Thermal Transport in Selected Food Processing Operations

Mukund V. Karwe, Ph.D.
Professor, Department of Food Science
Dean of International Programs
School of Environmental and Biological Sciences
Rutgers University
New Brunswick, NJ 08901

karwe@aesop.rutgers.edu
Food Processing Operations
## Examples of Preservation Processes

### Thermal Processing
- Thermal processing
- Aseptic packaging
- Baking
- Frying
- Ohmic heating
- **Microwave**
- Radio frequency
- Infrared
- **Impingement**
- Drying
- **Extrusion**
- Chilling
- **Freezing**
- Freeze drying

### Non-thermal (?) Processing
- **High Hydrostatic Pressure (HHP)**
- Pulsed Electric Field (PEF)
- Ultrasound
- Pulsed Light (PL)
- Irradiation
- Oscillating Magnetic Field (OMF)
- Cold plasma
Food Extrusion
Extruded Food Products
Extruded Food Products
Pasta manufacturing

8,000kg/h spaghetti production line

Close-up of the pasta press

8,000kg/h pasta press

www.foodprocessing-technology.com/
Industrial scale food extruder

- Silos or storage bins
- Solid Feed Hoppers
- Liquid Feed
- Drive
- Screws
- Barrel
- Die and Cutter
Types of screw extruders

Single Screw Extruders:

- for snacks, breakfast cereals, pasta, pet foods
Types of Twin-screw Extruders

Co-rotating, intermeshing Twin-screw extruder

Counter-rotating, intermeshing Twin-screw extruder
Modular Design of Twin-screw Extruders
Constitutive Equations

For Newtonian materials

\[ \mu = \mu_0 \exp[-b(T - T_{\text{ref}})] \]

Viscosity

For starchy materials

\[ \mu = \mu_0 \left( \frac{\gamma}{\dot{\gamma}_0} \right)^{n-1} \exp\left( \frac{\Delta E}{RT} \right) \exp(-K_m C) \]
Transport Phenomena is Characterized by

- Very low Re (<0.01)
- Very high viscous dissipation
- Yield stress
- Slip
- Viscoelastic behavior
- Reaction kinetics
- Irreversible properties/changes
Various flows in twin-screw channels
Food extrusion die
Corn flakes production line
Extrusion of corn strips

Conjugate Heat Transfer in a Single Hole Die

Extruder-Die Interface $T_{\text{interface}}$

Die Inlet $P_{\text{inlet}}, T_{\text{inlet}}$

Extruder Screw-tip

Steel Walls of Die

$h, T_\infty$

Die Outlet

Axis of Symmetry

Isotherms in flow of cornmeal (30% moisture) in a single hole die

\[ T_{\text{inlet}} = 394 \text{ K} \]

\[ T_{\text{interface}} = 344 \text{ K} \]

\[ k = 20 \]

\[ T_{\text{interface}} = 444 \text{ K} \]

\[ T_{\text{inlet}} = 394 \text{ K} \]

FUTURE RESEARCH IN FOOD EXTRUSION

- Modeling 3-d flow of real foods (viscoelastic)
- Models for screws with varying geometry (reverse, kneading, turbine, …)
- Velocity determination for real foods (ultrasonic)
- Better quantification of mixing
- Is the flow in kneading blocks chaotic or deterministic?
- Prediction of quality (texture, flavor, color, ..) of extruded products
- Deterministic or Fuzzy/Neural Network?
Moisture content (%, w.b.)

