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FOOD REFRIGERATION PROCESSES

ANALYSIS, DESIGN AND SIMULATION

ANDREW C. CLELAND

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ANDREW C. CLELAND

Department of Biotechnology, Massey University,
Palmerston North, New Zealand

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PREFACE

The application of refrigeration to food processing is one of many situations in the food industry in which a multidisciplinary approach is well suited to rapid solution of design and operational problems. The requirements of the refrigeration process are defined by the fragile nature of the biological material being chilled, frozen or stored. These are usually the realm of the food scientist or food technologist. Selection of process conditions for the chilling, freezing or storage process (e.g. air temperature, air velocity, relative humidity) is most often the realm of the food engineer. Design of the refrigeration system to achieve the process conditions can be carried out by a chemical or mechanical engineer, but the details of construction of buildings, pipework, etc., are normally the domain of the mechanical engineer. A complete process design or analysis requires interaction of all these disciplines.

Whilst most food engineering texts and reference works consider low temperature preservation (the application of refrigeration) in detail there is rarely any detailed analysis of how the refrigeration effect is created. I consider this to be an unbalanced approach since my experience suggests that the largest operating cost of a chiller, freezer or cold store is usually the energy needed to run the refrigeration system. It is as important to know whether refrigeration is being efficiently produced as it is to know that it is efficiently applied.

Broad-based research that simultaneously consider both the creation and application of refrigeration in the food industry is valuable. It provides insights that are not easily obtained by separate consideration of the mechanical refrigeration plant on the one hand and the chillers, freezers and cold stores on the other. The study must include the process dynamics because the interactions within the complete system are often so complex that the food product is never exposed to stable conditions during processing. Modelling of complete systems has not been extensively researched in the past, but there are already a number of important publications that have improved knowledge of the processes involved. In this volume I have tried to draw them together so that others can build better understanding of the methodology needed for the analysis, design and simulation of food refrigeration systems.

Within the design process for complete systems, one of the most difficult steps is to establish the rate of chilling or freezing of products in which the internal heat transfer is by conduction and for which the major mode of heat transfer at the product surface is convection. Modelling of the processes involved is complicated by factors such as irregular product shape, phase change in the case of freezing and, sometimes, significant evaporative heat transfer at the product surface. A wide variety of approaches for overcoming these and related problems have been tried. As a result, the literature covering freezing and chilling time prediction is both complex and substantial. In view of the importance attached to the subject by both researchers and industrial refrigeration engineers, detailed analysis of freezing and chilling time prediction methods was considered to be justified, so a major part of this volume has been dedicated to the subject.

ANDREW C. CLELAND

NOMENCLATURE

a	Numerical coefficient
a_w	Water activity
A	Area (m^2)
A_b	Fittings and structures surface area (m^2)
A_p	Product surface area (m^2)
b	Fraction of water existing as ice
Bi	Biot number = $h_e R/k$ (chilling); = $h_e D/k_s$ (freezing); $=h_e D/k_l$ (thawing)
c	Specific heat capacity (J/kg K)
c_a	Specific heat capacity of dry air (J/kg K)
c_b	Mean specific heat capacity of fittings, etc. (J/kg K)
c_c	Condenser coolant specific heat capacity (J/kg K)
c_l	Specific heat capacity of unfrozen material (J/kg K)
c_p	Specific heat capacity of product (J/kg K)
c_{pv}	Specific heat capacity of water vapour (J/kg K)
c_s	Specific heat capacity of frozen material (J/kg K)
C	Volumetric specific heat capacity (J/m^3K)
C_l	Volumetric specific heat capacity of unfrozen material (J/m^3K)
C_s	Volumetric specific heat capacity of frozen material (J/m^3K)
$\mathbf{C}$	Element capacitance matrix
D	Object diameter or characteristic dimension = $2R$ (m)
E	Equivalent heat transfer dimensionality
E_{ref}	Equivalent heat transfer dimensionality for reference shape

f	Time for 90% reduction in Y (s or h)
F_{12}	Radiation view factor
Fo	Fourier number = kt/CR^2
g	Ratio of mean conducting path length to radius
G	Geometry index
G_1	Parameter used in calculation of E and g
G_2	Parameter used in calculation of E and g
G_3	Parameter used in calculation of E and g
h	Enthalpy (J/kg)
h_a	Air enthalpy (J/kg)
h_c	Convection heat transfer coefficient (W/m^{2}K)
h_e	Surface (external) heat transfer coefficient (W/m^{2}K)
h_l	Liquid refrigerant enthalpy (J/kg)
h_r	Pseudo-convection heat transfer coefficient for radiation (W/m^{2}K)
h_{ri}	Enthalpy of refrigerant entering vessel (J/kg)
h_{ro}	Enthalpy of refrigerant leaving vessel (J/kg)
h_s	Enthalpy of saturated air at product surface temperature (J/kg)
h_v	Vaporised refrigerant enthalpy (J/kg)
h_1	Convection heat transfer coefficient in boiling refrigerant (W/m^{2}K)
h_2	Convection heat transfer coefficient between water and ice surface (W/m^{2}K)
Δh_{comp}	Refrigerant enthalpy change in isentropic compression (J/kg)
Δh_{cond}	Refrigerant enthalpy change in a condenser (J/kg)
Δh_{evap}	Refrigerant enthalpy change in an evaporator (J/kg)
Δh_f	Latent heat of freezing (J/kg)
Δh_{10}	Enthalpy change from T_f to –10°C (J/kg)
H	Enthalpy on a volumetric basis (J/m^3)
ΔH	Enthalpy change (J/m^3)
ΔH_f	Latent heat of freezing (J/m^3)
ΔH_{ref}	Enthalpy change from T_f to T_{ref} (J/m^3)
ΔH_{10}	Enthalpy change from T_f to –10°C (J/m^3)
H_a	Air absolute humidity or humidity ratio (kg water vapour/kg dry air)
H_e	Saturation humidity corresponding to T_e (kg/kg)
H_{ein}	Air absolute humidity onto a cooling unit (kg/kg)

