Food Processing with Air Impingement Systems –
Heat Transfer in Cylindrical and Flat Shaped Objects

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- Food industry is often seeking processes that result in low per-unit cost.
- Continuous processing is preferred over batch systems.
- Processes that require shorter times are preferred.
- Low cost processing aids – water, air.
- Air is used in numerous processes.
## Significant reduction in cook times

<table>
<thead>
<tr>
<th>Product</th>
<th>Time, min (Conventional oven)</th>
<th>Time, min (Microwave Impingement oven)</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey</td>
<td>210</td>
<td>80</td>
<td>61%</td>
</tr>
<tr>
<td>Biscuits</td>
<td>12</td>
<td>2:30</td>
<td>79%</td>
</tr>
<tr>
<td>Brownies</td>
<td>28</td>
<td>6</td>
<td>79%</td>
</tr>
<tr>
<td>Corn dog</td>
<td>15</td>
<td>2:30</td>
<td>83%</td>
</tr>
<tr>
<td>Baked potatoes</td>
<td>60</td>
<td>9</td>
<td>85%</td>
</tr>
<tr>
<td>Turnovers</td>
<td>22</td>
<td>5</td>
<td>77%</td>
</tr>
</tbody>
</table>
Foodservice - Pizza Hut, Dominos, Red Lobster
An Impingement Oven
Overview

- Fluid flow in impingement systems
  Design and operating variables
- Visualization studies
- Experimental trials
- Computational fluid dynamics and Particle Imaging Velocimetry
- Freezing, Thawing, and Cooling Studies
<table>
<thead>
<tr>
<th>Type</th>
<th>Rate (W/m²°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Convection</td>
<td>6 to 11</td>
</tr>
<tr>
<td>Forced Convection to Flat Surfaces</td>
<td>13.6 @ 3 m/s</td>
</tr>
<tr>
<td>Convection Ovens</td>
<td>22 to 45</td>
</tr>
<tr>
<td>Impingement Ovens</td>
<td>68 to 170</td>
</tr>
</tbody>
</table>
Air Impingement System
Published Literature

- Ford Motor Company, 1960s, Glass Division Technical Center, Gardon et al.
- Procter and Gamble Co., 1993, Polat et al.
- Institut fur Thermische Verfahrenstechnick der Universität Karlsruhe, Germany, 1977, Holger Martin
- Swedish Food Institute, SIK, Sweden, 2000, Skjoldebrand
- Nottingham Polytechnic, UK, 1992, Jambunathan et al.
- Kansas State University, 1996, Walker et al.
- Rutgers University, 2001, Karwe et al.
- Texas A&M University, 2001, Moreira et al.
- Michigan State University, 2002, Marks et al.
- University of California, 2002, Singh et al.
Tracer Particles (Helium Bubbles) in an Impingement System

**Bubble generating system (Sage Action Inc., Ithaca, NY)**
Visualization of Fluid Flow

Light source

Lens Arrangement

Plenum

Impingement Surface

Camera
Diameter = 1.5 cm
Length  = 7.5 cm
D/L ratio = 0.2
D = 1.5 cm
L = 0.79 cm
D/L ratio = 1.9
Principle of Impingement

- High Pressure
- Low Pressure
- Potential core
- Mixing/Free shear
- Jet hydraulic diameter ($D$)
- Stagnation region
  - $u = 0, v = 0$
- Wall jet region
- Boundary layer
- Plenum
- Z
- L
Design Considerations

- Jet type (round of slot)
- Jet configuration (array geometry)
- Nozzle to target surface spacing
- Location of exhaust ports
- Induced or imposed cross flow
- Surface motion
- Angle of impingement
- Nozzle design
- Temperature differences between the jet and the impingement surface
Shape of the Impingement Nozzle

- Round nozzles
- Slotted (rectangular) nozzles
- Elliptical nozzles
- Within each shape, length of the nozzle to diameter is an important variable
- Sharp edged or tapered nozzle and length of nozzle affects degree of turbulence
Principle of Impingement: Multiple Jets

Jet 1

Jet 2

Exhaust

Upward fountain
Number of Impingement Nozzles

- Most studies carried out with single nozzles
- All industrial applications use array of nozzles where the air jets may interact with each other.
Air velocity

- Recall: Heat transfer coefficient is contained in the Nusselt number, and velocity is contained in Reynolds number
- Correlation between Nusselt number and Reynolds number
- $N_{Nu} \propto N_{Re}^n$
  
  Where $n$ ranges from approximately 0.48 to 0.8
20 m/s
Distance from Nozzle to Impingement Surface

- Maximum Nusselt number occurs at the stagnation point when the jet is at a distance of six to eight diameters away from the impingement surface. This is the end of the potential core.