Temperature (°C)

Free flow region

Moisture flash-off

Heating

Rubbery region

Expansion

Cooling

Product

Dry flour

Glassy region

Wetting and mixing

$T_g + 100°C$
We still cannot predict accurately the quality (shape, porosity, color, flavor,...) of these extruded products, from first principles.
Transport Phenomena during the Baking Process in Jet Impingement and Hybrid Jet Impingement Microwave (JIM) Oven
Baking

Transport process:
Heat & Mass Transfer

Temperature rise, moisture migration & evaporation

Physical & chemical changes:
Starch gelatinization
Protein denaturation
Crust formation
Color development
Flavor formation

Quality:
Texture, Flavor
Color, Shelf-life
Jet Impingement Oven

- Forced convection oven
- High velocity (10 to 50 m/s) jets of hot air (100 – 250 °C) impinge vertically on a food product
Table Top Jet Impingement Oven

Plenum Chamber

Turntable
A Commercial Scale Jet Impingement Oven

Courtesy of Wolverine Corp.
Why Jet Impingement Oven?

- higher rate of heat transfer
- higher rate of moisture removal at the surface
- quick crust formation
- high moisture retention in the product

used for baking of tortilla, potato chips, pizza crust, pretzels, crackers, cookies, coffee beans, breads and cakes, cereals, matzo
Understanding Transport Phenomena
Transition from Laminar to Turbulent Region in a Round Jet (Reynolds Number ~30000)

From: Album of Fluid Motion by Van Dyke, Photograph by Fred Landis and Asher H. Shapiro, 1962
Numerical Simulation Results

Isovelocity Contours of an Impinging Jet at $Z/d = 5$

$V_{\text{max}} = 26 \text{ m/s}$

$Z/d = 1.4$

$Z/d = 4.4$

Experimental (LDA, Dry Ice fog) Isovelocity Contours

At Z/d = 4.4

Numerical Simulation Results

Isovelocity Contours in a Turbulent Jet Impinging on a Model Cookie

Jet Inlet
$V_{\text{max}} = 40 \text{ m/s}$

Potential Core

Stagnation Point

Axis

### Experimental Results

**Average Top Surface Heat Transfer Coefficient for a Model Cookie**

<table>
<thead>
<tr>
<th>Temp °C (°F)</th>
<th>Jet Velocity ($V_{max}$) m/s (ft/min)</th>
<th>Top surface $h$ with side areas covered W/m²K (BTU/h-ft² °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 (149)</td>
<td>22 (4331)</td>
<td>117 (20.6)</td>
</tr>
<tr>
<td>65 (149)</td>
<td>42 (8268)</td>
<td>165 (29.0)</td>
</tr>
<tr>
<td>150 (302)</td>
<td>22 (4331)</td>
<td>126 (22.2)</td>
</tr>
<tr>
<td>150 (302)</td>
<td>42 (8268)</td>
<td>180 (31.7)</td>
</tr>
</tbody>
</table>

Error~±10%
Heat Flux Measurements for $h_{\text{max}}$

\[ h_{\text{max}} = C_f \frac{q}{(T_{\text{jet}} - T_S)} \]

Where,

- $q$ = Heat flux (W/m$^2$)
- $T_{\text{jet}}$ = Jet air temperature (°C)
- $T_S$ = Heat flux gage surface temperature (°C)
Experimental Results
Comparison of $h_{\text{max}}$ with $h_{\text{avg}}$

MULTIPLE JETS & MULTIPLE COOKIES
Jet Impingement in a Finger Oven

Jet impingement fingers

Finger 1  Finger 2  Finger 3  Finger 4

Food

Conveyor

Hot air jets

1.05 m

1.25 m

1.23 m
Jet Impingement Finger
Schematic Diagram of Reverse Flow ("Interaction Fountain") in Multiple Jet Configurations
Multiple Model (?) Cookies
Experimental Results
Variation of $h$ with Size of the Model Cookie

