/m^2\text{-}hr\text{-}^oC$
h	vertical height, m
h_D	mass transfer coefficient, m/hr
h_{fg}	heat of vaporization, J/kg
$\bar{H}$	molar enthalpy, J/mole
$H(x)$	Heavyside step function, dimensionless
H_k	partial molar enthalpy of species k, J/mole
H^o	standard enthalpy, J/mole
J_{ch}	velocity of reaction, $kg/hr\text{-}m^3$
$\bar{J}_k$	diffusion current flux, $kg/m^2\text{-}hr$
$\bar{J}_Q$	heat current flux, $J/m^2\text{-}hr$
$\bar{J}_s$	entropy current flux, $J/m^2\text{-}hr\text{-}^oK$
$\bar{J}_u{}'$	non-convective current flux, $J/m^2\text{-}hr$

k	Boltzman constant, $erg/^{o}K$
k	thermal conductivity, $J/m\text{-}^{o}C\text{-}hr$
k_a	conductivity of air, $J/m\text{-}K\text{-}hr$
$\bar{K}_k$	molar external force on species k, N/mol
K_T	thermal diffusion ratio, $^{o}K^{-1}$
L	characteristic length, m
L_{ch}	phenomenological coefficient of chemical reaction, $kg\text{-}hr/m^5$
L_{KK}	convective mass flux coefficient, $kg\text{-}hr/m^3$
L'_{KK}	modified convective flux coefficient, $kg\text{-}hr/m^4$
L_{KQ}	cross-kinetic coefficient, kg/m-hr
L'_{KQ}	modified cross-kinetic coefficient, $kg/m^2\text{-}hr$
L_{QQ}	heat flux coefficient, J/m-hr
L'_{QQ}	modified heat flux coefficient, $J/m^2\text{-}hr$
m_a	mass of water in air, kg
m_p	mass of water in potato, kg
M	equilibrium moisture content, fraction
M	molecular weight, g
M_a	mass of dry air, kg
M_i	molecular weight of species i, g/mole
M_p	mass of potato solid matter, kg
P	pressure, N/m^2 (Pa)
Pe	Peclet number, dimensionless
P^{sat}	absolute saturation pressure, N/m^2
P_v	vapor pressure, N/m^2
q	heat of respiration, J/kg-hr
$q(U)$	local production of internal energy, $J/m^3\text{-}hr$

Q	rate of heat energy flow,	J/hr
r	radius,	m
r_{ch}	rate of carbon dioxide release by chemical reaction,	mg/kg-hr
r_h	hydraulic radius,	m
r_{12}	collision diameter,	angstroms
R	universal gas constant,	$J/kg-^{o}K$
Re_p	Reynolds number,	dimensionless
R_v	gas constant for water vapor,	$J/kg-^{o}K$
s_k	molar entropy of component k,	$J/mol-^{o}K$
S_t	total potato surface area,	m^2
S_v	entropy density,	$J/m^3-^{o}K$
t	time,	hr
T	absolute temperature,	^{o}K
U	internal energy,	J
U_v	internal energy density,	J/m^3
u	interstitial velocity,	m/hr
u_s	superficial velocity,	m/hr
v	specific volume,	m^3/g
v	velocity,	m/hr
$\bar{v}$	barycentric velocity,	m/sec
$\bar{v}_k$	average velocity of species k,	m/sec
V	volume,	m^3
V_b	molar volume of a liquid at its normal boiling point,	m^3
W	rate of doing work,	J/hr
x	vertical distance from bottom of bin,	m

x_k	mass fraction of species k
$\bar{X}_k$	generalized force for mass diffusion, J/kg-°K
$\bar{X}_Q$	generalized force for heat diffusion, $(m\text{-}^{o}K)^{-1}$

Greek symbols

α	thermal diffusivity, m^2/hr
α_p	surface area per linear meter of product, m^2/m
γ_m	humidity ratio, kg-water/kg-dry air
Γ	dissipation function, J/m^3-hr
ϵ	porosity, dimensionless
ϵ_{12}	energy of molecular interactions, J
η	skin resistance coefficient, dimensionless
η_c	combined skin resistance coefficient ($\eta_c = \eta RT$), m^2/hr^2
λ_a	mass per linear meter of water in the air, kg/m
λ_p	mass per linear meter of water in the potato, kg/m
Λ_a	mass per linear meter of the dry air, kg/m
Λ_p	mass per linear meter of the potato solids, kg/kg
θ	temperature, °C
μ	absolute viscosity, kg/m-sec
μ_i	chemical potential of species i, J/kg
μ_k	chemical potential, J/kg
μ_s^c	concentration-dependent chemical potential, J/kg
μ_{ss}	partial derivative of the chemical potential with respect to the concentration, $m^5/kg\text{-}hr^2$

ν	kinematic viscosity, m^2/sec
ξ	extent of reaction, mol
ρ	density, kg/m^3
σ	local volumetric entropy production, J/m^3-hr-^oK
$\bar{\tau}$	stress tensor, kg/hr^2
τ_{rz}	shear stress, kg/m-hr^2
ϕ	relative humidity, %
Φ	total energy dissipation, J
$\bar{\omega}$	reference velocity, m/sec
ω_k	weight factor, dimensionless

Subscripts and operators

a	ventilation air stream
ch	relating to chemical reaction
k	component identifier
p	potato or product
s	solute (water vapor)
Δ	delta operator
∇^2	the Laplacian
∇	del or nabla operator
∂	partial differential operator
$\int$	integral operator

1.0 INTRODUCTION

The subject of entropy has fascinated engineers and scientists for ages in spite of its very abstract nature (or, perhaps, because of it!) Engineering applications of entropy usually involve the determination of the efficiencies or the degree of irreversibility of a process, especially where the process involves steam and other idealized gases for which standard thermodynamic tables or charts are available.

Given the abstractness of the concept, the analysis of entropy production in the storage environment of agricultural products would appear to be simply an academic exercise. This is, however, not so. As will be shown in this thesis, entropy production is very intimately linked, not only to energy transport, but to all mass transport and to chemical reactions that may be taking place in a given system. Thus, an examination of entropy generation can be used to gain further insight into these processes, as well as any accompanying energy transformations. It also provides a convenient scheme for optimization, as is done here.

Perhaps, Adrian Bejan sums up the role of examining entropy generation best when he wrote that his engineering education led him to assume that "the importance of entropy generation through heat transfer was obvious and that the second law could sell itself. ... entropy generation should assume a central role in heat transfer, as central as the relation between temperature difference and heat transfer rate or the relation between pressure drop and flow through a channel" (Bejan, 1982).

In general, biological products in storage constitute a porous medium in which several thermodynamic processes may take place simultaneously. Invariably, these processes are irreversible. In addition, in almost any practical situation, the storage media are moist and subjected to temperature, moisture concentration and pressure gradients, among other thermodynamic forces that may be present. As pointed out by Haase (1969), whenever a continuous multi-component system is subjected to gradients of concentration, pressure and temperature, six different transport processes could occur simultaneously.

These processes are:

1. mass diffusion or mass convection: the transport of mass resulting from concentration gradients or concentration differences;

2. pressure diffusion: the transport of mass as a result of pressure gradients;

3. thermal diffusion (Soret effect): the transport of mass due to temperature gradients;

4. heat conduction or heat convection: the transport of thermal energy resulting from temperature gradients or temperature differences;

5. pressure thermal effects: the transport of thermal energy due to pressure gradients; and

6. Dufour effects: the transport of thermal energy as a result of concentration gradients.

In addition to the possible occurrence of cross-kinetic effects, further complications are created by the fact that a porous medium is essentially a random structure, whose details are largely unknown (Slattery, 1975). A complete mathematical analysis, employing classical thermodynamics, is therefore quite difficult without the use of an excessive number of assumptions.

Traditionally, Darcy's Law has been the foundation for the study of transport processes in porous media. It states that the rate of flow in a porous medium is directly proportional to the pressure gradient causing that flow (Carman, 1956). Mathematically,

$$v = k \frac{\nabla P}{L} \tag{1-1}$$

where v is the velocity, k the permeability coefficient, ∇P is the pressure gradient and L is a characteristic length. This is the defining equation for the permeability coefficient, k.

However, Darcy's Law has been shown to have severe limitations at high and low velocities for gases, and at high velocities for liquids (Scheidegger, 1960). Also, temperature gradients can induce moisture movement in porous media -- the phenomenon of thermal diffusion. Therefore, mass transport in porous media does not necessarily occur only as a result of mass concentration or pressure gradients. This phenomenon is not anticipated by Darcy's Law (Havens, 1980).

Classical thermodynamics is not very useful for describing processes in living organisms or biological products since these normally constitute systems that are not only open, but also in non-equilibrium. Without the necessary postulates or constitutive relations required by classical thermodynamics in the analysis of these systems, the mathematical description of the processes taking place require model-specific kinetic equations. Developing a proper kinetic relationship, however, often requires information that is more detailed than is readily available (Katchalsky & Curran, 1965).

The thermodynamics of irreversible processes is an empirical tool that gives one the opportunity of studying heat and mass transport in their often inseparable association. Through the use of Onsager's principle, this methodology allows one to model systems in which cross-kinetic effects such as thermal diffusion take place. Since the general relationships can be reduced to the standard linear relations of classical thermodynamics (Fick's law, Kirchhoff's law, Fourier's law, Darcy's law, etc.), the irreversible thermodynamics procedure essentially provides the researcher with additional useful information not readily available through the classical approach.

1.1 The Potato In Storage

The need for potato storage stems from the fact that while most of the nation's potato production occurs in the fall, potatoes must be made available to the consumer on a year-round basis (Smith, 1968). The goals of potato storage (Plissey, 1976) are to:

a) retain water in the tuber;

b) hold respiration to a minimum;

c) hold reducing sugars to a minimum; and

d) maintain external appearance.

Ultimately, the goal of potato storage is to have the product come out of storage as close to its pre-storage condition as possible. The two primary storage environmental variables that can be manipulated to achieve this objective are the temperature and the relative humidity. These two factors are instrumental in determining the degree of weight loss of the product.

Weight losses of less than 5% provide for a smooth-skinned, firm product; losses of 5 to 10% result in soft potatoes; while losses of greater than 10% lead to wrinkled products (Cargill, 1976). The limits of storage temperatures lie between 1.7°C and 18.3°C (Cargill, 1976). The storage must aim for relative humidities of 90-95% (Smith, 1968); this promotes early suberization and reduces shrinkage.

1.2 Modeling Approach

The local production of entropy in any biological storage system is the result of heat transport, mass transport and chemical reactions in the system. However, it is nearly impossible to measure entropy production experimentally in a biological storage. The approach taken in this thesis, therefore, was to formulate a model for heat and mass transport that predicts convective air temperatures, and product mass losses in the storage environment of suberized potatoes. The heat and mass transport relations resulting from this model were then used, in addition to appropriate chemical reaction equations, to examine the production of entropy and the dissipation of energy in the system.

Models for moisture loss in the environment of stored potatoes have usually been based on the vapor pressure deficit as the thermodynamic driving force (Misener, 1973; Hunter, 1976; Lerew, 1978; Brugger, 1979). This work deviates slightly from the approach of these and other researchers and treats the mass transport relationship as an explicit function of moisture concentration differences rather than vapor pressure deficits.

While vapor pressure deficits are implicit functions of concentration, it is the contention of the author that an explicit concentration-dependent expression provides a better casting for the mass transport equations and a more correct physical sense of the mass transfer process. The phenomenological coefficients for heat and mass transport are determined by curve-fitting to experimental data.

1.3 Data On Potato Storage

Since neither the rate of entropy production nor the total entropy production could be measured experimentally, the data required for the testing of this model is that of air temperatures, product temperatures and mass losses in the potato storage environment, and thermodynamic tables of entropy of moist air as a function of temperature.

There is already a tremendous amount of data available in the literature on convective air temperatures and product mass losses in the environment of agricultural products. Specifically, in the cooling or ventilation of potato storages, the work by Misener (1973), Hunter (1976), Grahs (1978), Lerew (1978) and Brugger (1979) provide sufficient data. It was felt that any additional experimental work would be a duplication of existing efforts. As a result, no new data was collected.

2.Ø OBJECTIVES

The primary objectives of this study are to apply the principles of the thermodynamics of irreversible processes to an open biological system subjected to forced convection to:

1. derive a model for the quantitative analysis of entropy production resulting from heat transport, mass transport and chemical reaction processes in the storage environment; and

2. examine the feasibility of using the model as a tool for the optimization of the ventilation rate.

3.0 LITERATURE REVIEW

Each section of this chapter is arranged chronologically to help give the reader a notion of the progress of research and analytical work in each area.

3.1 Thermodynamics Of Irreversible Processes

Miller (1960) tested the validity of the Onsager reciprocal relations and linear phenomenological equations for a variety of irreversible processes: thermoelectricity, electrokinetics, transference in electrolytic solutions, isothermal diffusion, conduction of heat and electricity in anisotropic solids, thermomagnetism and galvanomagnetism. Experimental results confirmed the validity of the Onsager relations for thermoelectricity, electrokinetics, isothermal diffusion and anisotropic heat conduction. Electrolytic transference showed good validity. In the other areas, experimental errors were too large to yield a significant test.

Coleman and Truesdell (1960) showed that, given any linear relation between forces and fluxes in irreversible thermodynamics, a redefinition of forces and fluxes by linear combination yields a relation with a symmetric matrix. That is, the rate of entropy production is invariant with respect to the redefinition.

Cary and Taylor (1962a, 1962b) and Cary (1963) experimented with thermally-induced water vapor diffusion through air and through moist soil at temperatures ranging from 15°C to 45°C to test the theory of the thermodynamics of irreversible processes and the Onsager reciprocal relationships. The general rate equations for heat and mass transfer were transformed into simple relations of the flux as a function of temperature. In addition to verifying the rate equations, it was found that the coefficient between heat and vapor flow and that between vapor and heat flow are identical, essentially validating Onsager's reciprocal theory.

In 1964, Cary considered a particular heat and water vapor transfer problem in a nonisothermal steady state system under conditions similar to what might develop during the normal drying of porous materials and again demonstrated that Onsager's reciprocal relations are valid.

Cary and Taylor (1964) gave a theoretical treatment of some transfer processes in soils and showed that the general theoretical relations of irreversible thermodynamics encompass Darcy's Law and the mass diffusion equation.

Wei (1966) recommended that the use of irreversible thermodynamics be restricted to situations where it improves the ability to describe, measure and predict outcomes, and when forces and fluxes are coupled; i.e., if the phenomenological coefficients L_{ij} are not zero, whenever i and j are different.

Sliepcevich and Hashemi (1968) analyzed a one-dimensional, one-component system in which the properties of temperature, pressure and chemical potential were assumed to be uniform throughout. Their results validated the Onsager reciprocal relations without using the theorem of macroscopic reversibility.

Fortes (1978) and Fortes and Okos (1978) developed a set of equations describing heat and mass transport in unsaturated hygroscopic-porous media. The phenomenological coefficients were obtained by making use of the commonly accepted expressions for liquid and vapor fluxes in porous media. A model was developed to analyze heat and moisture transport in sand induced by a spherical heat source, using available data from the literature. While the approach was basically one of irreversible thermodynamics, the work also attempted to utilize concepts from mechanistic or classical thermodynamics. It was postulated that both liquid and vapor fluxes are driven by temperature gradients and relative humidity gradients.

Fortes and Okos (1981a), in an analysis of transport phenomena in porous media, postulated that the gradient of the moisture content is the driving force for both liquid and vapor movement in the media. However, it is possible for water, in a capillary-porous matrix, to move against the moisture content gradient. On the contrary, vapor always moves in the direction of the equilibrium moisture content gradient. This finding was based on the principle of local equilibrium. It was proposed, further, that the driving force depends on $(\nabla\mu)_T$ and not on $\nabla\mu$, where μ is the chemical potential. To evaluate the phenomenological coefficients, the equations derived by non-equilibrium thermodynamics were compared to those obtained by using standard mechanistic principles.

Parikh, Havens and Scott (1979) utilized a transient method to measure thermal diffusivity of low thermal conductivity materials (specifically, glass beads and silt loam soil) over a range of volumetric moisture contents. The method was based on the solution of the transient heat conduction equation in a cylinder

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \qquad (3\text{-}1)$$

where T is the temperature, t is the time and r is the radius. The transient method was used because steady state measurements were found to be difficult to obtain. This was due to the fact that moisture content gradients at steady state were also accompanied by steady state heat transfer.

Havens (1980) analyzed the Cary and Taylor model for the description of coupled heat and moisture transport in water unsaturated glass beads. The transport coefficients appearing in the model equations were independently determined, and the equations were numerically integrated to predict steady state temperature and moisture content profiles. It was concluded that the coupling coefficient relating thermal gradients to moisture flux is strongly moisture-dependent; the coupling coefficient relating moisture content gradient to heat flux is extremely small; and the heat flux associated with the moisture content gradient was negligible.

Kung and Steenhuis (1982) investigated the movement of water in soil under freezing conditions, using what was termed "irreversible thermodynamic equilibrium" and a modified finite difference formulation to analyze the problem. Major conclusions were that the equations derived by the thermodynamics of irreversible processes provide correct values of heat, vapor, and water fluxes in a partially frozen soil.

3.1.1 Comments And Observations

Several of the pieces of literature reviewed here represent milestones in the development of irreversible thermodynamics. The findings helped open up new fields and/or applications to analysis by non-equilibrium principles.

Perhaps the most important principle of irreversible thermodynamics is the reciprocal relation of Onsager which relates the cross-coefficients. This principle has been experimentally validated by several researchers, including Miller (1960), Cary and Taylor (1962a), Cary (1963 and 1964), and Sliepcevich and Hashemi (1968), thus providing analytical and experimental evidence of the soundness of the concept.

Coleman and Truesdell (1960) made a significant contribution with the proof of the invariance of entropy production with respect to a redefinition of forces and fluxes. Just as important a contribution to researchers in porous media was made by Cary (1963, 1964 and 1966) when he showed that the theoretical development of the relations in irreversible thermodynamics includes Darcy's Law and the mass diffusion equation.

Fortes and Okos (1978) [heat and moisture transport in sand], and Parikh, Havens and Scott (1979) [measurement of the diffusivities of low thermal conductivity materials] provided valuable lessons in application.

The study by Fortes and Okos (1981a) also confirmed the validity of the standard practice of seeking coefficients in irreversible thermodynamics through a parallel analysis of equilibrium thermodynamics. Another result claimed by this study is that the driving force for mass transport depends on $(\nabla\mu)_T$ rather than on $\nabla\mu$. This conclusion follows directly from a formal derivation of the mass transport expression, and is therefore not a direct result of that study.

3.2 Porous Media Analyses

Furnas (1930) compiled extensive experimental data on heat transfer from gases (similar to air) to porous media of iron ore, coke, limestone, bituminous coal, anthracite and a typical blast-furnace charge and provided many graphical correlations of parameters.

In 1937, Muskat derived the generalized Darcy Law for gases

$$\Delta p^{(1+m)/m} = \frac{(1+m)\in \mu \, \rho_o^{\frac{1}{m}}}{k} \frac{\partial p}{\partial t} \tag{3-2}$$

where Δp is the pressure gradient, ρ_o is the initial fluid density, k is the permeability coefficient, t is the time, m = 1 for isothermal expansion and m = C_v/C_p for adiabatic expansion. Muskat stipulated that the density of a gas flowing in a homogeneous porous medium must obey this differential equation for both steady state and transient conditions.