- A spatial variation in convective heat transfer coefficient occurs away from the stagnation point.

- When the distance from nozzle to impingement surface is small (z/D<6), there is a secondary maximum of Nusselt number at a radial distance of 0.5 to 2 nozzle diameters due to the transition from laminar to turbulent boundary layer flow.
Geometrical shape of the Impingement surface

- Large number of studies with flat plates
- Convex and cylindrical surface
- Convex shape tends to thin the boundary layer at the impingement point causing an increase in heat transfer coefficient (Lee et al, 1997)
- Concave shapes: Nusselt number increases with increased surface curvature, the increase is due to turbulence (Choi et al, 2000)
Impingement surface

- Roughness of the surface can also affect heat transfer rates. Nusselt number was about 6% higher for rough surface due to increase turbulence.
Surface movement

- Most experimental studies have been done with jets impinged onto a stationary surface.
- In industrial practice, the product moves under the jet while placed on a conveyor belt.
- Heat transfer was not affected when the velocity of the surface was less than 60% the velocity of the jet.
A single slot jet impinging on a moving surface

Re = 35,400
z/D = 2.5

M\textsubscript{vs} = velocity of surface / velocity of jet

Polat (1993)
Air Entrainment

- Temperature of ambient air is different than that of the impingement jet
- Impingement heat transfer is affected by
  - Temperature of the air in the jet
  - Temperature of ambient air
  - Temperature of the surface
- When ambient air is cooler than the impingement jet, the ambient air becomes entrained in the jet flow and lowers the temperature of the flow reducing heat transfer (and vice versa).
Confinement

- In industrial applications, the impingement nozzles are enclosed or shrouded in the equipment.
- Enclosing the system, the ambient air temperature becomes nearer to the jet air, reducing the effect of entrainment.
- Exhaust ports may be placed between the nozzles. If located on the sides, flow field of jets may be drastically altered. Air exiting from center jets may influence jets on the sides.
- 15 – 30% decrease in $N_{Nu}$ with cross-flow arrangement.
5cm

Jet-to-Jet Interaction
The Measurement Device

Convective Heat Transfer Measurement Setup
Heat transfer variations under single circular jets (76mm nozzle to plate spacing)
Heat transfer variations under single slot jets (76mm nozzle to plate spacing)
Prototype Development

- Based on preliminary measurements, input from manufacturers and literature review
Development of Numerical Model

Nozzle

External Flow field

Separated boundary layer

Boundary layer

Product
Numerical Model : External Flow

- External flow - steady, turbulent, problem
- Grid generation - GAMBIT 3.1 adaptive meshing
- Solution - FLUENT 6.0 commercial CFD solver
- Solver parameters
  - Implicit “SIMPLEC” scheme with upwind discretization
  - $k-\varepsilon$ model for turbulence estimation
Heat transfer coefficients show considerable spatial and time dependence.
Simulation Results: Internal Heat Transfer

Temperature in °C
PIV setup

Introduction smoke in air

Laser source
Synchronizer
Camera
PC Computer
Slot jet
Cross-correlation to estimate velocity

Pair of images are processed at once

Both images are divided into smaller units of equal size called Interrogation-Areas (IA).

Corresponding interrogation areas from the two images are cross-correlated to estimate the displacement of particle $\Delta x$ and $\Delta y$.

Knowing the time delay between two images, velocity in the particular region is estimated as

$$u = \frac{\Delta x}{\Delta t} \quad \text{and} \quad v = \frac{\Delta y}{\Delta t}$$

Cross-correlation to find velocity vector
PIV – Particle Imaging Velocimetry

- A 2 component (2D) PIV system consisting of
  - Nd:Yag laser
  - PIV camera
  - Laser and camera synchroniser
  - Computer
  - PIV software
Experimental set-up cont.

- Simple air jet directed at flat surface from a distance of approximately 120mm
- Seeding – incense smoke introduced to air intake (3 sticks)
- Field of view approx 50mm x 70mm
- Pulse separation 10µs
- 50mm f/1.4 Nikon lens
- Camera fitted with narrow band pass filter to allow operation in normal lighting conditions
Analyze images
Results: Instantaneous vector magnitude

Video
PIV Results – Field Validation
PIV Results – Line validation

- Simulated data
- Experimental data
Heat Transfer Validation

- Nozzle arrangement
- Tylose sample
- Plaster of Paris cement
- Thermocouple junction
- To data acquisition
Validation – Freezing Profiles

-18 -16 -14 -12 -10 -8 -6 -4 -2 0 2

<table>
<thead>
<tr>
<th>Experimental</th>
<th>Simulated</th>
</tr>
</thead>
</table>