Results for Table Top Jet Impingement Oven
Computational Mesh

Jet orifices (31, top plate) $T_a, U_a$

Outflow (exhaust fan) $T, U$

Walls $\frac{\partial T}{\partial x_i} = 0, U_i = 0$

Model cookie 28.5 cm

Jet orifices (33, bottom plate) $T_a, U_a$

15.5 cm

28 cm
Velocity Vectors Around the Cookie

HYBRID

JET IMPINGEMENT

MICROWAVE
Electromagnetic Radiation

<table>
<thead>
<tr>
<th>Wavelength (m)</th>
<th>10^3</th>
<th>10^2</th>
<th>10^1</th>
<th>1</th>
<th>10^-1</th>
<th>10^-2</th>
<th>10^-3</th>
<th>10^-4</th>
<th>10^-5</th>
<th>10^-6</th>
<th>10^-7</th>
<th>10^-8</th>
<th>10^-9</th>
<th>10^-10</th>
<th>10^-11</th>
<th>10^-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources</td>
<td>AM radio</td>
<td>FM radio</td>
<td>Microwave oven</td>
<td>Radar</td>
<td>Light bulb</td>
<td>UV lamp</td>
<td>X-ray machines</td>
<td>Radioactive elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency (waves/sec)</td>
<td>10^6</td>
<td>10^7</td>
<td>10^8</td>
<td>10^9</td>
<td>10^10</td>
<td>10^11</td>
<td>10^12</td>
<td>10^13</td>
<td>10^14</td>
<td>10^15</td>
<td>10^16</td>
<td>10^17</td>
<td>10^18</td>
<td>10^19</td>
<td>10^20</td>
<td></td>
</tr>
<tr>
<td>Energy of 1 photon (eV)</td>
<td>10^-9</td>
<td>10^-8</td>
<td>10^-7</td>
<td>10^-6</td>
<td>10^-5</td>
<td>10^-4</td>
<td>10^-3</td>
<td>10^-2</td>
<td>10^-1</td>
<td>1</td>
<td>10^1</td>
<td>10^2</td>
<td>10^3</td>
<td>10^4</td>
<td>10^5</td>
<td>10^6</td>
</tr>
</tbody>
</table>

Adapted from http://www.lbl.gov (Berkeley Lab website)
Dielectric Heating
(MW and RF)

• Interaction of EM field with food (mainly water and fat)

• More penetration at lower frequency

• Non-contact

• Rapid heating

• Surface does not overheat (but no crust either)

915 MHz or 2450 MHz for MW
13.56 MHz, 27.12 MHz, and 40.68 MHz for RF
Why Microwave Oven?

- shorter process time
- accelerated heat transfer
- accelerated moisture migration
- used for dehydration, cooking, blanching, thawing, pasteurization, sterilization
- condensation of the vapor at the surface
- soggy & rubbery texture
- no crust formation & color development

Microwave

Cold air

Rapid heating of the inside of the product
microwave

- rapid heating of the inside of the product
- jet Impingement
- evaporation at the surface
- crust formation
- color development
hybrid jet impingement microwave oven (Fujimak SuperJet)
Fujimak SuperJet Specifications
Model of Crust and Crumb

before crust is formed

- convective mass transfer
- convective heat transfer

mass diffusion
heat conduction

$M > M_e, T \leq 100 \degree C$

after crust is formed

- water vapor transport through crust
- convective heat transfer

mass diffusion
heat conduction

$M = M_e, T > 100 \degree C$

Governing Equations

Heat transfer:
\[ \frac{\partial (\rho_i C_{pi} T)}{\partial t} = \nabla \cdot (K_i \nabla T) + Q \]

Mass transfer:
\[ \frac{\partial M}{\partial t} = \nabla \cdot (D_{\text{eff}} \nabla M) \]

Surface heat flux:
\[ k \frac{\partial T}{\partial n} \bigg|_s = h(T_a - T_s) - k_m H_v (P_{vs} - P_{va}) \]

Surface mass flux:
\[ -D_{\text{eff}} \frac{\partial W}{\partial n} \bigg|_s = k_m (P_{vs} - P_{va}) / \rho_s \]

Antoine’s law:
\[ P_{vs} = 133.3 \exp \left[ 18.3036 - \frac{3816.44}{T_s - 46.13} \right] \]
Lambert’s Law