Green and Duwez (1951) outlined a method of correlating experimental data obtained from studies of the flow of gases and liquids through porous metals. The correlation is based on expressing the pressure gradient accompanying liquid flow through a porous medium by a simple quadratic equation valid at both high and low Reynolds numbers

$$-\frac{dP}{dx} = \lambda\mu v + \beta\rho v^2 \tag{3-3}$$

where λ and β are viscous and inertial resistance coefficients, respectively. This derivation was necessary because Darcy's Law, which defines the permeability coefficient, is valid only for low velocity liquid flows.

Scheidegger (1965) discussed four standard attempts at statistical mechanics models of transport phenomena in porous media: random walk of individual fluid particles, quasi-turbulent flow analogy, analogy with thermodynamics and general statistical mechanics. Scheidegger concluded that while nothing in the transport processes in porous media is really random, a stochastic process is employed due to the fact that current knowledge of the porous medium is of such an incomplete nature that the only reasonable way to deal with it is in terms of averages.

Whitaker (1966) formulated the equations of continuity and motion in Cartesian coordinates for an anisotropic porous medium. In deriving the continuity equation, two assumptions were made: 1) that while the porosity may be a function of the spatial coordinates, the porous volume is large enough so that the porosity is independent of the volume; and 2) that the macroscopic velocity varies "slowly" with position. In 1969, Whitaker proposed three distinct (though not mutually exclusive) approaches to the problem of flow in porous media: statistical analysis, geometric modeling and averaging. Each approach results in unspecified parameters that can be determined experimentally.

Pinker and Herbert (1967) tested eight single gauzes placed perpendicular to the direction of air flow, and of such diameter and mesh to provide porosities between 0.3 and 0.7. Pressure losses were measured from Mach numbers of choking to 0.1. The data was used to provide a single relation between the incompressible loss factor and a form of Reynolds number.

Emmanuel and Jones (1968) treated the case of gas flow in a straight frictionless, insulated duct of constant cross-section, with a porous plate of uniform thickness situated in it. A simple one-dimensional equation was given for steady, compressible, adiabatic flow of a perfect gas through the porous plate. Darcy's equation was modified after Shapiro (1953) to allow for compressible adiabatic flow and high mass flow rates. The authors concluded that compressibility should be important when the mass flow rate (and hence the pressure across the plate) is large.

Curry (1970, 1974) investigated the flow of a compressible gas through a porous matrix externally heated at the fluid exit surface and formulated a numerical solution of the conservation equations of coupled heat transfer and fluid flow in a high temperature porous matrix. Analytical results were presented for one and two dimensions utilizing both non-isothermal and isothermal conditions between the solid and fluid phases. Curry concluded that the validity of the assumption of thermal equilibrium depends upon the type of porous material being studied.

Siegel and Goldstein (1970, 1972) devised a technique for obtaining exact solutions for the heat transfer behavior of a two-dimensional porous medium subjected to cooling and used Darcy's Law to arrive at an analytical solution. The problem involved forcing an ideal gas from a reservoir at constant temperature and pressure through a two-dimensional porous region, with the exit surface at a different uniform temperature and pressure. Both studies assumed isothermal conditions.

Moore (1973) investigated the convective heat and mass transport in granular porous media saturated with a wetting liquid. Small glass beads and granular aluminum oxide were used to constitute the porous medium between two concentric cylinders, each surface maintained isothermally. Moore concluded that the thermal conductance of a porous medium (with particle size small enough to allow surface tension effects to dominate) depends on the quantity of liquid contained in the medium and may be significantly increased by convective transfer.

Slattery (1975) postulated that characterizing mass transfer in a real porous medium requires empiricism, since with the unknown structural detail of the porous medium, mass transfer cannot be described totally on the basis of first principles.

Yaron (1975) used the well-established conservation equations for separate phases of the porous media, solved them separately, matched them at the common interphase and applied an averaging procedure to establish a constitutive relationship. Yaron recognized and commented on the conceptual problem of volume averaging: the need that the volume be small enough to be statistically homogeneous is often in serious conflict with the requirement that it be large enough to enclose a sufficiently representative portion of the system.

Duguid and Reeves (1976) developed a two-dimensional transient model for flow of a dissolved constituent through a porous medium. The model includes advective transport, hydrodynamic dispersion, chemical adsorption and radioactive decay. The model is expected to serve two purposes: allow the simulation of the transport of toxic materials through saturated-unsaturated porous media to predict future concentrations in ground water and to provide the toxic-material concentration data necessary for human-dose calculations.

Surkov and Skakum (1978) solved three versions of the heat and mass transfer equation in a porous medium (from linear to progressively non-linear) for a situation that may occur in the transpiration cooling of a rocket engine. The authors concluded that by allowing temperature dependence of the thermophysical properties of the porous wall (thus making the problem non-linear), a more exact description of the temperature field could be obtained. Steady state and isothermal conditions between the porous matrix and the coolant were assumed.

Montakhab (1979) presented a closed-form solution to the initial value problem governing convective heat transfer between a fixed bed of granular solids and a steady flow of heating or cooling gas at constant mass velocity. The model was for a storage system initially at thermal equilibrium at a uniform temperature before a step change in the temperature of the convective fluid is imposed.

Singh and Dybbs (1979) carried out an experimental and analytic study of non-isothermal flow in sintered metallic porous media. The experiments consisted of measuring the one- and two-dimensional temperature distributions and effective thermal conductivities of water-saturated copper and nickel sintered fiber metal wicks. The objective was to provide a self-consistent method for determining the heat transfer characteristics of porous metals. Volume-averaged forms of the conservation equations were used and local thermal equilibrium between the solid and liquid phases and the validity of Darcy's Law were assumed. The authors noted that for $Re \geq 10$, inertia effects become important and Darcy's Law ceases to be applicable. To extend the range of validity of Darcy's Law, an inertial term was added to the Darcy momentum equation.

3.2.1 Comments And Observations

The standard assumption in studies on transport processes in porous media has been that Darcy's Law is valid. In many studies, this assumption was made without showing justification, even under conditions that appear to be unsuitable to analysis by Darcy's Law, e.g., high flow velocities.

There have been several attempts at modifying Darcy's Law to enable the concept to be used in applications other than the restricted conditions under which Darcy proposed his law. For example, Muskat (1937) modified Darcy's Law to make provision for both isothermal and adiabatic expansion. Another modification was effected by Green and Duwez (1951) to allow for processes with high flow rates to be analyzed.

Emmanuel and Jones (1968) also modified the Darcy expression to make it suitable for application in a process with compressible adiabatic flow and large mass flow rates. Singh and Dybbs (1979) added an inertia term on discovering that for $Re \geq 10$, inertia effects become important and that this is not anticipated by Darcy's Law.

The lack of a complete understanding of the behavior of porous media makes rigorous mathematical analysis rather difficult. Recognizing this, several researchers, especially Scheidegger (1965) and Whitaker (1969) used stochastic or statistical models involving averages.

3.3 Agricultural Storage Analyses

Schaper and Hudson (1971) found from small lot studies that the influence of temperature and relative humidity may be time-dependent, suggesting that this dependency may be utilized to modulate storage conditions according to elapsed time and thereby reduce insulation requirements.

Schippers (1971) examined the effects of storage conditions on weight loss, change in specific gravity, susceptibility to damage, blackspot and color of chips and concluded that 1) storage conditions do not have much effect on susceptibility of blackspot and 2) whether temperature or relative humidity is the more important storage factor depends on the quality characteristic under consideration. Schippers also suggested that since chemical sprout inhibitors are being used extensively, low storage temperatures (intended to limit sprouting) are no longer necessary. Thus, potatoes can be stored above $5^{o}C$. This would reduce fan hours, weight loss, susceptibility to damage and blackspot.

Misener (1973) studied the drying characteristics of potatoes immediately following suberization and developed a model for simulating deep bed cooling of potatoes from known ambient conditions. The study included an optimization procedure for the ventilation rate as measured against potato shrinkage and ventilation costs and concluded that the optimum air flow for cooling a 4.8 meter deep bed of potatoes ranges from 5 to 7 $m^3/min\text{-}m^2$.

Roa (1974) developed a model to simulate different systems of the natural drying of layers of cassava. Experimental and analytical studies were conducted on several varieties of cassava to evaluate conventional (natural) and newly-designed systems of drying under variable weather conditions.

Hunter (1976) developed a steady-state simulation model for the white potato in storage. The model predicted air temperatures, relative humidity and weight losses and found the critical range of air velocities to be 0 to 3.05 meters per minute. A major conclusion was that the vapor pressure deficit (rather than boundary layer effect) provides the thermodynamic driving force for weight loss in white potatoes.

Yaeger (1977) stored potatoes for six months in constant temperature chambers at three levels of humidity and pressure. The effects of various treatments on weight loss and pressure flattening were evaluated. It was concluded that relative humidity has more influence on weight loss and pressure flattening than potato pile pressure.

Lerew and Bakker-Arkema (1977) gave a finite difference solution of the simultaneous heat and mass transfer equations in bulk stored potatoes. Temperature and weight loss were simulated for various types of instrumentation and ventilation system management schemes commonly applied to commercial storages. Effects of fan control by temperature sensors and time clock to that of continuous fan operation were examined.

Cloud and Morey (1977) presented an analysis of the effect of various parameters on the uniformity of air discharge from potato storage ventilation ducts. The parameters used were the ratio of discharge area to duct cross-sectional area, static pressure, equivalent duct diameter, duct wall roughness, discharge dynamic loss coefficient and duct length. Charts were developed to predict uniformity of air discharge for three ratios of discharge area to duct cross-sectional area.

Dwelle and Stallknecht (1978) measured weekly carbon dioxide release by whole tubers of six potato varieties from November through May. The objective was to examine respiration and sugar content in an attempt to compare the respiration rates of whole tubers and tissue slices under storage temperatures ranging from 1.7 to 10°C and a relative humidity of 95%. It was found that generalizations could not be made, even within a given potato variety, because prior physiology in the field and at harvest influence subsequent physiological behavior in storage.

Pratt and Buelow (1978) studied the relationship between vapor pressure deficit and time, on weight loss of potatoes in storage. It was found that stored potatoes ventilated with incoming air at 100% humidity still lost weight, leading to the conclusion that the potatoes must be slightly warmer than the ventilating air.

Brugger (1979) developed a mathematical model for the two-dimensional air flow and heat and mass transfer within a potato pile and reported that temperature and humidity of the storage air are the most important factors influencing the quality of stored potatoes and that these affect weight loss, respiration rates and biochemical reactions, among other factors.

Davis, et al. (1980) developed a mathematical model to predict air flow and pressures in perforated corrugated ducts. Even though the study was supposed to address air flow in agricultural storage (principally potato storage), it appears that the theoretical development and experimental results were for empty cylindrical containers.

Peterson, Wyse and Neuber (1981) compared respiration with the storage indicators of maturity, dry matter, invert sugars, harvest injury, bruise susceptibility and weight loss. The objective was to use respiration analysis as a guide to internal potato quality and a parameter for storage management. Respiration rates were found to be high immediately after harvest (as have other investigators), reaching steady state at about 162 hours. Respiration rates were calculated by measuring the CO_2 evolved per unit weight and time.

3.4 Entropy Production In Biological Systems

Very little previous work was found on the analysis of entropy production in biological systems. None of these has to do with agricultural storage.

Briedis (1981) studied the link between engineering thermodynamics and experimental and theoretical biology. The work includes derivations of material and energy balances for open, growing systems at thermodynamic states far from equilibrium. The derived relations were then used to study growth and development in the avian egg and microbial systems. The energy flows were linked to the relationship between oxygen consumption by and heat loss from the system.

Balmer (undated) developed a model for entropy rate balance for complex biological systems, using the growth equation of Bertalanffy and postulated that all living systems experience a continuously decreasing total energy, reaching biological death (defined as a state of minimum total entropy) at the end of their lifetime.

It is not clear what Balmer means by "decreasing total entropy", since it is the <u>rate</u> of entropy production rather than the total entropy production that reaches a minimum at biological death.

Bornhorst and Minardi (1970) developed a phenomenological theory for contracting muscle, based on the sliding filament theory. The phenomenological equations were obtained for the whole muscle by assuming that each cross bridge is a linear energy converter with constant coefficients.

4.0 MODEL DEVELOPMENT

4.1 Provisions Of The Model

The model is for entropy production and energy dissipation resulting from non-isothermal heat transport, mass transport and chemical reactions in a porous medium. It provides for:

a) heat generation within the product, resulting from biological metabolism;

b) mass transport from the product to the void space;

c) heat transport from the product to the void space;

d) evaporation of water from solid surfaces; and

e) chemical reaction resulting from respiration.

4.2 Assumptions

1. The medium is isotropic, i.e., the system has the same properties in all directions.

2. Magnetic and electric field effects are negligible.

3. The only significant chemical reaction taking place in the storage environment is that of respiration, as

governed by the relationship

$$C_6H_{12}O_6 + 6O_2 \text{ ----> } 6CO_2 + 6H_2O \tag{4-1}$$

4. The walls of the storage volume are adiabatic and impermeable.

4.3 Geometric Modeling of the Potato

The experimental data of Misener (1973) was collected using potatoes that averaged 9.50 cm in length and 5.10 cm in diameter. These dimensions are used to first model the potato as an ellipsoid with minor axes 4.75, 2.55 and 2.55 cm (Figure 4.1) and then as an equivalent sphere. The volume represented by the ellipsoid is modeled as the basic potato unit.

The volume of an ellipsoid of minor axis a, b and c is given by

$$V_{ell} = 4\pi abc/3 \tag{4-2}$$

A sphere of radius r has the volume relation

$$V_{sph} = 4\pi r^3/3 \tag{4-3}$$

From equations (4-2) and (4-3), the radius of a sphere of a volume equivalent to the volume of the ellipsoid is given by

$$r = (abc)^{0.333} \tag{4-4}$$

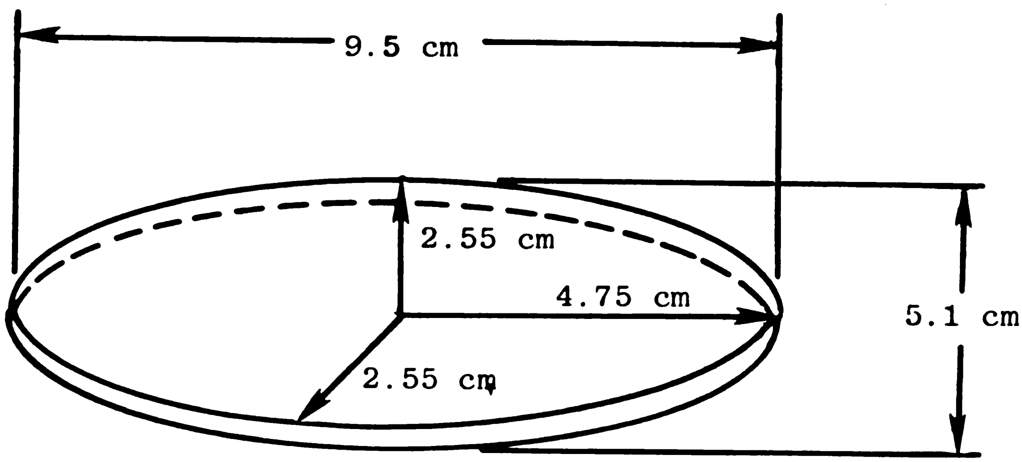

Figure 4.1 Basic potato unit

Given the relationship in equation (4-4) and the dimensions given above for the basic unit, the diameter of the equivalent sphere is computed as 0.063 m.

4.4 The Storage Volume as a Packed Column

Given that the potatoes are viewed as equivalent spheres, the storage volume can be modeled as a packed column (Figure 4.2). The Ergun (1952) relations for fluid flow through packed columns are used in this study.

The Reynolds number based on the particle is defined as

$$Re_p = \frac{Du_s\rho}{\mu(1 - \epsilon)} \tag{4-5}$$

where D is the particle diameter, u_s is the superficial velocity (the velocity the fluid would have in the storage volume if the storage volume were completely empty), ρ is the density, μ is the absolute viscosity and ϵ is the porosity of the medium.

The pressure drop is given by (Ergun, 1952; Bennett and Myers, 1974)

$$\Delta P = \frac{f_p L u_s^2 (1 - \epsilon)\ \rho}{D\epsilon^3} \tag{4-6}$$

where f_p is the friction factor and L is the length of the column. For intermediate Reynolds numbers -- between 1.0 and 10^3 -- (Bennett and Myers, 1974), the friction factor is

$$f_p = \frac{150}{Re_p} + 1.75. \tag{4-7}$$

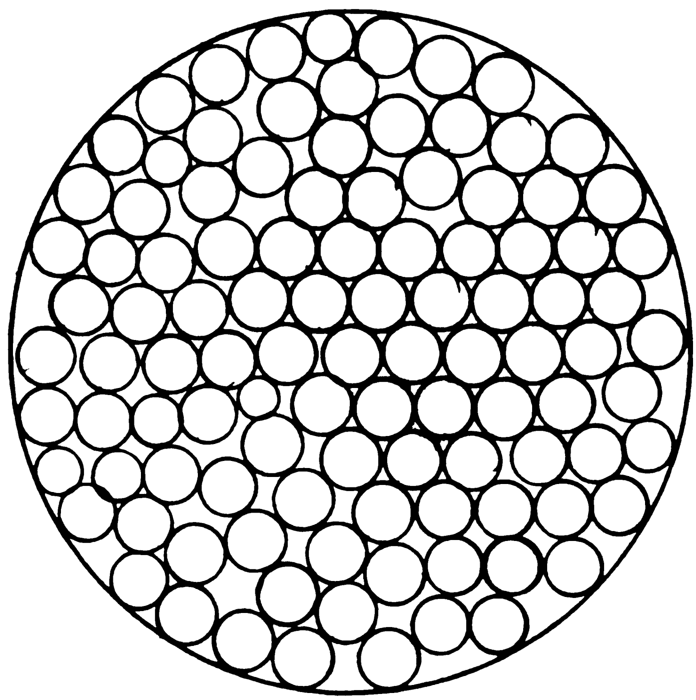

Figure 4.2 The storage volume as a packed column: cross-sectional view

4.5 Characterization of the Transport Processes

The storage volume comprises a solid phase (the product) and a fluid phase (the convective air). The primary transport processes involve heat and mass. Heat can be transported by radiation (considered negligible in this study), conduction and/or convection, while mass transport occurs by convection and/or diffusion.

4.5.1 Transport processes in the fluid phase

In the fluid phase, the relative importance of mass diffusion and convection can be evaluated by an examination of the Peclet Number, Pe. The same approach can be used for the comparison of heat conduction and heat convection in the fluid phase.

4.5.1.1 The Peclet Number

Given an arbitrary volume of fluid with no sources or sinks and a mass diffusion coefficient independent of concentration, a mass balance yields the equation

$$\frac{\partial c}{\partial t} + \bar{v} \cdot \nabla c = D_G \nabla^2 c \qquad (4\text{-}8)$$

where c is the concentration of matter, $\bar{v}$ is the velocity vector, t is time, D_G is the mass diffusivity, ∇ is the del operator defined as

$$\nabla = \Sigma_i \frac{\partial}{\partial x_i} \qquad (4\text{-}9)$$

and ∇^2 is the Laplacian operator. [The derivation of the expression for the mass diffusivity, as it is used for this study, is presented in Appendix A.]

For the steady state situation and for flow in the x direction only, equation (4-8) becomes

$$v_x \frac{\partial c}{\partial x} = D_G \frac{\partial^2 c}{\partial x^2} \tag{4-10}$$

where v_x is the velocity in the x direction. Equation (4-10) is made dimensionless by the use of the following parameters:

$$v^+ = \frac{v_x}{v_o} \; ; \qquad c^+ = \frac{c}{c_o} \; ; \qquad x^+ = \frac{x}{L} \tag{4-11}$$

where v_o and c_o are some reference velocity and concentration respectively and L is a characteristic length.