Temperature (°C) vs Time (s)

Jet centerline

Jet

1 2 3 4
Impingement system for Thawing

- $d = 1.95 \text{ cm}$
- $Z = 1.9 \text{ cm}$
- $R = 6.35 \text{ cm}$
- exit velocities = 23, 31, or 40 m/s
- $y = 4.2, 9.2, \text{ or } 14.2 \text{ cm}$
Thawing Experiments with Tylose

- A mold was fabricated from Teflon to measure temperatures at various heights and radial positions in the Tylose sample 1.9 cm thick and 12.6 cm diameter.
- Very fine thermocouples (44 gauge, type T) were used to measure temperatures.
- Tylose was prepared and equilibrated in the mold prior to testing.
Experimental vs. Predicted Temperatures

- Experimental temperatures matched well with predicted results
  - Predicted times for the product to reach 0°C matched within 10% of the experimental data 65% of the time

Time to reach 0°C
Predicted = 115 min
Experimental = 102 min
Difference = 13.3%
RMSE = 0.6°C
Thawing Times (1.9 cm thick Tylose) from -20 C to 0 C

- Refrigerator (5°C, h=5.5 W/m²K) : 30 hours
- Laboratory incubator (5°C, h=12 W/m²K) : 14 hours
- Laboratory incubator (12°C, h=12 W/m²K) : 5 hours
- A single air impingement jet (6°C) : <2 hours
Additional experiments with Bratwurst

- Packaged bratwurst were thawed using the impingement system
- Air velocity = 40 m/s; z = 4.2 cm
## Thawing time for Bratwurst

<table>
<thead>
<tr>
<th></th>
<th>Time to reach 0°C (min)</th>
<th>Standard deviation (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Impingement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original Package</td>
<td>448</td>
<td>30</td>
</tr>
<tr>
<td>Individually wrapped with aluminum foil</td>
<td>339</td>
<td>8</td>
</tr>
<tr>
<td><strong>Impingement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original package</td>
<td>192</td>
<td>14</td>
</tr>
<tr>
<td>Individually wrapped with aluminum foil</td>
<td>65</td>
<td>10</td>
</tr>
</tbody>
</table>
Fluid flow around a cylindrical object under air jet impingement

- Free jet
- Developing Flow
- Developed Flow
- Stagnation point
- Wall Jet
- Impingement surface
- Plenum
- Nozzle
- Potential Core
- Mixing Region
- H
- B
Modeling Our System

Jack to adjust H
System Model: The Computational Domain

- Symmetry along Jet centerline
- Symmetry along Exhaust centerline

Jet exit

Product
Flow and heat transfer simulations: FLUENT (CFD)

Computational domain: axi-symmetrical about the jet centerline

Heat transfer was solved using $k-\varepsilon$ turbulence model.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.

30 sec

Velocity contour

Nozzle

SIMULATED
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.

2.5 min

- Velocity contour
- Nozzle

Maximum
Minimum

Temperature contour
SIMULATED
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.

06 min

Velocity contour

Nozzle

Maximum

Minimum

Temperature contour

SIMULATED
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.
Contour outside the circle is velocity contour and that inside is temperature contour.

12.5 min

Nozzle

Maximum

Minimum

Velocity contour

Temperature contour

SIMULATED
Contour outside the circle is velocity contour and that inside is temperature contour.
Velocity Vectors (From PIV)
Velocity Contours (From PIV)

Flow separation

Flow recirculation

Velocity contours and streamlines (PIV)
Velocity Comparison (PIV vs. FLUENT)

Velocity contours of simulated and PIV measured flow field
Velocity Comparison (PIV vs. FLUENT)
Flow field validation

- Velocity Profile along jet centerline
  - Predicted
  - Experimental

- Velocity Profile along Line-1
  - Predicted
  - Experimental

- Velocity Profile along Line-2
  - Predicted
  - Experimental
Effect of Surface Curvature of the Cylinder

Angular position from stagnation point (degree)

Velocity (m/s)

- ○ d=19 mm
- □ d=25 mm
- ▲ d=32 mm

Nu

- - - d=19 mm
- - - d=25 mm
- - - d=32 mm

Angular position from stagnation point (degree)
Cooling of Boiled Eggs
A Range of Platforms and Configurations

Food Processing
- Stein (FMC)
- APV Baker
- FOODesign
- Amana

Restaurants
- Fujimak
- Lincoln
- Middleby
- Carter Hoffmann

Non-traditional
- Lincoln
- Fujimak

Vending
- KRh (Kaiser)
- ACT

Residential
- Thermador