Heat generation term (Q) was calculated by Lambert’s law:

\[ Q = 2 \alpha P^"_c \exp[-2 \alpha(H/2 - x)] + \frac{2 \alpha R P^"_c}{r} \exp[-2 \alpha(R - r)] \]

A critical thickness above which Lambert’s law applies (Ayappa et al., 1991):

\[ H_{\text{crit}}(\text{cm}) = 2.7D_p - 0.08 \]

\[ D_p = \lambda_0 / \pi (2 \varepsilon^`)^{0.5} \left[ 1 + \left( \varepsilon^"/\varepsilon^` \right)^2 \right]^{0.5} - 1 \]
Jet Impingement only heating

Temperature contours for jet impingement only heating after 15 min at $T_a = 450$ K, $U_a = 10$ m/s ($h = 40$ W/m$^2$K)

Moisture contours for jet impingement only heating after 15 min at $T_a = 450$ K, $U_a = 10$ m/s ($h = 40$ W/m$^2$K)

Microwave only heating

**Temperature contours**

for microwave only heating after
4 min with microwave power 50% (at $T_a = 300$ K, $h = 10$ W/m$^2$K)

**Moisture contours**

for microwave only heating after
4 min with microwave power 50% (at $T_a = 300$ K, $h = 10$ W/m$^2$K)

Hybrid JIM heating

**Temperature isotherms**

For JIM heating after 4 min at $T_a = 450$ K, $U_a = 10$ m/s ($h = 40$ W/m$^2$K), MW = 50%

**Moisture contours**

For JIM heating after 4 min at $T_a = 450$ K, $U_a = 10$ m/s ($h = 40$ W/m$^2$K), MW = 50%

Moisture Loss

JIM heating: Experimental vs. Numerical

(a) P1: 4 mm below the top surface

(b) P2: 12 mm below the top surface

(c) P3: 20 mm below the top surface

\[ T_a = 450 \text{ K}, \quad U_a = 10 \text{ m/s}, \quad h = 40 \text{ W/m}^2\text{K}, \quad \text{MW} = 50\% \]

Vapor transport is important and cannot be ignored
Moisture Content Vs. Time at Different Positions From Top Surface

Crust Thickness vs. Time

Sequencing

- Cooked crust moisture
- Path dependent
- Cooked dry, soggy surface no crust

extent of jet impingement

extent of microwave
Effect of Sequencing

**Moisture contours in potato for Case 1 (JI-MW-JI)**

**Moisture contours in potato for Case 2 (MW-JI)**

Other Hybrid Ovens

JI + IR

MW + IR

JI + IR + MW
Continuous Microwave for Pasteurizing Prepared Meals

Image: Tang http://microwavepasteurization.wsu.edu/
Sterilization of Solid Food

- Prepared food or meat in hermetically sealed barrier plastic trays/ pouches.
- FDA approved a method to pasteurize packaged food by immersing in pressurized hot water and simultaneously heating with microwaves.

**Microwave sterilization system at Washington State University**

Images: http://microwaveheating.wsu.edu/aboutus/benefits.htm
Broday A. (2011) "Advances in Microwave Pasteurization and Sterilization" IFT Food-Technology February Issue
Freezing
Food freezing

- Freezing ensures food safety by suppressing or stopping microbial activity.
- Freezing reduces deteriorating chemical reactions by decreasing reaction rates and by lowering water activity.
- A storage temperature of -18 °C or below is recommended for commercial products.
- Frozen US army rations are sent out for army personnel in various countries through cold chain transportation.
US army ration

Beefsteak

Danishes

French toast

Conc. Orange juice

Peppers and onions

French toast
Transportation System

Assembler → Conus Transport → Sea Transport → Oconus Transport

Prime Vendor

Dinner ← FOB/Base ← Distributor
Apparent specific heat method

\[ \rho c_{P(app)} \frac{\partial T}{\partial t} = \nabla (k \nabla T) \]