When the relations in equation (4-11) are substituted in equation (4-10) and the appropriate simplifications made, the following equation is obtained:

$$v^+ \frac{\partial c^+}{\partial x^+} = \frac{D_G}{v_o L} \frac{\partial^2 c^+}{\partial x^{+2}} \tag{4-12}$$

The coefficient on the right hand side of equation (4-12) is the reciprocal of the dimensionless Peclet number for mass transfer, defined as (Levich, 1962)

$$Pe = \frac{v_o L}{D_G} \tag{4-13}$$

It is worth noting the similarity between this Peclet number for mass transfer and its heat transfer counterpart. The thermal diffusivity, used in the heat transfer Peclet number expression, has been replaced by the mass diffusivity. Otherwise, the two expressions are identical.

The left side of equation (4-12) represents the convective transport of matter in the fluid in the x-direction; the right side accounts for molecular diffusion. Therefore, just as the Peclet number in heat transfer is a measure of the ratio of energy transport by convection to that by conduction in a given direction, in mass transfer, the parameter represents the relative importance of the convective and diffusive transport of matter (Levich, 1962) in the direction of flow.

When the Peclet number is much less than unity, molecular diffusion predominates, mass transfer by convection is negligible and the concentration gradients are dependent only on the process of diffusion. On the other hand, when the Peclet number is much greater than unity, molecular diffusion becomes negligible and the concentration gradients are determined solely by convective mass transport.

For the forced convection situation studied here, equation (4-13) yields a mass transfer Peclet number of 780, which is greater than unity by approximately three orders of magnitude. It is postulated from this that mass transport by convection predominates and that the fluid is, for all practical purposes, at a single concentration.

While it is important to keep moisture losses to a minimum in the storage environment, the cooling of the product to an acceptable and safe storage temperature is the major focus of fruit and vegetable storages. Therefore, even though the Peclet number for mass transfer offers needed insight into the nature of the mass transfer process, the more important aspect of this analysis is the heat transfer process. As already indicated, the Peclet number for heat transfer is given by

$$Pe = \frac{v_o L}{\alpha} \tag{4-14}$$

where α is the thermal diffusivity of the fluid and has the relation

$$\alpha = \frac{k}{\rho C} \tag{4-15}$$

where k is the thermal conductivity of the moist air (90 J/m-^{o}C-hr -- Lerew, 1978), ρ is the fluid density (1.25 kg/m^3) and C is the heat capacity of the air stream (1007 J/kg-^{o}C). Given the approximate values in parentheses, the expression in equation (4-15) yields a value of 0.0715 m^2/hr for the thermal diffusivity. When this value is substituted in equation (4-14), with a velocity of 24.0 m/hr and the length of the storage bin (2.4 m) as the characteristic dimension, a Peclet number of 806 is obtained, which is approximately the same as what was obtained for the mass transfer situation. A Peclet number of this magnitude indicates that internal temperature gradients are practically non-existent and that the fluid is at a uniform temperature.

4.5.2 Transport processes in the solid phase

The experimental work of Misener (1973) showed that gradients of moisture concentration and temperature across the potato are negligible. Thus in this study, mass diffusion and heat conduction within the potato will be considered negligible.

It is surmised from the discussions above that there is a step change in moisture concentration (Figure 4.3) and temperature across the boundary of the product and the convective air. The gradients of moisture and concentration at the boundary can be considered infinite.

4.6 Mathematical Relations

The mathematical derivation revolves around obtaining an appropriate expression for the local entropy production and assumes at least an elementary knowledge of the thermodynamics of irreversible processes. Readers who are unfamiliar with irreversible thermodynamics are directed to DeGroot and Mazur (1963), Haase (1969), Katchalsky and Curran (1965), Luikov (1966) or Prigogine (1967).

4.6.1 System Entropy Production

Since entropy production is a global quantity in this study, the control volume comprises the entire storage volume (Figure 4.4). Being an open system, it exchanges

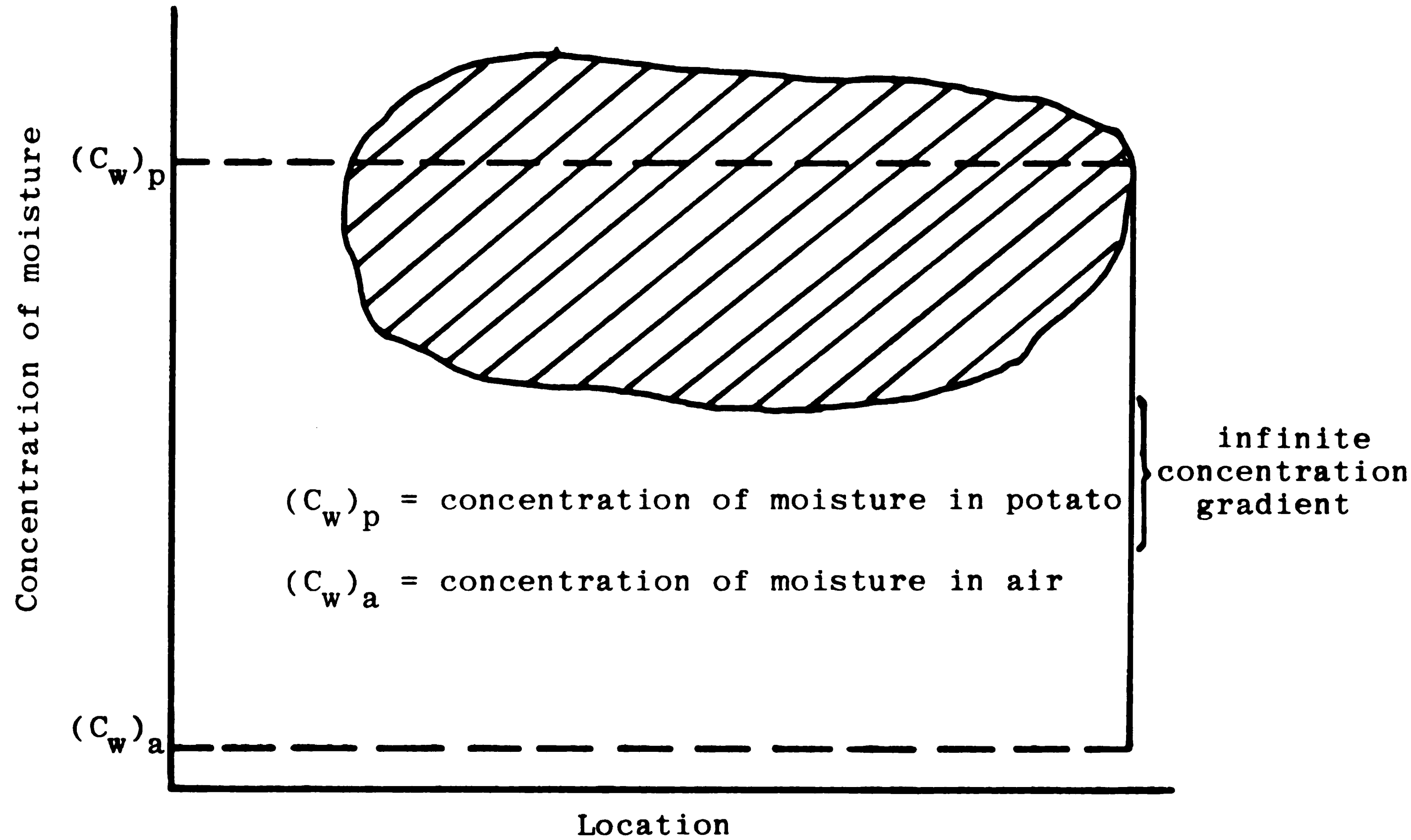

Figure 4.3 Concentration of moisture in the potato and the air

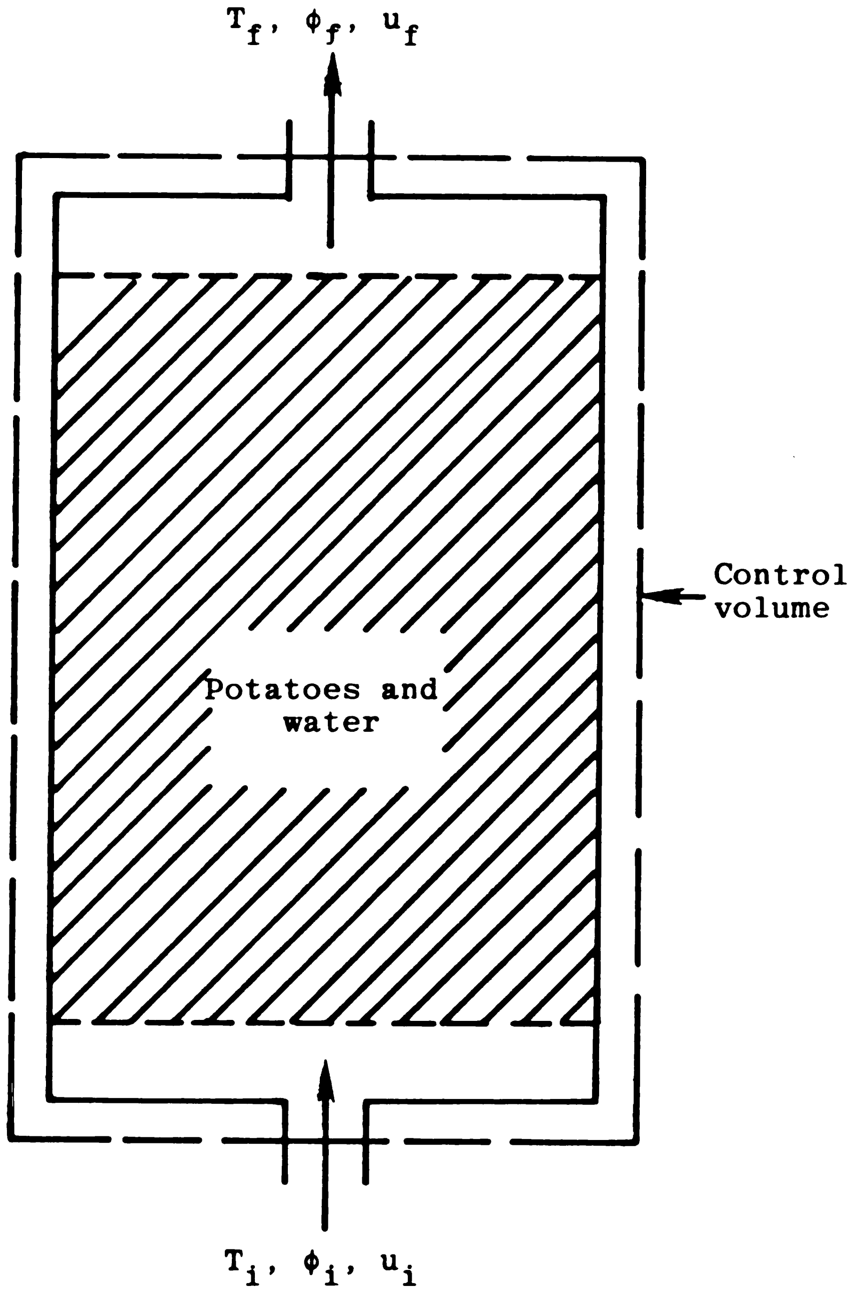

Figure 4.4 Control volume for the analysis of total entropy production (actual calculations were based on twelve subdivisions of the above control volume.)

both heat and mass with its environment. However, for mathematical convenience, the points of these exchanges are restricted to the entry and exit points of the ventilation air.

The rate of entropy production can be represented as

$$\frac{\delta s_v}{\delta t} = - \bar{\nabla} \cdot (\bar{J}_s) + \sigma \tag{4-16}$$

where

$$\bar{J}_s = \frac{\bar{J}_Q}{T} + \Sigma_k \; c_k S_k \bar{v}_k \tag{4-17}$$

is the entropy current flux and represents flows of entropy into and out of the system, while

$$\sigma = - \frac{\bar{J}_Q}{T^2} \cdot \nabla T - \frac{1}{T^2} \Sigma_k \; c_k H_k \bar{v}_k \cdot \nabla T + \frac{\bar{v}}{T} \cdot \nabla P$$

$$+ \frac{1}{T} \Sigma_k \; \bar{K}_k \cdot \bar{J}_k - \Sigma_k \; c_k \bar{v}_k \nabla \left(\frac{\mu_k}{T}\right) + \frac{J_{ch} A}{T} \tag{4-18}$$

represents the local production of entropy due to the occurrence of irreversible processes in the system (Haase, 1969). The production of entropy (rather than entropy flows into and out of the control volume) is the quantity of interest in this study since it relates directly to the dissipation of energy.

After several manipulations, the entropy production term reduces to

$$\sigma = - \frac{\bar{J}_Q}{T^2} \cdot \nabla T + \frac{1}{T} \Sigma_k \; \bar{J}_k \cdot [\bar{K}_k - (\nabla \mu)_T] + \frac{J_{ch} \; A}{T} \tag{4-19}$$

In arriving at equation (4-19), the following relations have been used:

$$\frac{\mu_k}{T} = \frac{H_k}{T} - S_k \qquad (4\text{-}20)$$

and

$$\bar{J}_k = c_k \, (\bar{v}_k - \bar{v}) \qquad (4\text{-}21)$$

in addition to the Gibbs-Duhem equation at constant temperature, given by

$$- \nabla P + \Sigma_k \; c_k (\nabla \mu_k)_T = 0 \qquad (4\text{-}22)$$

4.6.2 Generalized Fluxes And Forces

The control volume comprises potatoes and moist air. An examination of equation (4-19) shows three contributions to the local production of entropy: heat transfer due to a temperature difference between the potatoes and the air stream, mass transfer (almost entirely from the potatoes into the air stream) and chemical reaction due to metabolic processes inside the potatoes.

Given this framework, the summation sign can be removed from equation (4-19) and the subscript k used to refer to the water component of the potato.

One can define a dissipation function, Γ, such that

$$\Gamma = T \, \sigma \qquad (4\text{-}23)$$

Then

$$\Gamma = \bar{J}_k \cdot [\bar{K}_k - (\nabla\mu)_T] - \frac{\bar{J}_Q}{T} \cdot \nabla T + J_{ch} A \qquad (4\text{-}24)$$

Assuming linearity for the heat and mass fluxes and the chemical reaction,

$$\bar{J}_k = L_{KK} [\bar{K}_k - (\nabla\mu)_T] - L_{KQ} \frac{\nabla T}{T} \qquad (4\text{-}25)$$

for mass transport,

$$\bar{J}_Q = L_{QK} [\bar{K}_k - (\nabla\mu)_T] - L_{QQ} \frac{\nabla T}{T} \qquad (4\text{-}26)$$

for heat transport, and

$$J_{ch} = L_{ch} A \qquad (4\text{-}27)$$

for chemical reaction, with the Onsager reciprocal relations giving

$$L_{QK} = L_{KQ} \qquad (4\text{-}28)$$

Equations (4-25), (4-26) and (4-27) illustrate the application of the Curie-Prigogine principle which, for an isotropic system, forbids the coupling of vectorial quantities that differ in order by an odd number. Thus, heat and mass transfer, first order vectorial quantities, can be coupled with each other, but not with chemical reaction, a zero order vectorial (scalar) quantity.

The gradient terms of chemical potential and concentration, $(\nabla\mu_s{}^c)_T$ and ∇c_s, are related (Katchalsky and Curran, 1965) by

$$(\nabla\mu_s{}^c)_T = \frac{\delta\mu_s}{\delta c_s}\nabla c_s = \mu_{ss}\nabla c_s \qquad (4\text{-}29)$$

For ideal gases and ideal solutions, the concentration-dependent part of the chemical potential has the relationship (Katchalsky and Curran, 1965)

$$\mu_s{}^c = R\ T\ \ln c_s + \mu_s{}^o\ (T) \qquad (4\text{-}30)$$

It follows from equation (4-30) that

$$\frac{\delta\mu_s}{\delta c_s} = \mu_{ss} = \frac{R\ T}{c_s} \qquad (4\text{-}31)$$

With the above relations, the heat and mass transport equations (equations 4-25 and 4-26) then become

$$\overline{J}_k = L_{KK}\ [\overline{K}_k - RT\frac{\nabla c_s}{c_s}] - L_{KQ}\frac{\nabla T}{T} \qquad (4\text{-}32)$$

and

$$\overline{J}_Q = L_{QK}\ [\overline{K}_k - RT\frac{\nabla c_s}{c_s}] - L_{QQ}\frac{\nabla T}{T} \qquad (4\text{-}33)$$

4.6.3 Chemical Reaction

The following assumptions were made in the analysis of the contribution made by chemical reaction to the local entropy production.

a) the combustion of glucose is the only significant chemical reaction in the system;

b) neither carbon dioxide nor oxygen is significantly accumulated in the product; and

c) the respiration quotient for oxygen and carbon dioxide is approximately unity. The respiration quotient is the ratio of moles of oxygen consumed to moles of carbon dioxide produced.

The entropy production induced by the reaction is represented by

$$\sigma_{ch} = - J_{ch} \frac{A}{T} \tag{4-34}$$

where the term, J_{ch}, is the rate or velocity of reaction per unit volume and A is the chemical affinity. If the storage volume is assumed to be a linear system, then (as was done for the case of heat and mass transfer), the reaction velocity can be written as

$$J_{ch} = L_{ch}A \tag{4-35}$$

as represented in equation (4-27). The phenomenological coefficient, L_{ch}, must be determined from experimental data.

Since respiration data is usually available in terms of carbon dioxide evolved, J_{ch} can be directly related to experimental data by expressing it as

$$J_{ch} = \frac{1}{V} \frac{d\xi}{dt} \tag{4-36}$$

where ξ is the extent of reaction, or the reaction coordinate.

Ideally, the reaction coordinate must be written in terms of mass of moisture released by the reaction per unit time. Since the rate of carbon dioxide evolution is characterized by r_{ch} (with units of mg. CO_2 evolved per kilogram of product per hour), the extent of reaction is represented in this thesis as

$$\frac{d\xi}{dt} = \frac{18}{44} \frac{1}{10^6} r_{ch} \rho_p V \qquad (4\text{-}37)$$

where ρ_p is the potato density and V is the total volume of potatoes. The factor 18/44 accounts for the fact that for every 44 grams of carbon dioxide evolved, 18 grams of water is released; and 10^6 provides a conversion from milligrams to kilograms.

Given the expression above, the relationship for J_{ch} becomes

$$J_{ch} = 4.44 \times 10^{-4} r_{ch} \qquad (4\text{-}38)$$

The chemical affinity, A, for the reaction is a function of the chemical potential of each of the species involved in the reaction. In particular, for the respiration reaction,

$$A = \mu_a + 6\mu_b - 6\mu_c - 6\mu_d \qquad (4\text{-}39)$$

where a, b, c and d represent glucose, oxygen, carbon dioxide and water vapor, respectively.

While the chemical affinity can be computed as in equation (4-39) above, in many practical applications, it can be approximated by the standard heat of reaction, ΔH^o_{ch}. By the Gibbs-Helmholtz equation (Smith and Van Ness, 1975),

$$\frac{d\left(\frac{\Delta G^{o}_{ch}}{RT}\right)}{dT} = - \frac{\Delta H^{o}_{ch}}{RT^{2}} \tag{4-40}$$

If ΔH^{o}_{ch} is assumed to be constant over the temperature range of interest (278-288°K, in this case), then it is apparent from equation (4-40) above that

$$\Delta G^{o}_{ch} \simeq \Delta H^{o}_{ch} \tag{4-41}$$

For the respiration reaction, the value of ΔG^{o}_{ch} is -2870 kJ/mol of glucose combusted (Lehninger, 1970), or 26,600 kJ/kg of water released, assuming complete oxidation.