H_{eout}	Air absolute humidity off a cooling unit (kg/kg)
H_{es}	Saturation humidity corresponding to T_{es} (kg/kg)
H_{ext}	Air absolute humidity beyond a room (kg/kg)
H_r	Relative humidity
i	Time level in numerical calculations
I	Parameter used in variational statement of Fourier equation
I_c	Parameter used in variational statement of Fourier equation
I_k	Parameter used in variational statement of Fourier equation
j	Space position in x direction in numerical calculations
j_{av}	Lag factor for mass-average temperature
j_c	Lag factor for centre position
J_0	Zero-order Bessel's function
J_1	First-order Bessel's function
k	Thermal conductivity (W/mK)
k_g	Mass transfer coefficient (s/m)
k_i	Thermal conductivity of ith component (W/mK)
k_{ice}	Thermal conductivity of ice (W/mK)
k_l	Thermal conductivity of unfrozen material (W/mK)
k_s	Thermal conductivity of frozen material (W/mK)
k_w	Thermal conductivity of metal wall (W/mK)
k_1	Thermal conductivity of continuous phase (W/mK)
k_2	Thermal conductivity of dispersed phase (W/mK)
K	Fitted constant
$\mathbf{K}$	Global conductance matrix
L	Latent heat of evaporation/freezing/sublimation (J/kg)
L_x	Dimension of object in x direction (m)
L_y	Dimension of object in y direction (m)
L_z	Dimension of object in z direction (m)
L_1	Perimeter of first orthogonal cross-section (m)
L_2	Perimeter of second orthogonal cross-section (m)
m	Space position in y direction in numerical calculations
m_a	Air mass flow rate over cooling unit (kg/s)
m_c	Condenser coolant mass flow rate (kg/s)
m_r	Refrigerant mass flow rate (kg/s)
m_{ri}	Inlet refrigerant mass flow rate from vessel (kg/s)
m_{ro}	Outlet refrigerant mass flow rate from vessel (kg/s)
m_w	Mass flow rate of water (kg/s)
M	Mass (kg)

M_a	Mass of air (kg)
M_b	Mass of fittings and structures (kg)
M_p	Product mass (kg)
M_t	Total mass in system (kg)
M_w	Mass of liquid water in system (kg)
M_1	Parameter used in calculation of g
M_2	Parameter used in calculation of g
M_3	Parameter used in calculation of g
$(Mc)_a$	Thermal capacity of air in a refrigerated room (J/K)
$(Mc)_c$	Thermal capacity of a condenser (J/K)
$(Mc)_e$	Thermal capacity of an evaporator (J/K)
$(Mc)_v$	Thermal capacity of a refrigerant vessel (J/K)
N	Rate of water vapour movement (kg/s)
N_e	Rate of water vapour removal by a cooling unit (kg/s)
N_i	Rate of water vapour movement through a door (kg/s)
N_p	Water vapour release from product (kg/s)
N_s	Water vapour release from miscellaneous sources (kg/s)
p_a	Partial pressure of water vapour in air (Pa)
p_s	Partial pressure of water vapour in boundary layer over product surface (Pa)
p_{wa}	Vapour pressure of water at temperature T_a (Pa)
p_{ws}	Vapour pressure of water at temperature T_s (Pa)
P	Pressure (Pa)
P_d	Discharge pressure (Pa)
P_s	Suction pressure (Pa)
P_1	Empirical factor used to modify Plank's equation
P_2	Empirical factor used to modify Plank's equation
Pk	Plank number = $C_l\,(T_i - T_f)\,/\,\Delta H_{ref}$ (freezing); $C_s\,(T_f - T_i)\,/\,\Delta H_{ref}$ (thawing)
PR	Pressure ratio = $P_d\,/\,P_s$
q	Mass fraction of fat
Q_s	Compressor swept volume (m^3/s)
r	Displacement from centre along radius (m)
r_m	Mean radius (m)
R	Object radius or slab half-thickness = $0.5D$ (m)
R_x	Half-height of finite cylinder (m)
s	Mass fraction of solids
S_1	Orthogonal cross-section in second dimension (m^2)