Apparent Specific Heat (J/kgK)

Temperature

\[ c_{p(app)} = \begin{cases} 
    c_{p(frozen)} & T \leq T_F \\
    c_{p(phas\text{ change})} & T_F \leq T \leq T_T \\
    c_{p(thawed)} & T \geq T_T 
\end{cases} \]

unfw % (\Phi) = \begin{cases} 
    10 & T \leq T_F \\
    f(T) & T_F \leq T \leq T_T \\
    100 & T \geq T_T 
\end{cases}

Karthikeyan et al., Food Research International, 2015. DOI: 10.1016/j.foodres.2015.07.007
Case study:
Extended stay outside the freezer

Maximum allowed time ($t_m$)

Karthikeyan et al., Food Research International, 2015. DOI: 10.1016/j.foodres.2015.07.007
HIGH HYDROSTATIC PRESSURE PROCESSING OF FOODS (HHP, HPP, HHPP, UHP)
HIGH HYDROSTATIC PRESSURE PROCESSING

- Novel Non-Thermal Food Processing Technology
- Subjects Foods (Liquids or Solids) to Pressures between 100 and 1000 MPa
Three African elephants (~5 tons each) standing on a 18 mm (dia.) disk.

(18 mm in diameter)

600 MPa or 87,000 psi
WHY HIGH HYDROSTATIC PRESSURE?

High Pressure Processing

- Fresh, high quality product
- Extends shelf life
- Modified texture
- Reduces /eliminates use of preservatives
- Inactivation of microorganisms
- Denaturation of enzymes
- No post process contamination
- Retains flavor and color
CURRENT HPP PRODUCTS IN THE MARKET

GUACAMOLE

JUICE & SMOOTHIES

RTE - MEATS

OYSTERS

JAMS & JELLIES

www.nchyperbaric.com
NEW HPP JUICES FROM STARBUCKS ($70 M)
NOVEL NON-THERMAL TECHNOLOGY

- Minimum detrimental effects of thermal processing
- Causes denaturation of enzymes
- Inactivation of spoilage and pathogenic microorganisms
- Produces safe and high quality products

The pressure acts instantaneously and uniformly throughout the mass so the process pressure and time are independent of size and shape of the food.
PRESSURIZATION/ COMPRESSION PHASE

- Decrease in Volume
  - the volume of water (polar) is reduced by 15% at 600 MPa
  - the volume of hexane (non-polar) is reduced by 25% at 600 MPa

- Generation of Heat

\[
\frac{dT}{dP} = \frac{T v \beta}{C_p}
\]

Where,

- \( v \) = specific volume (m\(^3\)/kg)
- \( \beta \) = coefficient of thermal expansion (1/K)
- \( C_p \) = heat capacity (J/[kg K])
- \( T \) = temperature (K)
## COMPRESSION HEATING VALUES

Temperature change due to Adiabatic Compression Heating

<table>
<thead>
<tr>
<th>Substance at 25°C</th>
<th>Temperature change per 100 MPa (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>~ 3.0</td>
</tr>
<tr>
<td>Orange Juice</td>
<td>~ 3.0</td>
</tr>
<tr>
<td>2% Fat Milk</td>
<td>~ 3.0</td>
</tr>
<tr>
<td>Tomato Salsa</td>
<td>~ 3.0</td>
</tr>
<tr>
<td>Salmon</td>
<td>~ 3.2</td>
</tr>
<tr>
<td>Chicken Fat</td>
<td>~ 4.5</td>
</tr>
<tr>
<td>Beef Fat</td>
<td>~ 6.3</td>
</tr>
<tr>
<td>Olive Oil</td>
<td>~ 6.0 to 8.7</td>
</tr>
<tr>
<td>Soy Oil</td>
<td>~ 6.2 to 9.0</td>
</tr>
<tr>
<td>Hexane</td>
<td>~ 40.0</td>
</tr>
</tbody>
</table>
MICROBIAL INACTIVATION UNDER HHPP