4.6.4 Modification Of The Dissipation Relationship

In view of the earlier discussion on the significance of the Peclet number and the subsequent assumption that there is no continuity in either concentration or temperature across the product boundary, the relations in equations (4-32) and (4-33) which call for temperature and concentration gradients are not very useful and do not lend themselves to practical analysis of the situation here. As a result, the mass and heat flux equations in this study are modified as follows.

With the nature of the application considered here, the external force term, $\bar{K}_k$, is made up entirely of viscous forces in the system. Viscous forces are, generally, considered internal to the system. However, a simple sign change is all that is required in this case to change the frame of reference.

Now, define a relationship between $\bar{K}_k$ and the divergence of the stress tensor, $\bar{\nabla}\cdot\bar{\tau}$, such that

$$\bar{K}_k = \frac{\bar{\nabla}\cdot\bar{\tau}}{\rho_k} \tag{4-42}$$

where ρ_k is the mass density of component k.

Given the one-dimensional treatment used here and the fact that the shear stresses are generated entirely as a result of the air flow, equation (4-42) can be reduced to

$$K_k = \frac{\tau_{rz}}{L\,\rho} \tag{4-43}$$

where L is a characteristic dimension in the vertical direction of the bin. In this thesis, L is taken as the length of the bin.

From Ergun's analysis (Ergun, 1952),

$$\tau_{rz} = \frac{\Delta p\, A_c\, \epsilon}{S_t} \tag{4-44}$$

where Δp is the pressure drop, A_c is the cross-sectional area of the empty column, ϵ is the porosity and S_t is the total surface area of the solids in the bed, given by Ergun (1952) as

$$S_t = \frac{A\, L\, \epsilon}{r_h} \tag{4-45}$$

where r_h is the hydraulic radius, defined as (Bennett and Myers, 1974)

$$r_h = \frac{\epsilon\, D}{6(1 - \epsilon)} \tag{4-46}$$

Combining equations (4-44), (4-45) and (4-46),

$$\tau_{rz} = \frac{D}{L}\, \frac{\epsilon}{6(1 - \epsilon)}\, \Delta p \tag{4-47}$$

Finally, combining equation (4-47) with equation (4-6) for the pressure drop

$$\tau_{rz} = \frac{f_p\, u_s^{\,2}\, \rho}{6\, \epsilon^2} \tag{4-48}$$

where f_p is defined as in equation (4-7) and u_s is the superficial velocity.

4.6.4.1 The Modified Relations

Given the need to use temperature and concentration differences rather than gradients, the heat and mass transfer equations (equations 4-32 and 4-33) are modified to read

$$J_k = L'_{KK} \left[\frac{\tau_{rz}}{\rho} - \eta_c \frac{\Delta c_s}{c_s}\right] - L'_{KQ} \frac{\Delta T}{T} \tag{4-49}$$

for mass transfer and

$$J_Q = L'_{QK} \left[\frac{\tau_{rz}}{\rho} - \eta_c \frac{\Delta c_s}{c_s}\right] - L'_{QQ} \frac{\Delta T}{T} \tag{4-50}$$

for heat transfer, with τ_{rz} as given in equation (4-48).

The factor η_c in equations (4-49) and (4-50) is termed the combined skin resistance coefficient. It is used to account for the resistance to mass transport presented by the skin membrane of the potato. Without the coefficient, the use of Δc_s in equation (4-49) and (4-50) essentially implies a free water-to-air interface, which is not true for the situation considered in this thesis. Note also that the gas constant and the absolute temperature have been absorbed into the combined skin resistance coefficient, i.e., $\eta_c = \eta RT$, where η is the skin resistance coefficient.

The major difference between the equation pairs, (4-32, 4-33) and (4-49, 4-50), is that the temperature and concentration gradients in the former have been replaced by simple differences in the latter. This step was made necessary because of the discontinuities in the system. The modification of the equations makes it necessary to redefine the phenomenological coefficients, L_{ij}. The mass, cross-phenomenological and heat transport coefficients are, therefore, respectively modified to take the forms

$$L'_{KK} = \frac{h_D \rho}{g D} \tag{4-51}$$

$$L'_{KQ} = L'_{QK} = \frac{D^T T_\rho}{D} \tag{4-52}$$

$$L'_{QQ} = h T \tag{4-53}$$

where h_D is the mass transfer coefficient, ρ is the air density, g is the gravitational constant used here to provide dimensional homogeneity, D is the diameter of the storage volume, D^T is a modified Soret coefficient and h is the heat transfer coefficient.

Given the mass flux expression, $\bar{J}_k$, the rate of mass transport out of the potatoes is obtained by integrating the scalar product of $\bar{J}_k$ and the directed differential area. Thus,

$$\frac{dm_p}{dt} = - \int_A \bar{J}_k \cdot \overline{dA} \tag{4-54}$$

In a one-dimensional formulation using equations (4-49), (4-51), and (4-52), the mass transport expression becomes

$$\frac{dm_p}{dt} = - S_t \left[\frac{h_D \rho}{g D} \left(\frac{\tau_{rz}}{\rho} - \eta \frac{\Delta c_s}{c_s}\right) - D^T \frac{\Delta T}{D}\right] \tag{4-55}$$

Even though this equation is derived from a global formulation, it can be used as a local equation based on the fact that the potatoes are the only materials inside the control volume producing moisture.

4.6.5 The Thermal Diffusion Coefficient

The thermal diffusion coefficient, in a binary system, is often related to the thermal diffusion ratio, K_T, through the expression (Bird, et al., 1960; Bennett and Myers, 1974)

$$K_T = \frac{\rho D^T}{D_{AB} c^2 M_A M_B} \tag{4-56}$$

where ρ is the density, D^T the binary thermal diffusion coefficient, D_{AB} the binary mass diffusivity, c the concentration, and the M_i are the molecular weights.

Using equation (4-56) as a defining equation for the thermal diffusion coefficient would require a knowledge of K_T, a quantity that is not available for the application considered here.

To circumvent this problem, the expression for D^T is modified for this study. The defining equation used here is

$$D^T = \frac{D_{AB}\, \rho_a}{T_p} \tag{4-57}$$

where T_p is the absolute temperature of the product and D_{AB} is the binary diffusivity.

4.6.6 The Resistance Coefficient for Mass Transport

An analytical expression could not be obtained a priori for this coefficient. It is therefore determined by curve-fitting to experimental data. It is expected that, once value(s) is (are) obtained for the coefficient(s), appropriate regression equations can be developed for use as a predicting tool.

4.6.7 The Rate of Local Entropy Production

From equation (4-19), the local entropy production is

$$\frac{\delta s_v}{\delta t} = \sigma = -\frac{\bar{J}_Q}{T^2} \cdot \nabla T + \frac{1}{T}\,\bar{J}_k \cdot [\bar{K}_k - (\nabla \mu)_T] + \frac{J_{ch}\,A}{T} \tag{4-58}$$

where the subscript T on the chemical potential gradient term implies that the gradient is spatial isothermal. From equations (4-32) and (4-33), equation (4-58) can be written as

$$\sigma = - \frac{L'_{QK}}{T^2} [\overline{K}_k - RT \frac{\nabla c_s}{c_s}] \cdot \nabla T + \frac{L'_{QQ}}{T^2} \frac{\nabla T}{T} \cdot \nabla T$$

$$+ \frac{L'_{KK}}{T} [\overline{K}_k - RT \frac{\nabla c_s}{c_s}] \cdot [\overline{K}_k - RT \frac{\nabla c_s}{c_s}]$$

$$- \frac{L'_{KQ}}{T} \frac{\nabla T}{T} \cdot [\overline{K}_k - RT \frac{\nabla c_s}{c_s}] + \frac{J_{ch} A}{T} \qquad (4\text{-}59)$$

An examination of equation (4-59) reveals immediately that it presents the same type of problem encountered with the mass transport equation and which necessitated the introduction of the skin resistance coefficient. Three of the terms in equation (4-59) contain the gradient of the temperature, a quantity that has physical meaning but no real mathematical form or significance owing to the discontinuity of the temperature across the potato skin membrane. It became necessary therefore to modify the first, second and fourth terms of the equation that contain the temperature gradient. This was done by replacing the derivative of the temperature resulting from the scalar product operations by the quotient of the temperature and a characteristic dimension L.

From the Onsager reciprocal relationship and the definition of the dot or scalar product, the first and fourth terms on the right hand side of equation (4-59) are identical. After combining these terms, performing the inner product and using the modification described above, with equation (4-43) incorporated, equation (4-59) becomes

$$\sigma = \frac{L'_{QQ}}{TL} - \frac{2L'_{KQ}}{TL^2}\left[\frac{\tau_{rz}}{\rho} - RT\right] + \frac{L'_{KK}}{TL}\left(\frac{\tau_{rz}}{\rho} - RT\right)^2 + \frac{J_{ch}A}{T} \qquad (4\text{-}60)$$

4.6.8 The Dissipation Function

From equation (4-23), the dissipation function is

$$\Gamma = T\,\sigma \qquad (4\text{-}61)$$

Given equation (4-60) above, the expression for the dissipation function is

$$\Gamma = \frac{L'_{QQ}}{L} - \frac{2L'_{KQ}}{L}\left[\frac{\tau_{rz}}{\rho} - RT\right] + \frac{L'_{KK}}{L}\left(\frac{\tau_{rz}}{\rho} - RT\right)^2 + J_{ch}A \qquad (4\text{-}62)$$

4.7 Other Thermodynamic Relations

The principal objective of this thesis is to calculate the rate of entropy production and from that the dissipation of energy in the system. However, the relations for these two quantities contain coefficients that are dependent on the potato temperature, the moist air temperature and the concentration of moisture in the system.

To enable the calculation of the air and potato temperatures in the storage environment, an energy balance analysis must be done on the system. For the purpose of performing appropriate balances, the storage volume may be divided into two sub-systems: the potato and its water content and the moist air and its moisture content. The entire storage volume is a combination of the two.

4.7.1 First Law Analysis

The thermodynamic system under consideration is the storage bin, which contains potatoes and moist air, as shown schematically in Figure 4.4. The variables of interest are the potato and air temperatures, T_p and T_a, the mass of the water content of the potato, m_p, and the mass of the water content of the moist air, m_a. All four variables are functions of time and location inside the bin.

Each of the two control volumes discussed above is contained in the boundaries of the bin. The first law is applied only to the collection of particles located inside the control volume at time t.

4.7.1.1 Control Volume 1

The fixed collection of particles contained in this control volume consists of the potatoes bounded by the planes x and x+dx and their water at time t. The formulation assumes that the potatoes and their water content are in thermal equilibrium.

The first law is given by

$$dQ + dW = dE \tag{4-63}$$

where heat added to and work done on the fixed collection of particles are considered positive here.

The total change in energy, dE, is made up of the change in energy of the potato solid mass and the change in energy of the water content of the potato over a time interval dt; note that some of this water may leave the potato during the time interval dt.

Mathematically,

$$dE = M_p C_{vp} dT_p + m_p C_{vw} dT_p + (-dm_p)\ h_{fg}\ H(-dm_p)$$

$$+ (-dm_p)\ C_{vv}(T_a - T_p)\ H(-dm_p) \tag{4-64}$$

where M_p is the solid mass of the potato, assumed to be a constant, C_{vp} is the constant volume heat capacity per unit mass of the potato, C_{vv} and C_{vw} are the constant volume heat capacities per unit mass of the water vapor and liquid water, respectively, T_p is the potato temperature, T_a is the air temperature, h_{fg} is the heat of vaporization per unit mass of water at the potato temperature, dm_p is the change in moisture content of the potato and H is the Heavyside step function defined by

$$H(x) = \begin{vmatrix} 1; & \text{if} \quad x>0 \\ 0; & \text{if} \quad x\leq 0 \end{vmatrix} \tag{4-65}$$

The variables T_a and T_p are absolute temperatures and are functions of both time and location.

Note that the energy associated with the change of phase of the moisture lost from the potato is treated in equation (4-64) as an internal energy term rather than a heat flow term. This is because during the time interval dt, the moisture lost from the potato remains a part of the control volume associated with the potato, even though part or all of it may be outside the boundary of the potato. Thus the conversion from a liquid to a vapor does not constitute an exchange of energy with the environment; it simply constitutes a change in the internal energy of the control volume.

The heat flow to the system of particles is given by

$$dQ = hA_s(T_a - T_p)\ dt - (kA_{ct}\ \frac{dT_p}{dx})_x\ dt$$

$$+ (kA_{ct}\ \frac{dT_p}{dx})_{x+dx}\ dt + q(M_p + m_p)dt \qquad (4\text{-}66)$$

where A_s is the surface area of the potato, A_{ct} is the potato-to-potato contact area, h is the convective heat transfer coefficient, k is the thermal conductivity of the potato, q is the rate of heat release by metabolic processes and x and x+dx refer to spatial locations.

The sum in parenthesis in the last term of equation (4-66) is the total mass of the potatoes, including their water content. This is because the expression for the metabolic term (derived later in this chapter) is based on the total mass of the potato, even though only the carbohydrate portion is undergoing the chemical reaction that generates the heat.

Assuming that the potatoes are "arranged" in the bin in such a manner that only point contacts occur between any set of adjacent pieces, A_{ct} is very small; thus the thermal conduction term is negligible. Therefore, equation (4-66) can be reduced to

$$dQ = hA_s(T_a - T_p)dt + q(M_p + m_p)dt \tag{4-67}$$

As water is lost from the potato, it comes to the surface of the product as liquid water which must be evaporated into the air stream. Due to the volume expansion that occurs as the liquid becomes a gas, negative work is done by the environment on the gas. If it is assumed that the potatoes experience a negligible change in volume, then dV_p is nearly zero and the total work associated with the control volume can be represented as

$$dW = - p\, dV_v \tag{4-68}$$

where dV_v is the volume change of the water vapor.

Since water vapor behaves as an ideal gas, equation (4-68) can be rewritten as

$$dW_{on} = - m_v R_v T_v \frac{dV_v}{V_v} \tag{4-69}$$

where m_v, R_v and T_v are the mass, gas constant for water vapor and temperature of the water vapor respectively. A reasonable assumption is that the water vapor and the air reach thermal equilibrium instantaneously, so that T_v is essentially T_a.

The volume of the liquid before evaporation is much smaller than its volume after being vaporized, therefore the change in volume is nearly equal to the final volume, so that

$$\frac{dV_v}{V_v} \simeq 1.0 \tag{4-70}$$

Equation (4-69) becomes

$$dW_{on} = -\ (-dm_p)\ R_v T_a\ H(-dm_p) \tag{4-71}$$

where m_v has been replaced by $(-dm_p)\ H(-dm_p)$.

Substituting equations (4-64), (4-67) and (4-71) in equation (4-63), the first law yields

$$\begin{aligned} hA_s(T_a - T_p)dt + q(M_p + m_p)dt - (-dm_p)\ R_v T_a\ H(-dm_p) \\ = M_p C_{vp} dT_p + m_p C_{vw} dT_p + (-dm_p) h_{fg}\ H(-dm_p) \\ + (-dm_p)\ C_{vv}\ (T_a - T_p)\ H(-dm_p) \end{aligned} \tag{4-72}$$

or, simplifying,

$$\begin{aligned} hA_s(T_a - T_p)dt + q(M_p + m_p)dt + [- R_v T_a \\ - h_{fg} - C_{vv}\ (T_a - T_p)]\ (-dm_p)\ H(-dm_p) \end{aligned}$$

$$= M_p C_{vp} dT_p + m_p C_{vw} dT_p \tag{4-73}$$

Equation (4-73) can be transformed into a continuum formulation by using the following definitions:

$$M = \Lambda_p \, dx \tag{4-74}$$

$$m_p = \lambda_p(x,t) \, dx \tag{4-75}$$

$$dm_p = \frac{\partial m_p}{\partial t} dt = \frac{\partial \lambda_p}{\partial t} \, dx \, dt \tag{4-76}$$

$$A_s = \alpha_p \, dx \tag{4-77}$$

where

$$\Lambda_p = \frac{\text{total potato mass in bin}}{\text{length of bin}} \tag{4-78}$$

is a constant,

$$\lambda_p = \frac{\text{mass of water in potato at time t}}{\text{differential length dx of potato}} \tag{4-79}$$

is a function of time and location and

$$\alpha_p = \frac{\text{total potato surface area}}{\text{length of bin}} \tag{4-80}$$

is a constant.

Using equations (4-74) to (4-77), equation (4-73), divided by (dt dx) becomes

$$h\alpha_p(T_a - T_p) + q(\Lambda_p + \lambda_p) - (-\frac{\partial \lambda_p}{\partial t}) R_v T_a H(-\frac{\partial \lambda_p}{\partial t})$$

$$= [\Lambda_p C_{vp} + \lambda_p C_{vw}] \frac{DT_p}{Dt} + (-\frac{\partial \lambda_p}{\partial t}) h_{fg} H(-\frac{\partial \lambda_p}{\partial t})$$

$$+ \left(- \frac{\partial \lambda_p}{\partial t}\right) C_{vv} (T_a - T_p) \; H\left(- \frac{\partial \lambda_p}{\partial t}\right) \qquad (4\text{-}81)$$

Solving for the substantial or material derivative of the potato temperature

$$\frac{DT_p}{Dt} = \frac{\partial T_p}{\partial t} + u \frac{\partial T_p}{\partial x} \qquad (4\text{-}82)$$

where $u = 0$ for the potatoes, equation (4-81) becomes

$$\frac{\partial T_p}{\partial t} = \frac{1}{\Lambda_p C_{vp} + \lambda_p C_{vw}} [h\alpha_p (T_a - T_p) + q (\Lambda_p + \lambda_p)$$

$$+ (- R_v T_a - h_{fg}) \left(\frac{-\partial \lambda_p}{\partial t}\right) H\left(- \frac{\partial \lambda_p}{\partial t}\right)$$

$$- C_{vv} (T_a - T_p) \left(\frac{-\partial \lambda_p}{\partial t}\right) H\left(- \frac{\partial \lambda_p}{\partial t}\right)] \qquad (4\text{-}83)$$

Since the cross-sectional area is treated as constant, the continuity and momentum equations are respectively (Eckert and Drake, 1972)

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial \rho}{\partial t} = 0 \qquad (4\text{-}84)$$

and

$$\frac{\partial}{\partial x}(p + \rho u^2) + \frac{\partial}{\partial t}(\rho u) + \rho g = 0 \qquad (4\text{-}85)$$

where ρ is the density, u the velocity and p the pressure, all relating to the potato, x is the vertical coordinate and g is the standard acceleration due to gravity. Since ρ is essentially constant and $u = 0$ for the potato, these equations give

$$\frac{\partial p}{\partial x} = - \rho g \tag{4-86}$$

or

$$p = \rho\, g\, (L - x) \tag{4-87}$$

which says that the potato pressure at x is due to the weight of the potatoes above location x.

Only the moisture given up by the potatoes is in relative motion (on exit from the potato). Since this moisture eventually appears as a moisture gain for the moving air mass, the continuity equation expressing this fact is deferred until the control volume comprising the moist air is analyzed.

4.7.1.2 Control Volume 2

This control volume comprises the air and its water vapor located in the bin between the planes x and x+dx at time t. At time t + dt, this collection of particles would be located partially outside the original control volume due to the movement of air (Figure 4.5). Therefore, this thermodynamic system is an open one.