S_2	Orthogonal cross-section in third dimension (m^2)
Ste	Stefan number = $C_s (T_f - T_a) / \Delta H_{ref}$ (freezing); = $C_l (T_a - T_f) / \Delta H_{ref}$ (thawing)
t	Time (s or h)
Δt	Time step in numerical calculations (s)
t_f	Freezing time (s or h)
t_{slab}	Freezing or thawing time for a slab (s or h)
t_t	Thawing time (s or h)
$t_{0.5}$	Half life time (s)
T	Temperature (°C)
T_a	Cooling medium (air) temperature (°C)
T_{av}	Average product temperature (°C)
T_{ave}	Average final product temperature at the completion of freezing or thawing (°C)
T_c	Product thermal centre temperature (°C)
T_d	Refrigerant condensation temperature (°C)
T_{din}	Condenser coolant inlet temperature (°C)
T_{dout}	Condenser coolant outlet temperature (°C)
T_e	Refrigerant evaporation temperature (°C)
T_{ein}	Evaporator process fluid inlet temperature (°C)
T_{eout}	Evaporator process fluid outlet temperature (°C)
T_{es}	Evaporator surface temperature (°C)
T_{ext}	Temperature beyond a room (°C)
T_f	Initial phase change temperature (°C)
T_{fave}	Average phase change temperature (°C)
T_{fin}	Final product (centre) temperature at end of freezing (°C)
T_i	Initial temperature of an object (°C)
T_p	Product temperature (°C)
T_{ref}	Reference temperature related to completion of freezing (°C) — often taken as –10°C
T_s	Product surface temperature (°C)
T_t	Temperature of fittings in a refrigerated facility (°C)
T_v	Vessel temperature (°C)
ΔT_m	Mean temperature driving force (°C)
TS	Total:sensible heat ratio for a cooling unit
U	Overall heat transfer coefficient (W/m^2K)
$(UA)_c$	Product of overall heat transfer coefficient and heat transfer area for a condenser (W/K)

$(UA)_e$ Product of overall heat transfer coefficient and heat transfer area for an evaporator (W/K)
v Specific volume of refrigerant vapour (m^3/kg)
v_a Velocity of air through an open door (m/s)
V Volume (m^3)
V_l Volume of liquid refrigerant in vessel (m^3)
V_v Volume of vaporised refrigerant in vessel (m^3)
w Mass fraction of water
w' Mass fraction of bound water
x Displacement in x direction (m)
Δx Space step in x direction in numerical calculations (m)
x_i Ice thickness (m)
x_s Distance of freezing front from product surface (m)
x_w Wall thickness (m)
y Displacement in y direction (m)
Δy Space step in y direction in numerical calculations (m)
Y Fractional unaccomplished temperature change $= (T - T_a)/(T_i - T_a)$
Y_{av} Y value based on mass average temperature $= (T_{av} - T_a)/(T_i - T_a)$
Y_c Y value based on centre temperature $= (T_c - T_a)/(T_i - T_a)$
z Displacement in z direction (m)
Z Dimensionless parameter
Z_1 Dimensionless parameter
Z_2 Dimensionless parameter
α Thermal diffusivity (m^2/s)
β Root of transcendental equation
β_1 Geometric factor for regular shapes — ratio of side lengths
β_2 Geometric factor for regular shapes — ratio of side lengths
δ_x Difference operator in x direction
δ_y Difference operator in y direction
ε Fraction of volumes as voids
ε_i Volume fraction of ith component
η_{is} Isentropic efficiency of a compressor
η_m Motor efficiency
η_v Volumetric efficiency of a compressor
∇_1 Geometric factor describing shape in the second dimension for all shapes

∇_2	Geometric factor describing shape in the third dimension for all shapes
ρ	Density (kg/m^3)
ρ_a	Density of air (kg/m^3)
ρ_{ice}	Density of ice (kg/m^3)
ρ_l	Density of unfrozen (liquid) material (kg/m^3)
ρ_l	Liquid refrigerant density (kg/m^3)
ρ_s	Density of frozen material (kg/m^3)
ρ_v	Vaporised refrigerant density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^{2}K^4)
ϕ	Heat flow (W)
ϕ_b	Heat flow from fittings and structures (W)
ϕ_{comp}	Actual compressor energy use (W)
ϕ_{conv}	Heat flow due to convection (W)
ϕ_{evap}	Heat flow due to evaporation (W)
ϕ_f	Sensible heat input due to fans, lights, people, etc. (W)
ϕ_i	Sensible heat flow due to air interchange (W)
ϕ_l	Latent heat transfer to a cooling unit (W)
$\phi_{p'}$	Sensible heat flow from product (W)
ϕ_p	Total heat flow from product (W)
ϕ_{pl}	Latent heat flow from product (W)
ϕ_r	Heat release by respiration (W)
ϕ_{rad}	Heat flow due to radiation (W)
ϕ_s	Sensible heat transfer to a cooling unit (W)
ϕ_w	Heat flow through walls, floor, etc. (W)
ϕ_x	External heat load (W)

CONTENTS