- For orange juice processed at 483 MPa, 60 s, 7 log reduction of pathogens (E. coli, Salmonella)

- For RTE meats, processed at 600 MPa, 3-4 log reduction of L. monocytogenes

- Spores > 600 MPa (60-70 °C) C.botulinum spores are most resistant

- Prions associated BSE and CJD 690-1200 MPa and 121-137 °C to reduce their infectivity in meats
**COMBINED PRESSURE-TEMPERATURE PROCESS**

- **Pressure Assisted Thermal Pasteurization (PATP)**
  - 25 °C – 60 °C
- **Pressure Assisted Thermal Sterilization (PATS)**
  - 60 °C – 120 °C
- **High Pressure “Cold Pasteurization”**
  - < 25 °C

2009 US FDA approved a petition for PATS of low-acid shelf stable product

[http://members.ift.org/IFT/Pubs/Newsletters/weekly/nl_030409.htm](http://members.ift.org/IFT/Pubs/Newsletters/weekly/nl_030409.htm)
TEMPERATURE VARIATION DURING HHPP

Pressure [MPa]

Temperature [°C]

Pressure Hold

Time [sec]
➢ Rutgers 10 liter HHPP Facility
   Manufactured by Elmhurst Inc.,
   Albany, NY

➢ LABVIEW ® (National Instruments)
   Pressure vs. Time
   Temperature vs. Time
NUMERICAL SIMULATION

FLUENT® (Version 6.0, Fluent, Inc., Lebanon, NH)

(a) Shaded portion shows the radial section for numerical simulation

(b) Computational domain with Ri = 71 mm, Ro = 223 mm
TEMPERATURE CONTOURS ($T_i = 288 \, K$, $P = 586 \, MPa$)

Before Pressurization

End of Pressurization

Velocity Vectors

End of Hold Time (10 min)

288 K

301 K

Steel Sleeve

Water

Vessel wall of steel

Khurana and Karwe, Food and Bioprocessing Technologies, 2:279-290, 2009
**HIGH INITIAL TEMPERATURE**

**TEMPERATURE CONTOURS** ($T_i = 353$ K, $P = 586$ MPa)

Before Pressurization

End of Pressurization

End of Hold Time (10 min)

Steel Sleeve

Water under high pressure

Vessel wall of steel

Water

Vessel wall of steel

HEAT TRANSFER WITH MULTIPLE OIL POUCHES

Water under high pressure

Vessel wall of steel

Oil under high pressure

Water under high pressure

Vessel wall of steel

Oil under high pressure
QUANTIFICATION of CLOSTRIDIUM BOTULINUM SPORES INACTIVATION

Impact of temperature non-uniformity on inactivation of *C. botulinum* spores

\[
F = \int_0^t 10^{\frac{T(t) - T_{ref}}{z_T}} \, dt = -D \log_{10} \frac{N}{N_0}
\]

\(T_{ref} = 121^\circ C, \quad z_T = 10^\circ C, \quad D = 0.2 \text{ min}\)
Inactivation of *C. botulinum* spore at $T_i = 353$ K (80 °C)

Some New and Emerging Areas
Cold Plasma

1. Not fully ionized

2. Gas molecules are at much lower temperature whereas electrons are much hotter. \((T_e >> T_{ions} >> T_{gas\ molecules})\)

3. Can be generated at low pressure or at atmospheric pressure (www.plasmauniverse.com, 09/13/13)
Cold atmospheric plasma on almonds

http://www.ars.usda.gov/is/pr/2008/coldplasma080722.jpg
Cold plasma treatment of blueberries in a simple glass jar

Cold atmospheric plasma on fresh lamb’s lettuce

Plasma

Heat Transfer

Fluid Flow

O₂

NO

O₃

OH

H₂O

Ions
In-Package Plasma Generation

From: Kevin Keener, Purdue University
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