Again the first law statement of equation (4-63) is used. The total differential energy, dE, is given by

$$dE = M_a C_{va} dT_a + m_a C_{vv} dT_a \tag{4-88}$$

where M_a is the mass of the dry air, m_a is the mass of moisture in the air and C_{va} and C_{vv} are the specific heats of

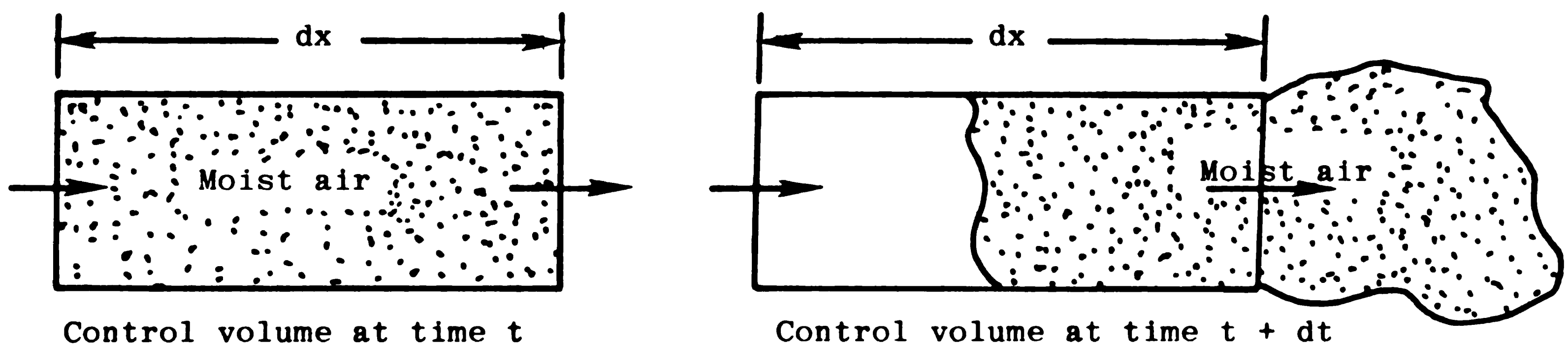

Figure 4.5 Control volume for analysis of the ventilation air

the dry air and the water vapor, respectively.

Now, define

$$M_a = \Lambda_a dx \tag{4-89}$$

and

$$m_a = \lambda_a dx \tag{4-90}$$

with

$$\Lambda_a = \frac{\text{total dry air mass in bin at time t}}{\text{length of bin}} \tag{4-91}$$

a function of T_a and

$$\lambda_a = \frac{\text{mass of water in the air at time t}}{\text{length of bin}} \tag{4-92}$$

a function of the temperature and relative humidity of the air, and the history of moisture transmission from the potatoes into the air stream.

Substituting terms, the change in the internal energy is given by

$$dE = \Lambda_a C_{va} dT_a \, dx + \lambda_a C_{vv} dT_a \, dx \tag{4-93}$$

The heat flow into the system of particles is

$$dQ = hA_s(T_p - T_a)\, dt - \left(k_a A_{ac} \frac{dT_a}{dx}\right)_x dt$$

$$+ \left(k_a A_{ac} \frac{dT_a}{dx}\right)_{x+dx} dt \tag{4-94}$$

where A_{ac} is the cross-sectional area open to air flow, a function of the porosity and k_a is the thermal conductivity of the air.

The thermal conductivity of the air, k_a, is a small quantity; therefore convection predominates. As a result, the last two terms of equation (4-94) may be dropped.

With equations (4-74) to (4-77), (4-89) and (4-90), equation (4-94) without the conduction terms reduces to

$$dQ = h\alpha_p(T_p - T_a)dt\ dx \tag{4-95}$$

The total work done consists of four parts: air pressure work, potato pressure work, work against gravity and work done by the expanding dm_p of the first control volume. Mathematically,

$$dW = [(pA_{ac}u)_x\ dt - (pA_{ac}u)_{x+dx}\ dt] + p_a\ dV_p$$

$$- (M_a + m_a)\ g\ u\ dt + (-dm_p)\ R_vT_a\ H(-dm_p) \tag{4-96}$$

or, again making the assumption that dV_p is negligible,

$$dW = -A_{ac}\frac{\partial}{\partial x}(pu)\ dx\ dt - (\Lambda_a + \lambda_a)\ g\ u\ dx\ dt$$

$$+ (-\frac{\partial\lambda_p}{\partial t})\ R_vT_a\ H(-\frac{\partial\lambda_p}{\partial t})\ dx\ dt \tag{4-97}$$

where u is the speed of the convective air.

The above equation introduces two new variables, p and u, that must be transformed into previously defined variables.

This can be done by using the continuity and momentum equations (equations 4-84 and 4-85) written with respect to the air stream, in addition to the perfect gas law, given by

$$P = \rho R_a T_a \tag{4-98}$$

The Mach number for this system is the ratio of the velocity of air flow to the speed of sound in air, approximately 340 m/s for the temperatures of interest in this study ($3^\circ C \leq T \leq 17^\circ C$). When the Mach number for a system is low, the flow can be considered incompressible (Cambel and Jennings, 1958; Benedict, 1983); that is

$$\frac{D\rho}{Dt} = 0. \tag{4-99}$$

where the term on the left hand side of equation (4-99) is the substantial derivative of the air density.

For the system under consideration, the Mach number is approximately 2.0×10^{-5}, thus incompressibility is assumed.

The continuity equation can be rewritten as

$$\frac{\delta}{\delta x}(\rho u) + \frac{\delta \rho}{\delta t} = 0 = \rho\frac{\delta u}{\delta x} + \frac{D\rho}{Dt} \tag{4-100}$$

from which it follows, given the assumption of incompressibility, that

$$\frac{\delta u}{\delta x} = 0 \tag{4-101}$$

Thus the velocity is constant along the bin, even though it may still be a function of time.

The momentum equation can be rewritten as

$$\frac{\delta p}{\delta x} + \frac{\delta}{\delta x}(\rho u \cdot u) + \frac{\delta}{\delta t}(\rho \cdot u) + \rho g = 0 \tag{4-102}$$

or

$$\frac{\delta p}{\delta x} + u \frac{\delta}{\delta x} (\rho u) + \rho u \frac{\delta u}{\delta x} + u \frac{\delta \rho}{\delta t} + \rho \frac{\delta u}{\delta t} + \rho g = 0 \quad (4\text{-}103)$$

or

$$\frac{\delta p}{\delta x} + u \left[\frac{\delta}{\delta x} (\rho u) + \frac{\delta \rho}{\delta t}\right] + \rho u \frac{\delta u}{\delta x} + \rho \frac{\delta u}{\delta t} + \rho g = 0 \quad (4\text{-}104)$$

The terms in square brackets in the above equation constitute the continuity equation and thus sum to zero. When equation (4-101) is incorporated, equation (4-104) reduces to

$$\frac{\delta p}{\delta x} = - \rho \frac{\delta u}{\delta t} - \rho g \quad (4\text{-}105)$$

For the ventilation system under consideration, the inlet velocity is kept constant. Therefore, at $x = 0$,

$$\frac{\delta u}{\delta t} = 0 \qquad \text{for all } t. \quad (4\text{-}106)$$

In addition, from equation (4-101), the velocity is not a function of x; therefore, it follows that

$$\frac{\delta u}{\delta t} = 0 \qquad \text{for all } x \text{ and } t. \quad (4\text{-}107)$$

from which

$$\frac{\delta p}{\delta x} = - \rho g \quad (4\text{-}108)$$

Therefore equation (4-97) becomes

$$dW = [A_{ac} \rho g u - (\Lambda_a + \lambda_a)\, g\, u$$

$$+ \left(-\frac{\delta \lambda_p}{\delta t}\right) R_v T_a\, H\left(-\frac{\delta \lambda_p}{\delta t}\right)]\, dx\, dt \quad (4\text{-}109)$$

However, by the definition of ρ,

$$A_{ac}\rho \, dx = (\Lambda_a + \lambda_a) \, dx \qquad (4\text{-}110)$$

Therefore the air pressure work cancels the work against gravity and

$$dW = \left(-\frac{\partial \lambda_p}{\partial t}\right) R_v T_a \; H\left(-\frac{\partial \lambda_p}{\partial t}\right) dx \; dt \qquad (4\text{-}111)$$

Combining dE (equation 4-93), dQ (equation 4-95) and dW (equation 4-111),

$$\Lambda_a C_{va} dT_a dx + \lambda_a C_{vv} dT_a dx = h\alpha_p (T_p - T_a) \; dt \; dx$$

$$+ \left(-\frac{\partial \lambda_p}{\partial t}\right) R_v T_a \; H\left(-\frac{\partial \lambda_p}{\partial t}\right) dx \; dt \qquad (4\text{-}112)$$

Dividing through by dt-dx and solving for the material of substantial derivative of the air temperature,

$$\frac{DT_a}{Dt} = \frac{1}{\Lambda_a C_{va} + \lambda_a C_{vv}} \left[h\alpha_p (T_p - T_a)\right.$$

$$\left. + R_v T_a \left(-\frac{\partial \lambda_p}{\partial t}\right) H\left(-\frac{\partial \lambda_p}{\partial t}\right)\right] \qquad (4\text{-}113)$$

where

$$\frac{DT_a}{Dt} = \frac{\partial T_a}{\partial t} + u \frac{\partial T_a}{\partial x} \qquad (4\text{-}114)$$

Finally,

$$\frac{\partial T_a}{\partial t} = \frac{1}{\Lambda_a C_{va} + \lambda_a C_{vv}} \left[h\alpha_p (T_p - T_a)\right.$$

$$+ R_v T_a \left(-\frac{\partial \lambda_p}{\partial t}\right) H\left(-\frac{\partial \lambda_p}{\partial t}\right)] - u \frac{\partial T_a}{\partial x} \qquad (4\text{-}115)$$

It must be true that since the air receives moisture from the potatoes,

$$d\lambda_a = - d\lambda_p \; H(-d\lambda_p) \qquad (4\text{-}116)$$

and since these are both material derivatives,

$$\frac{\partial \lambda_a}{\partial t} + u \frac{\partial \lambda_a}{\partial x} = \left(- \frac{\partial \lambda_p}{\partial t}\right) H\left(- \frac{\partial \lambda_p}{\partial t}\right) \qquad (4\text{-}117)$$

There are four unknowns in equations (4-83), (4-115) and (4-117): T_p, T_a, λ_p and λ_a. These three equations, together with the mass loss equation developed from irreversible thermodynamics (4-55) constitute a sufficient number of field equations to enable solutions to be obtained for the listed unknowns.

Equation (4-55) can be cast in the four unknown variables by using the following definitions.

$$\frac{\partial m_p}{\partial t} = \left(- \frac{\partial \lambda_p}{\partial t}\right) H\left(- \frac{\partial \lambda_p}{\partial t}\right) dx \qquad (4\text{-}118)$$

$$S_t = \alpha_p \, dx \qquad (4\text{-}119)$$

$$\Delta T = T_p - T_a \qquad (4\text{-}120)$$

The concentration of moisture in the potato and in the air stream are given respectively by

$$(c_s)_p = \frac{\lambda_p}{A_{ct} - A_{ac}} \qquad (4\text{-}121)$$

$$(c_s)_a = \frac{\lambda_a}{A_{ac}} \qquad (4\text{-}122)$$

where A_{ct} is the total cross-sectional area of the bin.

From these relations,

$$\frac{\Delta c_s}{c_s} = \left(\frac{\lambda_p}{A_{ct} - A_{ac}} - \frac{\lambda_a}{A_{ac}}\right) \cdot \left(\frac{A_{ct} - A_{ac}}{\lambda_p}\right) \qquad (4\text{-}123)$$

which, on simplification and noting that $\lambda_p >> \lambda_a$, gives

$$\frac{\Delta c_s}{c_s} = 1.0 \qquad (4\text{-}124)$$

With the above equations, equation (4-55) can be written as

$$-\frac{\partial \lambda_p}{\partial t} = -\alpha_p \left[\frac{h_D \rho}{g\, D} \left(\frac{\tau_{rz}}{\rho} - \eta_c\right)\right.$$

$$\left. - \frac{D^T}{D} (T_p - T_a)\right] \qquad (4\text{-}125)$$

4.8 Modeling Of Parameters

Several parameters have been employed in the development of this model. These are discussed below.

4.8.1 Heat And Mass Transfer Coefficients

Following Misener (1973), the mass transfer coefficient is defined as

$$h_D = 8.96 \times 10^{-4}\, h \qquad (4\text{-}126)$$

where h is the heat transfer coefficient which is modeled after the McAdams relationship (Holman, 1976) for heat transfer from spheres to a flowing gas, primarily because it is quite simple, yet accurate. The McAdams equation is

$$h = 0.37\ Re^{0.6}\ k_a\ /\ D_{sp} \qquad (4\text{-}127)$$

where Re is the Reynolds number, k_a is the conductivity of the convective air and D_{sp} is the diameter of the sphere.

The values obtained by the use of equation (4-127) are in very good agreement with generally-accepted values of the heat transfer coefficient for suberized potatoes in storage.

4.8.2 Moist Air Relations

Based on the ideal gas law, the humidity ratio, γ_m, is given by

$$\gamma_m = 0.622\ \frac{\phi P^{sat}}{P - \phi P^{sat}} \qquad (4\text{-}128)$$

where ϕ is the relative humidity, P^{sat} is the saturation pressure and P is the atmospheric pressure.

Assuming that Dalton's Law of partial pressures is valid, the relative humidity ϕ is defined as the ratio of the vapor pressure to the saturation pressure, i.e.,

$$\phi = \frac{P_v}{P^{sat}} \qquad (4\text{-}129)$$

where P_v is the vapor pressure.

For vaporization processes at low pressures (about one atmosphere), the Clausius-Clapeyron equation is valid and gives the following relationship for the saturation pressure

$$\frac{dP^{sat}}{P^{sat}} = \frac{h_{fg}}{R_v}\frac{dT}{T^2} \qquad (4\text{-}130)$$

where h_{fg} is the heat of vaporization, T is the absolute temperature and R_v is the gas constant for water vapor. Using data available from standard steam tables, h_{fg} was derived for this study as

$$h_{fg} = (3147.4 - 2.365T) \times 10^3 \qquad (4\text{-}131)$$

This expression is valid for temperatures between 273.15°K and 313.15°K. Using equation (4-131), equation (4-130) then becomes

$$\frac{dP^{sat}}{P^{sat}} = \frac{3147.4}{R_v T^2}\,dT - \frac{2.365}{R_v}\frac{dT}{T} \qquad (4\text{-}132)$$

After integrating from a lower limit of 273.15°K to T, the expression for the saturation pressure becomes

$$P^{sat} = \exp\left(60.08 - \frac{6814.03}{T} - 5.12 \ln T\right) \qquad (4\text{-}133)$$

4.8.3 The Heat Capacities

The heat capacities for liquid water, water vapor and moist air are all defined as having acceptable values of 4184, 1880 and 1007 J/kg-K, respectively (Bolz & Tuve, 1976). The heat capacity for potatoes results from an expression, derived for this study, relating the heat capacity of the product to its moisture content. This expression is

$$C_v = 1430 + 2765 \text{ m.c.} \qquad (4\text{-}134)$$

where m.c. is the moisture content of the potato. This expression provides excellent agreement with published data (Mohsenin, 1980), with absolute errors of less than 4%.

4.8.4 The Rate Of Heat Generation

Misener (1973) derived the following expression for the heat generation rate, for $\theta_p > 4.0^\circ C$

$$Q_{res} = 1.45\, \theta_p - 3.3 \qquad (4\text{-}135)$$

where θ_p is the product temperature, $^\circ C$. Given the units reported for Q_{res} (J/kg-hr), the above expression would yield low and inaccurate values for the heat generation rate. Expressions by several other researchers (Brugger, 1979; Hunter, 1976; Lerew, 1978) were found to be similarly unsatisfactory.

Based on the experimental data of Listov and Kalugina, 1964 (as reported by Mohsenin, 1980), the expression below was derived for the heat generation rate for the temperature range $4.0^\circ C < \theta_p < 16.0^\circ C$:

$$Q_{res} = 5.6\, \theta_p + 21.4 \qquad (4\text{-}136)$$

Except at 10°C where a reliable experimental value for the heat generation rate could not be obtained, this expression compares quite well with available data (Table 4.1).

4.8.5 Other Input Parameters

The value of the bulk volume of potatoes used in this study is 1085 kg/m^3. The initial storage temperature, the incoming ventilation air temperature and the incoming relative humidity, as reported by Misener (1973) are, respectively, 15.5° C, 6.7° C, and 60%. The ventilation rate is 24 m^3/hr/m^2.

The porosity of the Misener experimental sample was calculated to be 0.641. Porosity, in this study, is defined as the ratio of the pore volume to the total volume.

Table 4.1 The heat generation expression vs. experimental data, kJ/hr-kg.

Temp.	Exp. Data	Eq. 5-73	% diff.
4	43.7	43.8	0.2
6	54.8	55.0	0.4
15	105.0	105.4	0.4

Source: Listove & Kalugina, 1964.
(from Mohsenin, 1980)

5.0 COMPUTER SIMULATION

5.1 Introduction

The determination of energy dissipation is accomplished three steps. The first involves the determination of η_i, the skin resistance coefficients, by a trial and error procedure based on a comparison between actual data and predicted values for heat and mass transfer in the potato storage environment. The second involves the use of regression formulas, if necessary, for the coefficients. The last step uses the regression results together with the energy dissipation equation (equation 5-2) below to calculate the rate of entropy production and the dissipation of energy in the system.

5.2 Relevant Equations

The entropy production and energy dissipation terms are given by

$$\sigma = \frac{L'_{QQ}}{TL} - \frac{2L'_{KQ}}{TL^2}\left[\frac{\tau_{rz}}{\rho} - RT\right] + \frac{L'_{KK}}{TL}\left(\frac{\tau_{rz}}{\rho} - RT\right)^2 + \frac{J_{ch}A}{T} \tag{5-1}$$

and

$$\Gamma = \sigma T \tag{5-2}$$

The four relevant equations (with the Heavyside function suppressed) that must be solved before solutions can be obtained for σ and Γ are

$$\frac{\partial T_p}{\partial t} = \frac{1}{\Lambda_p C_{vp} + \lambda_p C_{vw}} [h\alpha_p (T_a - T_p) + q\ (\Lambda_p + \lambda_p)$$

$$+ (R_v T_a + h_{fg} + C_{vv}(T_a - T_p))\ (\frac{\partial \lambda_p}{\partial t})] \tag{5-3}$$

for the potatoes,

$$\frac{\partial T_a}{\partial t} + u \frac{\partial T_a}{\partial x} = \frac{1}{\Lambda_a C_{va} + \lambda_a C_{vv}} [h\alpha_p (T_p - T_a)$$

$$- R_v T_a\ (\frac{\partial \lambda_p}{\partial t})] \tag{5-4}$$

for the ventilation air stream,

$$- \frac{\partial \lambda_p}{\partial t} = \frac{\partial \lambda_a}{\partial t} + u \frac{\partial \lambda_a}{\partial x} \tag{5-5}$$

for continuity and

$$- \frac{\partial \lambda_p}{\partial t} = - \frac{\alpha_p h_D \tau_{rz}}{g\ D} + \frac{\alpha_p h_D\ \rho}{g\ D} \eta_c$$

$$+ \frac{\alpha_p D^T}{D} (T_p - T_a) \tag{5-6}$$

for the mass transfer.

These equations can be simplified with the use of the following definitions:

$$A = \frac{h\,\alpha_p}{\lambda_p C_{vw} + \Lambda_p C_{vp}} \tag{5-7}$$

$$B = \frac{q\,(\Lambda_p + \lambda_p)}{\lambda_p C_{vw} + \Lambda_p C_{vp}} \tag{5-8}$$

$$a = \frac{h_{fg}}{\lambda_p C_{vw} + \Lambda_p C_{vp}} \tag{5-9}$$

$$b = \frac{R_v + C_{vv}}{\lambda_p C_{vw} + \Lambda_p C_{vp}} \tag{5-10}$$

$$c = \frac{C_{vv}}{\lambda_p C_{vw} + \Lambda_p C_{vp}} \tag{5-11}$$

$$C = \frac{h\alpha_p}{\lambda_a C_{vv} + \Lambda_a C_{va}} \tag{5-12}$$

$$d = \frac{R_v}{\lambda_a C_{vv} + \Lambda_a C_{va}} \tag{5-13}$$

$$e = \frac{\alpha_p D^T}{D} \tag{5-14}$$

and

$$f = \frac{\alpha_p h_D \rho}{g\,D}\,\eta - \frac{\alpha_p h_D \tau_{rz}}{g\,D}. \tag{5-15}$$

Note that in general, all of the above parameters may be functions of T_a, T_p, λ_a and λ_p and that the term f embodies the skin resistance coefficient.

The mass transfer equation can then be written as

$$-\frac{\partial \lambda_p}{\partial t} = f + e\,(T_p - T_a) \tag{5-16}$$

Substituting this into the two temperature derivative equations and the continuity equation and simplifying with the use of the above definitions,

$$\frac{\partial T_p}{\partial t} = (A - b\,f + a\,e)\,T_a - (A - c\,f + a\,e)\,T_p + (c\,e - b\,e)\,T_a T_p + b\,e\,T_a^{\,2} - c\,e\,T_p^{\,2} + B - a\,f \tag{5-17}$$

$$\frac{\partial T_a}{\partial t} + u\,\frac{\partial T_a}{\partial x} = -\,d\,e\,T_a^{\,2} + (d\,f - C)\,T_a + d\,e\,T_a T_p + C\,T_p \tag{5-18}$$

and

$$\frac{\partial \lambda_a}{\partial t} + u\,\frac{\partial \lambda_a}{\partial x} = f + e\,(T_p - T_a) \tag{5-19}$$

Several boundary and initial conditions are required to solve equations (5-16) through (5-19). The necessary conditions are the initial potato and air temperature profiles in the bin, the initial air and potato moisture profiles in the bin, and the moisture content and temperature of the ventilation air at the entrance to the bin.

Equations (5-16) through (5-19) are non-linear. Note that if the potato moisture loss is negligible, then by equations (5-17) and (5-20),

$$f \dashrightarrow 0; \quad e \dashrightarrow 0 \tag{5-20}$$

which reduces equations (5-18) and (5-19) to

$$\frac{\partial T_p}{\partial t} = A\ (T_a - T_p) + B \tag{5-21}$$

and

$$\frac{\partial T_a}{\partial t} + u\,\frac{\partial T_a}{\partial x} = C\ (T_p - T_a), \tag{5-22}$$

both of which are linear equations.

It immediately becomes apparent that the non-linearity of equations (5-18) and (5-19) is associated with the loss of moisture from the potato and its subsequent evaporation from the system. This result is as would be expected.

Many of the parameters in the above equations are temperature-dependent but since the range of temperatures over which the system operates is rather small ($277.0 < T_a < 290.0^{\circ}K$), it is not crucial to adhere to the temperature-dependency. As a result, these parameters are all evaluated at a temperature of $10.5^{\circ}C$ and treated as constants for all temperatures between $4^{\circ}C$ and $17^{\circ}C$ (Table 5.1). Other parameters used in the analysis and their numerical values are tabulated in Table 5.2.

Table 5.1 Temperature-dependent input parameters

Parameter and units	Values at 4°C	at 17°C	at 10.5°C	Max. error, %
k_a, J/m-sec-°C	0.024	0.025	0.025	0.04
ρ_a, kg/m^3	1.274	1.218	1.246	2.25
μ_a, kg/m-sec x 10^5	1.736	1.799	1.767	1.81
ν_a, m^2/sec x 10^5	1.362	1.477	1.420	4.01
h_{fg}, J/kg x 10^{-6}	2.49	2.46	2.47	0.81
D_G, m^2/sec x 10^5	1.97	2.15	2.06	4.37

Table 5.2 Parameters used in computer program.

Parameter	Value used
Initial storage temperature	15.5°C
Heat capacities:	
Liquid water	4184 J/kg-°K
Potato (at 0 % m.c.)	1430 J/kg-°K
Water vapor	1880 J/kg-°K
Air	1007 J/kg-°K
Porosity	0.641
Bulk density of potatoes	1085 kg/m^3
Material densities:	
Air	1.25 kg/m^3
Potato	1800 kg/m^3
Liquid water	1000 kg/m^3
Initial potato moisture content	80%
Outside air temperature	6.7°C
Outside air relative humidity	60%
Air velocity	37.4 m/hr
Characteristic length	0.2 m
Time step	0.00534 hr.

5.3 Computer Implementation

The rate of entropy production and the system energy dissipation are given by equations (5-1) and (5-2), respectively. These equations are functions of the air and product temperatures, which in turn depend on the product mass losses and the degree of saturation of the convective air.

As pointed out previously, the solution is a trial and error process, since the skin resistance coefficient, η, is not known a priori. The process begins with guessing a value for η to obtain a solution for the rate of mass loss. This result then becomes an input to equations (5-17) and (5-18), which then give the parameter f, along with values for the time rates of change of the convective air temperatures. These rates of change are then used to compute the temperature profiles via finite differences for the next time step. This process is repeated until the potato and air temperature profiles are known over the length of the bin for a period of time covering 24 hours. These profiles are then compared to the experimental results of Misener (1973). If the simulated results are in reasonable agreement with the experimental values, the value of the skin resistance coefficient is considered valid. If not, the process is repeated until convergence is obtained.

Once convergence is achieved, equations (5-1) and (5-2) are solved to find the rate of entropy production and the dissipation of energy in the system, respectively.

The Fortran 5 computer programming language was used, and the solution was carried out on the MSU 750 Cyber computer. The ninety-two hour simulation required 25.1 seconds of Central Processing Unit (CPU) time. The output consisted of the air temperatures, product temperatures percentage mass loss of the product for each level of the storage bin. The cumulative entropy production by the products and the amount of energy dissipated were also calculated for the entire storage bin as a function of time. Printouts were initiated at intervals of four hours for the entire 92-hour simulation period.

The simulations were based on the experimental data of Misener (1973). The Nordreco data of 1975 as reported by Lerew (1976) could have provided additional reliable material for testing the model. However, the geometric dimensions of the storage bin were not documented well enough to enable the simulation of the data by this model. To get around the problem of the lack of reliable data to test the heat and mass transport portion of the model, the first 24 hours of the Misener (1973) data was used to determine η_c, with the remaining 68 hours of data being used to test the model.

The Misener experiment is described below.

5.3.1 Misener's Experimental Procedure

Misener (1973) created a vertical column by welding three 208 liter metal drums together. The column, 2.4

meters high and 0.7 meters in diameter, was wrapped with four layers of fiberglass insulation. A plenum was constructed at the base. Iron-copper thermocouples were installed along the centerline of the column, and then relayed to a multipoint Honeywell recorder. Temperatures were taken on an hourly basis. The set-up is shown in Figure 5.1.

Air was fed through the base of the column by a centrifugal fan, and the air flow rate was measured by a Flowtronic air velocity meter. Three hundred and sixty-four kilograms of freshly harvested Kennebec potatoes were loaded into the column and suberized at 15.5°C for eleven days before beginning of the experimental procedure. The entire experiment took place in a constant temperature room.

For the experiment, the potatoes were subjected to a constant volumetric air flow rate of 24 m^3/hr-m^2, with the temperature and relative humidity of the convective air held constant at 6.7°C, and 60%, respectively. To determine the moisture lost by the product, the potatoes were weighed before and after the cooling test.

A second experiment was conducted to determine whether significant temperature gradients existed in the potatoes themselves. The results of this phase of the experiment led to the conclusion that there were negligible gradients.

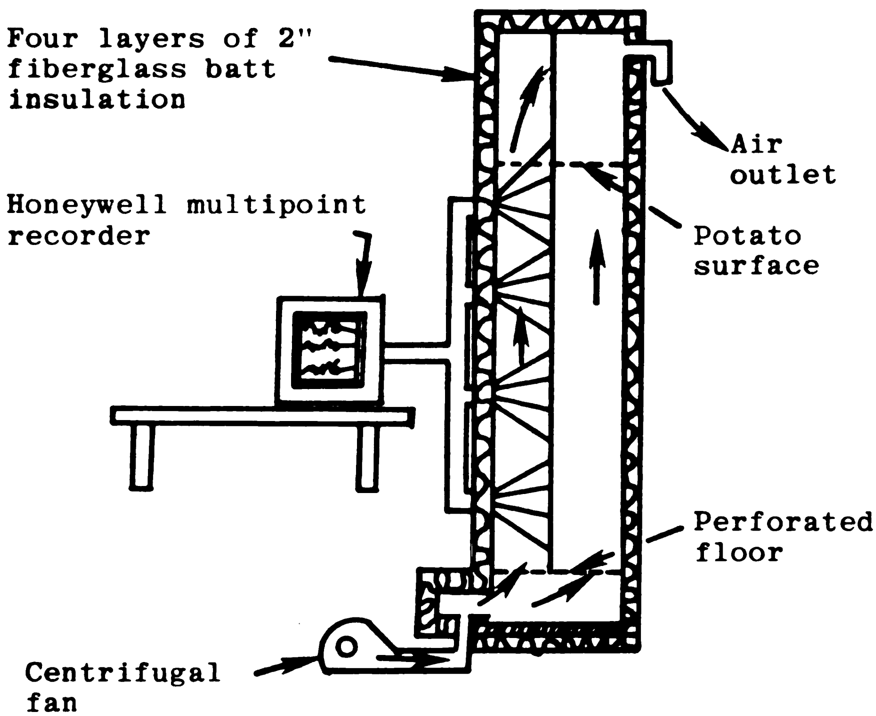

Figure 5.1 Misener's experimental set-up

5.3.2 Computer Solution Techniques

The procedure used to solve the governing field equations for the potato and air temperatures is similar to the thin layer approach often used in the solution of grain drying problems. The 2.4 meter deep storage bin was divided into twelve "thin" layers, each 0.2 m deep. The ventilation air was brought in at the entry level at 6.7°C and 60% relative humidity, and allowed to interact with the existing contents of the volume. After that, the mass lost by the product is computed, and the new temperatures for the air stream and the products in that layer are calculated. The body of ventilation air, now at a new temperature and new relative humidity, is then moved on to the next layer, where the procedure is repeated.

Although the spacing, Δx, and the time step, Δt, are independent, Δt was chosen such that

$$\Delta t = \frac{\Delta x}{u} \qquad (5\text{-}23)$$

where u is the interstitial velocity of the ventilation air. This was done so that whatever moisture is lost from the potatoes at location x and time t appears as a moisture gain for the air at the next assigned location $x + \Delta x$ after a time Δt. All of this makes the accounting much easier.

5.3.4 Computer Program Listing And Results

A complete listing of the program is provided in Appendix B. Figures 5.2 and 5.3 show typical program outputs.

S I M U L A T I O N   R E S U L T S

TIME: 4.0 HOURS

DEPTH	RATE ENT. PROD.	TOTAL ENT. PROD.	INST. DISS.	TOTAL DISS.
.2	5328.	21588.	1504404.	6101896.
.4	5475.	22131.	1549315.	6268855.
.6	5606.	22613.	1589686.	6417669.
.8	5724.	23039.	1625974.	6550139.
1.0	5829.	23417.	1658593.	6667902.
1.2	5924.	23751.	1687912.	6772440.
1.4	6008.	24046.	1714267.	6865093.
1.6	6084.	24306.	1737955.	6947071.
1.8	6153.	24534.	1759247.	7019464.
2.0	6214.	24735.	1778385.	7083255.
2.2	6268.	24910.	1795586.	7139330.
2.4	6318.	25063.	1811046.	7188482.

Figure 5.2 Program output: entropy production and energy dissipation (output from Xerox 9700)

TIME : 4.0 HOURS

DEPTH	AIR TEMP	POT. TEMP	PCT. MASS LOSS
.2	9.2	15.1	.0330
.4	9.8	15.1	.0326
.6	10.4	15.2	.0322
.8	10.9	15.2	.0319
1.0	11.4	15.2	.0316
1.2	11.8	15.2	.0313
1.4	12.2	15.3	.0311
1.6	12.5	15.3	.0308
1.8	12.8	15.3	.0306
2.0	13.1	15.3	.0304
2.2	13.3	15.3	.0303
2.4	13.5	15.3	.0301

EDI = 12.78

Figure 5.3 Program output: heat and mass transfer (output from Xerox 9700)

6.0 RESULTS AND ANALYSIS

6.1 The Resistance Coefficient for Mass Transport

From the results of the heat and mass transfer simulation, the skin resistance coefficient turns out to be a function of the reciprocal of the absolute temperature,

$$\eta = \frac{\eta_c}{R_v \; T} \tag{6-1}$$

where η_c is the combined coefficient introduced in equations (4-49) and (4-50), R_v is the gas constant for water vapor and T is the absolute temperature. From the experimental data of Misener (1973), the combined coefficient, η_c was determined to be 447.0. The coefficient η is plotted in Figure 6.1.

The result represented by equation (6-1) is a very important one for two reasons. First, the fact that η_c is a constant means that η is a function only of the temperature. This is typical of many physical coefficients which occur in nature -- the heat transfer coefficient is a prime example. Second and just as important, it enables one to transfer this model to analysis of other agricultural products subjected to forced convection. To use the model, all one has

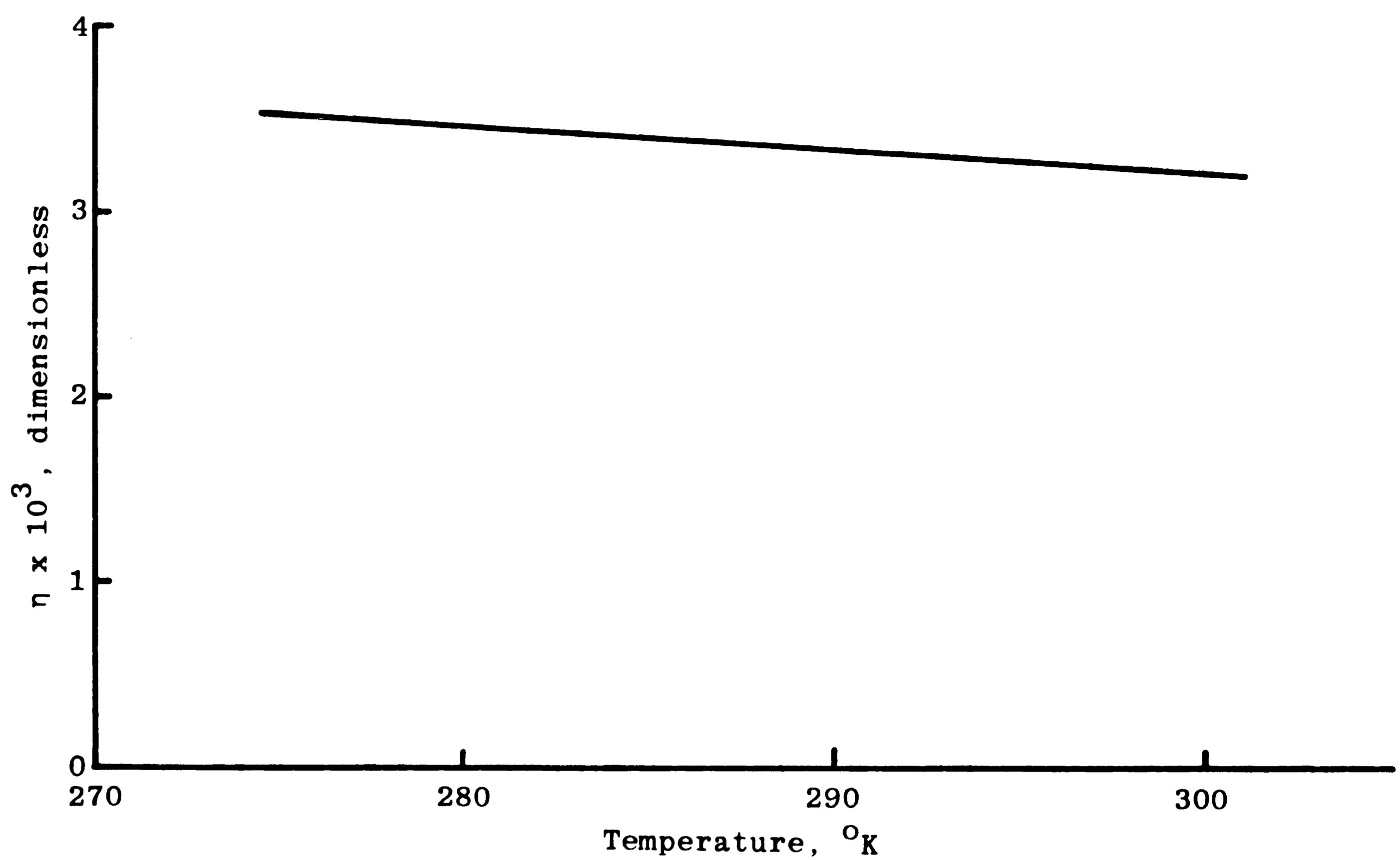

Figure 6.1 The resistance coefficient, $\eta = 447.0/RT$

to do is determine η_c from reliable experimental data.

Equation (6-1) represents the value of the coefficient that provides the best fit to Misener's experimental data. Tables 6.1 through 6.4 present the Misener (1973) experimental air temperature data from which η was determined, along with the simulation results. The deviation of the simulated temperatures from the experimental values range from 0% to 0.4%

In addition, as was explained in chapter 5, the first 24 hours of Misener's data was used to determine η_c. The model was then tested using the remainder of the data and compared to those of Lerew (1978) and Misener (1973) at 48 hours and 92 hours. The comparisons, depicted in Figures 6.2 and 6.3, show that this model performs as well as the other two models.

6.2 Entropy Production

The rate of entropy production is a smooth nearly linear profile (Figure 6.4) that reaches a steady state after 72 hours of ventilation. The rate of production ranges from 5.9 kJ/m^3-^{o}K-hr at the initiation of ventilation to a steady state value of 5.0 kJ/m^3-^{o}K-hr, with an average production rate of 5.4 kJ/m^3-^{o}K-hr for the 92-hour simulation.

The results of the simulation are presented in Table 6.5. The total entropy produced in the system is 494

Table 6.1 Comparison of simulated & experimental air temperatures at 24 hours, ^{o}K

Depth, m	Experimental	Simulated	% Diff.
0.2	279.0	279.0	0.0
0.4	280.0	280.0	0.0
0.6	281.0	281.0	0.0
0.8	282.0	282.0	0.0
1.0	283.0	283.0	0.0
1.2	285.0	284.0	-0.3
1.4	286.0	285.0	-0.3
1.6	286.0	285.0	-0.3
1.8	287.0	285.0	-0.7
2.0	288.0	286.0	-0.7
2.2	288.0	286.0	-0.7
2.4	-	287.0	-

Table 6.2 Comparison of simulated & experimental air temperatures at 48 hours, ^{o}K

Depth, m	Experimental	Simulated	% Diff.
0.2	279.0	279.0	0.0
0.4	280.0	280.0	0.0
0.6	280.0	280.0	0.0
0.8	280.0	280.0	0.0
1.0	280.0	281.0	0.4
1.2	281.0	281.0	0.0
1.4	281.0	282.0	0.4
1.6	283.0	282.0	-0.3
1.8	284.0	284.0	0.0
2.0	285.0	285.0	0.0
2.2	286.0	285.0	-0.3
2.4	287.0	286.0	-0.3

Table 6.3 Comparison of simulated & experimental air temperatures at 72 hours, ^{o}K

Depth, m	Experimental	Simulated	% Diff.
0.2	280.0	280.0	0.0
0.4	280.0	280.0	0.0
0.6	279.0	280.0	0.4
0.8	279.0	279.0	0.0
1.0	279.0	279.0	0.0
1.2	280.0	280.0	4.8
1.4	280.0	281.0	0.4
1.6	281.0	282.0	0.4
1.8	282.0	282.0	0.0
2.0	282.0	283.0	0.4
2.2	283.0	283.0	0.0
2.4	284.0	283.0	-0.3

Table 6.4 Comparison of simulated & experimental air temperatures at 92 hours, ^{o}K

Depth, m	Experimental	Simulated	% Diff.
0.2	280.0	279.0	0.4
0.4	280.0	279.0	0.4
0.6	279.0	2790.0	0.0
0.8	279.0	280.0	0.4
1.0	279.0	280.0	0.4
1.2	279.0	280.0	0.4
1.4	280.0	280.0	0.0
1.6	280.0	281.0	0.4
1.8	280.0	281.0	0.4
2.0	281.0	282.0	0.3
2.2	282.0	283.0	0.3
2.4	283.0	283.0	0.0

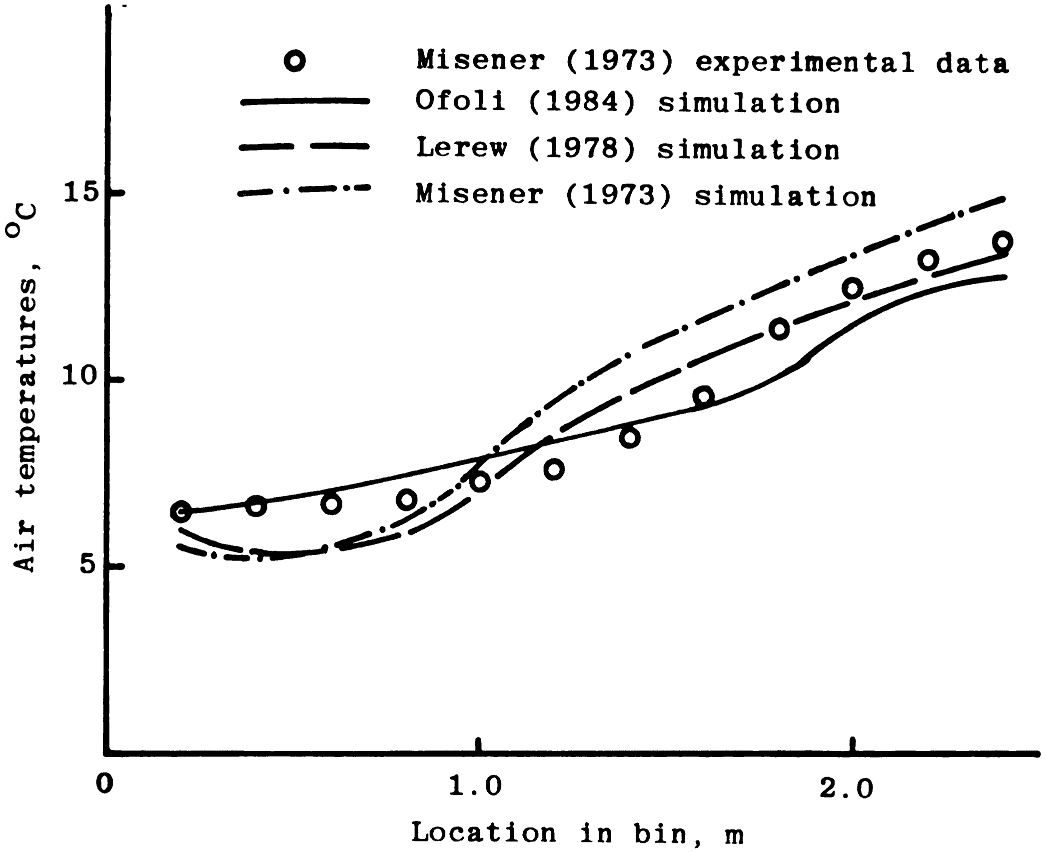

Figure 6.2 Comparison of three heat and mass transfer models at 48 hours

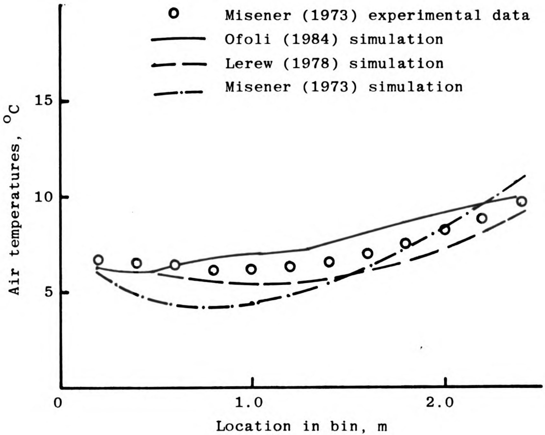

Figure 6.3 Comparison of three heat and mass transfer models at 92 hours

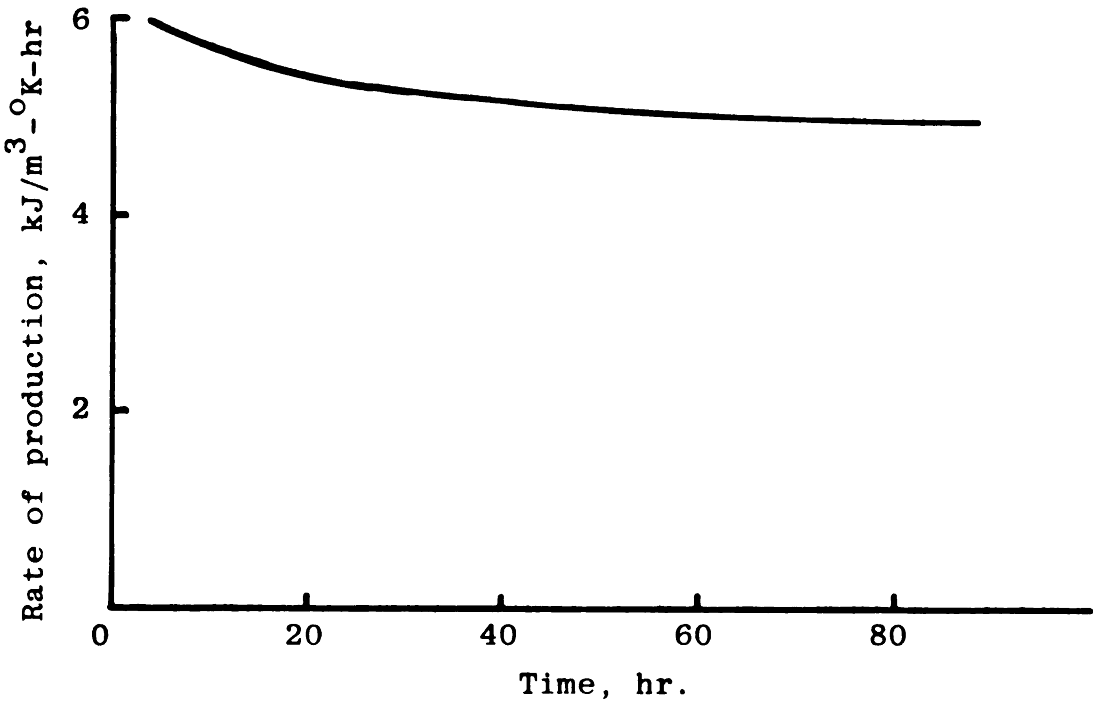

Figure 6.4 Rate of entropy production

Table 6.5 System entropy production

Time, hr	Production rate kJ/m^3-^{o}K-hr	Cumulative production kJ/m^3-^{o}K
4	5.9	24.0
8	5.8	47.0
12	5.7	69.0
16	5.6	93.0
20	5.5	115.0
24	5.5	137.0
28	5.5	160.0
32	5.4	183.0
36	5.4	205.0
40	5.4	227.0
44	5.3	248.0
48	5.2	269.0
52	5.1	290.0
56	5.1	311.0
60	5.1	331.0
64	5.1	352.0
68	5.1	372.0
72	5.0	393.0
76	5.0	413.0
80	5.0	433.0
84	5.0	453.0
88	5.0	474.0
92	5.0	493.0

kJ/m^3-^{o}K.

To help put this result in perspective, standard thermodynamic tables for moist air were used to calculate the average rate of entropy production associated with heating a given volume of air from 6.7^{o}C (the temperature of the ventilation air on entry) to 15.0^{o}C (the temperature of the exit air after 24 hours). The average rate of production was calculated to be 4.3 kJ/m^3-^{o}K-hr. In contrast, the average rate of entropy production over the first 24 hours of the simulation is 5.7 kJ/m^3-^{o}K-hr, which is 32% greater. This value is reasonable since the process involves a chemical reaction not represented in the thermodynamic tables.

The dissipation of energy in the system follows the same pattern as that of entropy production, as would be expected from equation (4-61). The rate of energy dissipation, however, reaches steady state earlier than the rate of entropy production. The steady state occurs after 48 hours of ventilation, compared to 72 hours (Figure 6.5 and Table 6.6).

6.3 Optimization By Minimizing Entropy Production

The rate of entropy production provides a key parameter for system optimization. If a given system or process can be designed to operate in a zone of minimum entropy production, the system energy dissipation would be at a minimum, leading to higher efficiencies. The variables that can be

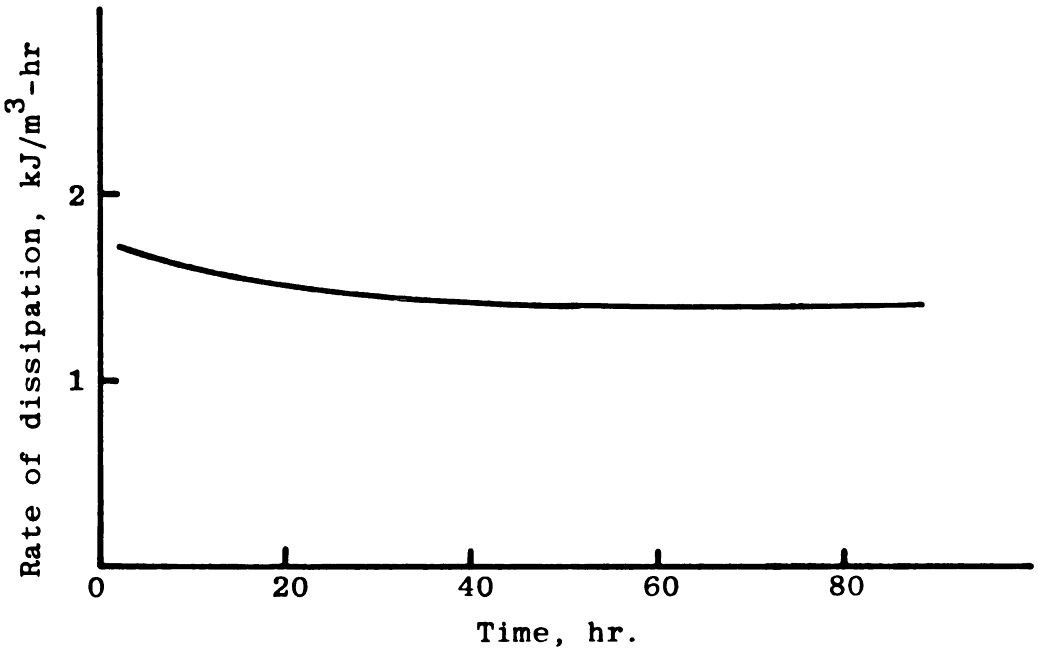

Figure 6.5 Rate of energy dissipation

Table 6.6 System dissipation of energy

Time, hr	Dissipation rate kJ/m^3-hr	Cumulative dissipation kJ/m^3
4	1.7	7.0
8	1.6	13.0
12	1.6	20.0
16	1.6	26.0
20	1.6	33.0
24	1.5	39.0
28	1.5	45.0
32	1.5	52.0
36	1.5	58.0
40	1.5	64.0
44	1.5	70.0
48	1.4	76.0
52	1.4	82.0
56	1.4	88.0
60	1.4	94.0
64	1.4	100.0
68	1.4	105.0
72	1.4	111.0
76	1.4	117.0
80	1.4	123.0
84	1.4	128.0
88	1.4	134.0
92	1.4	139.0

manipulated to provide the minimum entropy production would vary from system to system.

The rate of entropy production for the system under analysis in this thesis is given by equation (5-1) and can be represented as

$$\sigma = \frac{h}{L} - \frac{D_{AB}\, \rho\, f_p\, u_s^2}{3\, D\, L\, \epsilon^2\, T} + \frac{2\, D_{AB}\, R\, \rho}{D\, L} + \frac{h_D\, \rho\, f_p^2\, u_s^4}{36\, g\, D\, L\, \epsilon^4\, T}$$

$$- \frac{h_D\, \rho\, R\, f_p\, u_s^2}{3\, g\, D\, L\, \epsilon^2} + \frac{h_D\, \rho\, R^2 T}{g\, D\, L} + \frac{J_{ch}\, A}{T} \qquad (6\text{-}2)$$

It is apparent from equation (6-2) that σ is a function of both the velocity and the temperature. The dependence on temperature is, however, not as pronounced as the dependence on velocity. Under normal modes of cooling, most agricultural storages operate in a limited range of temperatures. In addition, equation (6-2) contains several terms involving powers of the velocity. Given these circumstances, it would appear that the minimization of the rate of entropy production can be done most effectively through control of the ventilation rates.

One might be tempted to approach the optimization problem by taking the partial derivative of equation (6-2) with respect to the velocity and, using the standard practice of calculus, determine the velocity at which the derivative is zero. While this approach is mathematically appealing, it would be physically meaningless because it would imply that the temperatures in the storage volume remain constant over a range of ventilation rates, a situation that does not occur in practice.

The global entropy production is

$$\Delta S = \int_t \int_V \sigma \, dV \, dt \tag{6-3}$$

and the total dissipation of energy is

$$\Phi = A_t \int_t \int_x \Gamma \, dx \, dt \tag{6-4}$$

where ΔS is the total change in entropy of the system, Φ is the dissipation function and A_t is the total cross-sectional area of the system, a constant.

Since

$$\Gamma = \sigma T, \tag{6-5}$$

the expression for σ in equation (6-2) multiplied by the appropriate absolute temperature can be substituted in equation (6-4) and the equation can be integrated over the length of the bin and over a specified length of time to obtain the total system energy dissipation.

This approach enables one to define a dimensionless energy dissipation index (EDI) such that

$$EDI = \frac{\Phi}{p \, A_{ac} \, u_i \, t} \tag{6-6}$$

where p is the internal pressure, A_{ac} is the cross-sectional area available for air flow, u_i is the interstitial velocity and t is the elapsed time.

From a force balance, the internal pressure is related to the known external atmospheric pressure, p_a, by

$$p = \frac{p_a}{\epsilon} \tag{6-7}$$

where ϵ is the porosity of the porous medium.

Equation (6-6) thus measures the energy dissipation through entropy production against the external energy input required to move the ventilation air. This approach normalizes the result for all ventilation rates and thus allows direct comparisons to be made.

The solution of equation (6-6) for various ventilation rates and for four different inlet temperature conditions is plotted in Figure 6.6. The four conditions used are inlet ventilation air temperatures of 3°C, 6.7°C (the temperature of the ventilation air for Misener's data), 10°C and a sinusoidal inlet temperature that satisfies the equation

$$\theta = 6.0 + 6.0 \sin \frac{\pi t}{12} \tag{6-8}$$

where t is the elapsed time in hours. Equation (6-8) represents an inlet temperature that oscillates between 0°C and 12°C, with a 24-hour period.

The optimum ventilation rate for the inlet condition under which the data was collected is 22 m^3/m^2-hr. Given the size of the experimental storage volume and the high porosity, this rate is quite reasonable. The zone of optimum ventilation rates ranges from about 20 to 25 m^3/m^2-hr. The optimum ventilation rates for the 3°C, 10°C and

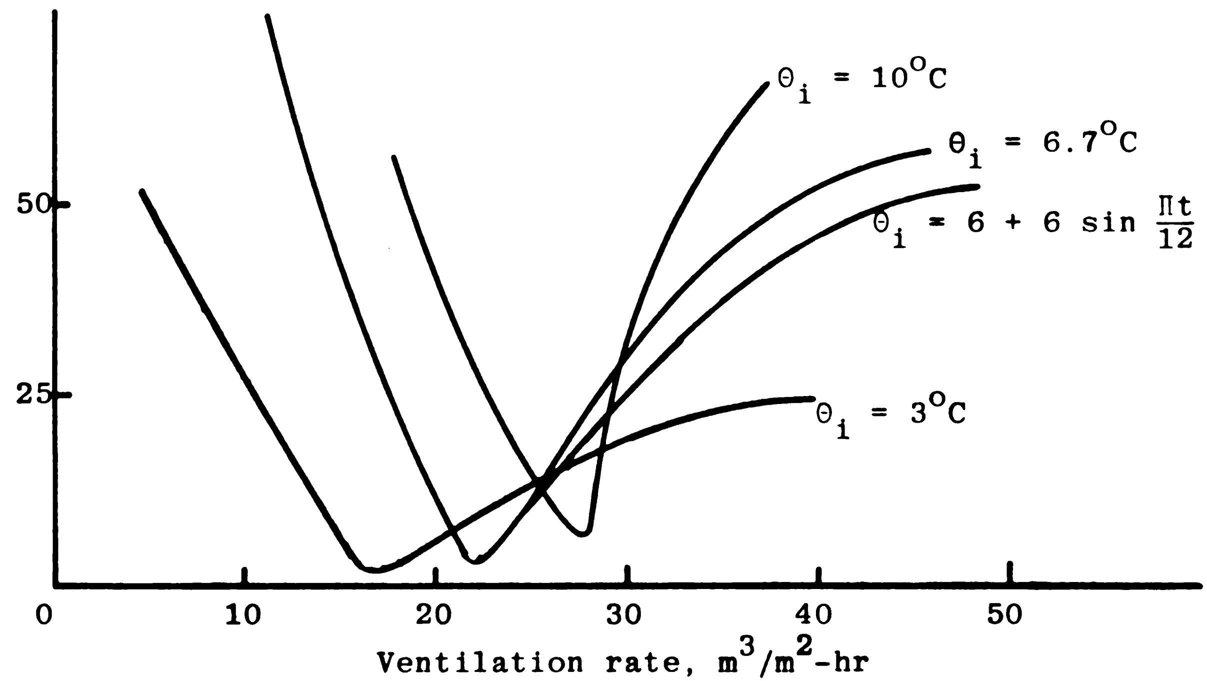

Figure 6.6 Energy dissipation index (EDI) for various ventilation rates at four different inlet temperature (Θ_i) conditions.

sinusoidal conditions are 17, 28 and 22 m^3/m^2-hr, respectively. The fact that the EDI curve for the sinusoidal condition is essentially the same as the one for the 6.7°C entry condition is to be expected, since the mean temperature for the sinusoidal condition is 6°C.

These results suggest strongly that, from at least a heat transfer point of view, the EDI can be effectively used to optimize the ventilation rate. The optimum ventilation rates predicted by the EDI are very logical: a lower volumetric flow rate of air is required for cooling the potatoes when outside air is available at 3°C than when it is available at 10°C. The shapes of the curves also suggest that the need for optimization is more critical at high ventilation rates than at lower rates. The steepness of the EDI curves indicate that at high ventilation rates, the effect of the ventilation rate on the EDI coefficient is more pronounced.

It must be pointed out, however, that these results are viewed only from the point of view of energy dissipation. Another important factor that must be considered is the effect of the ventilation rates on product quality. The quality factor was not considered in this thesis because of the inherent difficulties in characterizing "quality" mathematically. The information represented by Figure 6.6 would seem to indicate that the EDI does account in some measure for the cooling rates of the potatoes, although it may not totally account for the rate of mass loss.

6.4 The Effect of Thermal Diffusion

The last term of the equation for the rate of mass transfer (equation 5-6) includes the Soret coefficient. The Soret coefficient is a measure of the importance of the phenomenon of thermal diffusion. The second term on the right hand side of the equation for the rate of local entropy production (equation 5-1) incorporates the cross-phenomenological coefficient which is a function of the Soret coefficient (equation 4-52). It is of interest to assess the effect of the thermal diffusion phenomenon on the analysis done in this study.

Simulation results indicate that setting the Soret coefficient to zero has a negligible effect on both the product mass loss and the temperature profile in the storage environment. It does reduce the rate of entropy production by 9%, thus reducing the magnitude of the EDI. However, the location of the minimum value of the EDI with respect to the ventilation rate does not change. Thus the essential results of this study are unaffected by the Soret coefficient.

Since the EDI is designed to be a measure of the relative (rather than the absolute) rate of entropy production, these results would suggest that the effect of thermal diffusion is negligible for the type of system analyzed in this thesis.

7.0 CONCLUSIONS

A model for entropy production and energy dissipation in the storage environment of agricultural products has been derived using the principles of the thermodynamics of irreversible processes. The model includes a scheme for optimizing the rate of ventilation, based on the principle of minimum entropy production.

To compute the entropy production within the storage environment, equations for heat transfer, mass transfer and chemical reaction (respiration) were derived and solved. The results of the heat and mass transfer part of the model compare favorably with those obtained by Misener (1973) and Lerew (1978).

It has been shown that non-equilibrium thermodynamics can be used for the analysis of heat and mass transport in the storage environment of agricultural products. The heat and mass transport part of the problem requires a single temperature-dependent coefficient -- the skin resistance coefficient. This method of analysis is applicable to other forced-air ventilation systems if reliable data is available to determine the skin resistance coefficient.

The optimization scheme is based on a single parameter -- the energy dissipation index (EDI). The EDI is defined as the ratio of the total energy dissipated by the system to the input energy required to move the ventilation air. Under this definition, minimum entropy production and energy dissipation occur at the minimum value of the EDI. Simulation results indicate that this parameter may be a useful tool for system optimization.

Setting the Soret coefficient (D^T) to zero (thus neglecting the contribution of thermal diffusion to mass transfer) has little effect on the mass loss and the temperature profile in the storage environment, but it reduces the rate of entropy production by 9%. Although the lower rate of entropy production reduces the magnitude of the EDI, the position of the minimum value of the EDI with respect to the ventilation rate does not change. Thus the phenomenon of thermal diffusion can be neglected without changing the essential results of this study.

8.0 SUGGESTIONS FOR FUTURE RESEARCH

Possible applications of irreversible thermodynamics in agricultural engineering are many and varied. This thesis has explored only one such application. Further applications lie in the areas of food processing and in the controlled environmental storage of agricultural products.

It is suggested that the methodology also be used in analyzing physiological responses in animals to various stimuli through a study of muscle movement as has been done with human muscle in the fields of bio-engineering.

The area of biotechnology is becoming important for agricultural engineering. As Dr. Norman Scott of Cornell University remarked at the 1984 American Society of Agricultural Engineers (ASAE) summer meeting in Knoxville, Tennessee, the role of agricultural enginners in this relatively new field would not be genetic improvements, but rather the modeling of biotechnological systems. Since the area is fairly new and all the required kinetic equations have not yet been developed, the field appears to be ripe for modeling and analysis by irreversible thermodynamics. It is an area of endeavor that would be worth pursuing.

APPENDIX A

APPENDIX A

EXPRESSION FOR THE MASS DIFFUSIVITY

In a binary system, the mass diffusivity of component A in relation to component B, D_{AB}, has the relationship

$$D_{AB} = D_{BA} = D_G \qquad \text{(A-1)}$$

where D_G is the diffusivity of the gas.

D_G can be calculated for the diffusion of water vapor into moist air by using the kinetic theory of gases (Perry & Chilton, 1973). Wilke and Lee's 1955 modification of the equation by Hirschfelder, Bird and Spotz (derived in 1949) is used in this study. This modification, which gives a fairly accurate estimate of the diffusion coefficient, is

$$D_G = \frac{B\ \theta^{3/2} \sqrt{\frac{1}{M_1} + \frac{1}{M_2}}}{P\ r_{12}^{\ 2}\ I_D} \qquad \text{(A-2)}$$

where

$$B = (10.7 - 2.46 \sqrt{\frac{1}{M_1} + \frac{1}{M_2}} \times 10^{-4}) \qquad \text{(A-3)}$$

and the M_i are the molecular weights of the two gas components involved. P represents the absolute pressure in atmospheres, and r_{12} is the collision diameter in angstroms, computed as

$$r_{12} = \frac{(r_o)_1 + (r_o)_2}{2} \qquad \text{(A-4)}$$

where the r_i are the collision diameters of the respective gases.

From Perry and Chilton (1973),

$$r_o = 1.18\ V_b^{1/3} \qquad \text{(A-5)}$$

where V_b is the molar volume of the liquid at its normal boiling point. For water vapor, V_b = 18.9 cc/g-mole, and for air, V_b = 29.9 cc/g-mole (Perry & Chilton, 1973).

I_D, in eq. (A-2) is the collision integral for diffusion, and is a function of $k\theta/\epsilon_{12}$, where ϵ_{12}, the energy of molecular interactions, is given by (Perry & Chilton, 1973)

$$\epsilon_{12} = \sqrt{\epsilon_1\ \epsilon_2} \qquad \text{(A-6)}$$

and k is the Boltzman constant, 1.38 x 10^{-6} erg/K.

Using tabulated values from Perry and Chilton (1973), the following temperature-dependent relationship was derived for I_D, the collision integral,

$$I_D = T^{-0.09007} - 6.3 \times 10^{-4}\ T + 0.1764 \qquad \text{(A-7)}$$

Using eq. (A-7) to calculate values of the collision integral in the temperature range $0^{\circ}C \leq t \leq 40^{\circ}C$ results in an absolute error of less than 0.4%. The use of eq. (A-2) provides accuracies within 7-8% for most systems (Perry & Chilton, 1973).

APPENDIX B

APPENDIX B

```
      PROGRAM OFOLI (INPUT,OUTPUT,TAPE4=INPUT,TAPE6=OUTPUT)
C
C DEFINITION OF VARIABLES
C
C    A       :  CHEMICAL AFFINITY
C    AC      :  TOTAL CROSS-SECTIONAL AREA
C    AK      :  AIR CONDUCTIVITY
C    ALP     :  POTATO SURFACE AREA PER LINEAR METER
C    AM      :  AIR MASS AT ENTRY POINT
C    AS      :  SURFACE AREA OF POTATOES IN ELEMENT
C    CAPA    :  MASS OF AIR IN BIN PER LINEAR METER
C    CAPP    :  MASS OF POTATO PER LINEAR METER
C    CL      :  CHARACTERISTIC DIMENSION
C    CMP     :  CURRENT MASS OF WATER IN POTATO
C    CUMDIS  :  CUMULATIVE ENERGY DISSIPATION
C    CVA     :  HEAT CAPACITY OF AIR
C    CVP     :  HEAT CAPACITY OF POTATO
C    CVV     :  HEAT CAPACITY OF WATER VAPOR
C    CVW     :  HEAT CAPACITY OF LIQUID WATER
C    D       :  DIAMETER OF BIN
C    DAB     :  MASS DIFFUSIVITY
C    DELT    :  TEMPERATURE DIFFERENCE
C    DEPTH   :  BIN DEPTH
C    DISS    :  INSTANTANEOUS ENERGY DISSIPATION
C    DS      :  DIAMETER OF SPHERICAL POTATO
C    DST     :  SORET COEFFICIENT
C    DT      :  TIME STEP
C    DTDX    :  SPATIAL DERIVATIVE OF AIR TEMPERATURE
C    EP      :  POROSITY
C    ETA     :  OFOLI COEFFICIENT
C    FP      :  FRICTION FACTOR
C    FR      :  PERCENTAGE MASS LOSS
C    G       :  GRAVITATIONAL ACCELERATION
C    H       :  HEAT TRANSFER COEFFICIENT
C    HD      :  MASS TRANSFER COEFFICIENT
C    HFG     :  HEAT OF VAPORIZATION
C    HR      :  HUMIDITY RATIO
C    JCH     :  REACTION VELOCITY
C    LKK     :  MASS TRANSFER PHENOMENOLOGICAL COEFF.
C    LQK     :  CROSS-KINETIC PHENOMENOLOGICAL COEFF.
C    LQQ     :  HEAT TRANSFER PHENOMENOLOGICAL COEFF.
C    MC      :  MOISTURE CONTENT OF POTATO
C    M       :  TOTAL MASS LOSS
C    N       :  NUMBER OF THIN LAYERS
C    NMA     :  MOLES OF AIR ON ENTRY
C    P       :  ATMOSPHERIC PRESSURE
C    PHI     :  RELATIVE HUMIDITY
C    PD      :  POTATO DENSITY
C    PSAT    :  SATURATION PRESSURE
C    PTM     :  INITIAL TOTAL MASS OF POTATOES
C    PV      :  VAPOR PRESSURE
C    Q       :  RATE OF HEAT GENERATION
C    R       :  UNIVERSAL GAS CONSTANT
C    RE      :  REYNOLDS NUMBER
C    RHOA    :  AIR DENSITY
C    RV      :  GAS CONSTANT FOR WATER VAPOR
C    S       :  RATE OF TOTAL MASS LOSS
```

```
C    SAPA   :  MASS OF WATER IN AIR PER LINEAR METER
C    SAPP   :  MASS OF WATER IN POTATO PER LINEAR METER
C    SDIFF  :  RATE OF CONVECTIVE MASS LOSS
C    SMP    :  SOLID MASS OF POTATO
C    ST     :  TOTAL SURFACE AREA
C    STHERM :  RATE OF MASS LOSS BY THERMAL DIFFUSION
C    SVEL   :  SUPERFICIAL VELOCITY
C    T      :  TIME
C    TA     :  AIR TEMPERATURE
C    TP     :  POTATO TEMPERATURE
C    TAU    :  SHEAR STRESS
C    TDISS  :  TOTAL DISSIPATION OF ENERGY
C    TENTP  :  TOTAL ENTROPY PRODUCTION
C    THETA  :  ABSOLUTE AIR TEMPERATURE
C    THETAP :  ABSOLUTE POTATO TEMPERATURE
C    TML    :  CUMULATIVE MASS LOSS
C    TPI    :  INITIAL POTATO TEMPERATURE
C    VA     :  VOLUME OF AIR
C    VAT    :  VENTILATION AIR TEMPERATURE
C    VEL    :  AIR FLOW VELOCITY
C    VENT   :  VENTILATION RATE
C    VE     :  VOLUME OF ELEMENT
C    VOL    :  VOLUME OF STORAGE ENVIRONMENT
C    VP     :  VOLUME OF POTATO
C    WMA    :  WATER MASS IN AIR
C    WMP    :  WATER MASS IN POTATO
C    X      :  TIME RATE OF CHANGE OF POTATO TEMPERATURE
C    XI     :  RATE OF ENTROPY PRODUCTION
C    Y      :  TIME RATE OF CHANGE OF AIR TEMPERATURE
      DIMENSION DELT (12), DISS (12), TDISS (12), S (12), TA (12)
      DIMENSION TP (12), TML (12), XI (12), TENTP (12), FR (12)
      REAL MC, NMA, LKK, LQK, LQQ, MT (12), JCH
C     CALCULATE OR INPUT ALL PROGRAM PARAMETERS
      N = 12
      VAT = 6.7
      PHI = 0.6
      MC = 0.8
      PI = 3.1416
      CL = 0.2
      DT = 0.00534
      TPI = 15.5
      R = 8.314
      EP = 0.641
      RHOA = 1.246
      AK = 90.0
      D = 0.7
      DS = 0.063
      G = 9.81
      DAB = 0.0742
      AC = PI * D * D / 4.0
      VE = 0.077
      VA = 0.049
      VP = 0.028
      AS = 0.0987
      ALP = AS / CL
      ST = 1.184
      CVA = 1007.0
      CVV = 1880.0
      CVW = 4184.0
      CVP = 1430.0
      RV = 462.0
```

```
      HFG = 2470000.0
      PD = 394.0
      P = 101353.0
      JCH = 0.025
      A = 26600000.0
C     INITIAL TOTAL MASS OF POTATOES
      PTM = PD * VE
C     INITIAL MASS OF WATER IN POTATO
      WMP = PTM * MC
C     SOLID MASS OF POTATOES
      SMP = PTM * (1.0 - MC)
C     INITIAL MASS OF WATER IN THE AIR
      NMA = P * VA / (R * (VAT + 273.15))
      PSAT = EXP (60.08 - 6814.03 / (VAT + 273.15) -
     +5.12 * LOG (VAT + 273.15))
      HR = 0.622 * PHI * PSAT / (P - PHI * PSAT)
      AM = 29.0 * NMA / 1000.
      WMA = 29.0 * NMA * HR / 1000.
      VENT = 24.0
C    BEGIN VELOCITY LOOP
      SVEL = VENT
      VEL = VENT / EP
      WRITE (6,5) VENT
5     FORMAT ('1', //////////////, T49, 'SIMULATION AT  ', F4.1,
     + 1X, 'M**3/M**2-HR')
C     CALCULATE PROGRAM VARIABLES
      RE = 13.755 * SVEL / (1 - EP)
      FP = 150.0/RE + 1.75
      TAU = (FP * SVEL * SVEL * RHOA)/(6.0*EP*EP)
      H = 0.165 * (RE **0.6) * AK / DS
      HD = 0.000896 * H
C     INITIALIZE TEMPERATURES
      DO 15 I = 1, N
      DO 15 J =1,N
      TA (I) = 15.5
15    TP (I) = TPI
C     START TIME LOOP
      T = 0.0
      L = 0
      DO 18 I = 1, N
      TENTP (I) = 0.0
      TDISS (I) = 0.0
18    TML (I) = 0.0
C     CALCULATE PROGRAM PARAMETERS
      CAPP = SMP / CL
      SAPP = WMP / CL
      CAPA = AM / CL
      SAPA = WMA / CL
      DIV1 = SAPP * CVW + CAPP * CVP
      DIV2 = SAPA * CVV + CAPA * CVA
      CA = H * ALP / DIV1
      SA = HFG / DIV1
      SB = (RV + CVV) / DIV1
      SC = CVV / DIV1
      CC = H * ALP / DIV2
      SD = RV / DIV2
      SF1 = ALP * HD * RHOA / (G * D)
      SF2 = ALP * HD * TAU / (G * D)
      VOL = 0.924
      ETA = 447.0
      DO 100 J = 1, 750
```

```
      T = T + DT
      PAC = 0.385 * P * VEL * T
      L = L + 1
C
C    CALCULATE DRIVING FORCES
C      CONCENTRATION
      M = N
      IF (J .LE. N) M = J
      IF (L .EQ. 750) THEN
C   CALCULATE THE ENERGY DISSIPATION INDEX
      CUMDIS = 0.0
      DO 1 NT = 1, N
      CUMDIS = CUMDIS + TDISS (NT)
1     CONTINUE
      EDI = CUMDIS * VOL / PAC
      WRITE (6,25) T
25    FORMAT ('1', /////, T52, 'S I M U L A T I O N   R E S U L T S
     +',/////, T62, 'TIME: ', F4.1, ' HOURS', /)
      END IF
      DEPTH = 0.0
      DO 30 I = 1, M
      DEPTH = DEPTH + 0.2
      Q = 5.6 * TP (I) + 21.4
      CMP = WMP - TML (I)
C
C    CALCULATE MASS LOSS
      THETA = (TA (I) + 273.15)
      THETAP = (TP (I) + 273.15)
      DST = DAB * RHOA / THETAP
      LKK = HD * RHOA / (3600. * 3600. * G * D)
      LQK = DST * THETAP / D
      LQQ = H * TA (I)
      DELT (I) = TP (I) - TA (I)
      SF = SF1 * ETA - SF2
      SE = ALP * DST / D
      SDIFF = SF * CL
      STHERM = SE * CL * DELT (I)
      S (I) = SDIFF + STHERM
      XI (I) = LQQ/(CL * THETA) - (2.0*LQK / (CL * THETA))
     + * (TAU / (3600. * 3600. * RHOA) - RV * THETA)
     + + (LKK / (CL * THETA)) * ((TAU / (3600. * 3600. * RHOA)
     + - RV * THETA) ** 2) + JCH * A / THETA
      TENTP (I) = TENTP (I) + XI (I) * DT
      DISS (I) = XI (I) * (TA (I) + 273.15)
      TDISS (I) = TDISS (I) + DISS (I) * DT
      TML (I) = TML (I) + S (I) * DT
C    CALCULATE TEMPERATURE GRADIENTS AND NEW TEMPERATURES
C      AIR TEMPERATURES
      IF (I .EQ. 1) THEN
      DTDX = 0.7 / CL
      IF (J .GT. 4496) DTDX = 0.4 / CL
      ELSE
      DTDX = (TA (I) - TA (I-1)) / CL
      END IF
      CB = Q * (CAPP + SAPP) / DIV1
C   AIR TEMPERATURES
      Y = -SE * SD * TA (I) * TA (I) + (SD * SF - CC) * TA (I)
     + + SE * SD * TA (I) * TP (I) + CC * TP (I)
     + - VEL * DTDX
C   POTATO TEMPERATURES
      X = (CA - SB * SF + SA * SE) * TA (I)
```

```
     + - (CA - SC * SF + SA * SE) * TP (I)
     + + (SE * SC - SE * SB) * TA (I) * TP (I)
     + + SE * SB * TA (I) * TA (I) - SE * SC * TP (I) * TP (I)
     + + CB - SA * SF
      TA (I) = TA (I) + Y * DT
      TP (I) = TP (I) + X * DT
30    CONTINUE
C    WRITE RESULTS
C   PRINT VALUES EVERY FOUR HOURS
C
      IF (L .EQ. 750) THEN
      L = 0
      WRITE (6, 37)
37    FORMAT (/, T30, 'DEPTH', T41, 'RATE ENT. PROD.', T62,
     + 'TOTAL ENT. PROD.', T84, 'INST. DISS.', T101,
     + 'TOTAL DISS.', //)
      DEPTH = 0.0
      DO 39 K = 1, M
      DEPTH = DEPTH + 0.2
      WRITE (6,38) DEPTH, XI (K), TENTP (K), DISS (K), TDISS (K)
38    FORMAT (//, T31, F3.1, T44, F7.0, T66, F7.0, T84, F10.0,
     + T99, F12.0)
39    CONTINUE
      WRITE (6,40) T
40    FORMAT ('1', /////, T44, 'TIME : ', F4.1, 2X, 'HOURS')
      WRITE (6,50)
50    FORMAT (//, T27, 'DEPTH', 5X, 'AIR TEMP', 5X, 'POT. TEMP',
     + 5X, 'PCT. MASS LOSS',/)
      DEPTH = 0.0
      DO 70 K = 1, M
      DEPTH = DEPTH + 0.2
      FR (K) = TML (K) * 100.0 / PTM
      WRITE (6, 60) DEPTH, TA (K), TP (K), FR (K)
60    FORMAT (//, T28, F3.1, T39, F4.1, T53, F4.1, T68, F6.4)
70    CONTINUE
      WRITE (6,2) EDI
2     FORMAT (//////, T47, 'EDI =', F6.2)
      END IF
100   CONTINUE
      STOP
      END
```

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BIBLIOGRAPHY

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