Sustainability in Refrigeration Systems –

Opportunities for energy efficiency improvements in low temperature freezing systems

Frozen Dessert Center
2022 ANNUAL TECHNICAL CONFERENCE

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Director, Industrial Refrigeration Consortium
University of Wisconsin-Madison
The industrial sector is consistently the largest energy consumer

Share of total U.S. energy consumption by end-use sectors, 2020

Total = 92.94 quadrillion British thermal units

- Industrial: 33%
- Transportation: 26%
- Residential: 22%
- Commercial: 18%

Source: U.S. Energy Information Administration, Monthly Energy Review, Table 2.1, April 2021, preliminary data
Note: Sum of individual percentages may not equal 100 because of independent rounding.
Within the manufacturing sector, food industry is in the top five

![Manufacturing Energy Consumption (TBtu)]

- Chemicals: 4,252
- Petroleum Refining: 3,542
- Forest Products: 3,158
- Food & Beverage: 1,837
- Iron & Steel: 1,463
- Plastics: 586
- Fabricated Metals: 557
- Transportation Equipment: 541
- Electronics: 493
- Aluminum: 456
- Cement: 307
- Glass: 294
- Machinery: 288
- Textiles: 242
- Foundries: 173
- Other: 1,055

Frozen desserts require energy-intensive freezing systems for hardening!

- **Mechanical freezing systems**
  - Predominantly dynamic freezing systems
  - Common configurations include spiral, tunnel
  - Capital cost intensive
  - Not optimized

- **Cryogenic freezing systems**
  - Low capital cost but high operating costs
  - Quick freezing times
  - Sustainability?
AIM Act phasing down HFC refrigerants

**Phasedown Schedule**

The following illustrates the HFC production and consumption phasedown schedule as outlined in the AIM Act.
Next generation fluorochemical refrigerants

- Fluorochemical refrigerant choices are limited and have additional concerns
  - Many are “slightly flammable” (2L classified by ASHRAE 34)
  - Medium and low pressure refrigerant alternatives have moderately high GWP
  - Many options have poorer inherent operating efficiencies
  - Owners are experiencing phase-out fatigue
  - Concerns about TFA and PFAS and inclusion of HFC and HFO refrigerants in PFAS-related phase-out planning
End-users have a lot of balls in the air!
Mechanical blast freezing systems

• Large insulated rooms with high powered fans (40+ mph) that force cold air (-40°F) over product
• Used in food processing industry to rapidly cool food products like poultry, pizza, vegetables, and ice cream before moving into holding freezers or packaged for transport.
• Cooling times range from 10 to 60+ minutes
Blast freezers present opportunities for improved performance and efficiency

- Lots of “Brute Force” to achieve product freezing
- Air flow is not optimized (semi not sportscar)
- Often difference between design and actual freezing performance
What are we doing about it?

• **Project Goal:**
  Reduce the end-use energy consumption, source fuel requirements, and GHG emissions associated with the manufacture of frozen foodstuffs

• **Approach:**
  • Conduct research to determine desirable characteristics of the next generation of low temperature freezing systems
  • Identify candidate field sites with low-temperature freezing systems
  • Screen for potential EE/performance improvement opportunities
  • Collaborate with end-user to evaluate EE opportunities and implement ECMs with assessment of impact
Research team

- Eric Alar, Ph.D. Student, Mechanical Engineering
- Tyler Young, M.S. Student, Mechanical Engineering
- Todd Jekel, Assistant Director, IRC
- Marc Claas, Research Engineer, IRC
- Douglas Reindl, Professor & Director, IRC
- Greg Nellis, Professor, Mechanical Engineering
Energy efficiency improvement opportunities

• Food freezing system
  • Improved air-side
    • Air flow patterns
    • Air delivery across product
    • Fan and fan motor efficiency
  • Improved blast freezing enclosures
    • Minimized air infiltration
    • Tighten enclosure
• Improved evaporator design / integration
  • Optimized coil selection
  • Improved refrigerant feed
  • Improved defrost controls & sequencing
Energy efficiency improvement opportunities

- **Refrigeration systems infrastructure**
  - Compressor sequencing & control
  - Condenser & head pressure minimum/control
  - Oil cooling
  - Suction pressure setpoints
  - Make-up liquid throttling (single vs. multiple stages)
  - Other
Modeling blast freezers with computational fluid dynamics (CFD) in an effort to quantify potential methods for freezing performance improvement.
Predicting performance of a freezing system begins with a solid model of the blast freezer

- Plant drawings
- On-site measurements
- Capture major components and design features

Plant A

Plant B
Simplifying complex components – spiral belt

- Use simple spiral to reduce element count

**Full-scale semi-real spiral**
- 2.8 million elements with no belt holes

**Full-scale simple spiral**
- 1.3 million elements
Evaluation of airflow inside Plant A’s spiral freezer

- Plant A’s fan curve data applied to each “Fan” surface

- Majority of airflow hits ceiling and back wall
- Airflow that does hit product is towards the bottom of the spiral where product is colder
Plan view cross section of spiral
Spiral velocity results from CFD analysis

Spiral infeed

Spiral outfeed
Performance metrics

• Spiral point clouds for average velocity and velocity distribution across product
• Average air velocity across evaporator coils
• Throughput rate
• Product normalized energy consumption

Plant A’s current performance

<table>
<thead>
<tr>
<th></th>
<th>Avg. Velocity [ft/min] {m/s}</th>
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<tbody>
<tr>
<td>Spiral</td>
<td>672 {3.42}</td>
</tr>
<tr>
<td>Coils</td>
<td>552 {2.81}</td>
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</table>

<table>
<thead>
<tr>
<th>Energy per Product [Btu/prod]</th>
<th>Throughput [prod/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>173</td>
<td>145</td>
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Existing spiral freezer (Plant A)

<table>
<thead>
<tr>
<th>Average Velocity</th>
<th>Spiral [m/s]</th>
<th>Coils [fpm]</th>
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</thead>
<tbody>
<tr>
<td>[m/s]</td>
<td>3.42</td>
<td>2.81</td>
</tr>
<tr>
<td>[fpm]</td>
<td>672</td>
<td>552</td>
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</table>
Air-side modifications to improve performance
Baffling modifications for Plant A

- Same fans currently used by Plant A
- Top portion of spiral now receives greatest flow

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<thead>
<tr>
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<tr>
<td>Spiral</td>
<td>825 {4.19}</td>
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<tr>
<td>Coils</td>
<td>492 {2.50}</td>
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<thead>
<tr>
<th>Energy Per Product [Btu/prod]</th>
<th>Throughput [prod/min]</th>
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<tr>
<td>154 (with baffling)</td>
<td>175</td>
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<tr>
<td>173 (Plant A)</td>
<td>145</td>
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Percent Change

-11.0%  20.8%
4 ft straight long throw adapter

<table>
<thead>
<tr>
<th>Average Velocity</th>
<th>Spiral</th>
<th>Coils</th>
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<tr>
<td>[m/s]</td>
<td>3.00</td>
<td>2.12</td>
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<tr>
<td>[fpm]</td>
<td>591</td>
<td>417</td>
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4 ft bent long throw adapter

<table>
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<tr>
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<th>Spiral</th>
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<tr>
<td>[m/s]</td>
<td>3.59</td>
<td>2.61</td>
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<td>[fpm]</td>
<td>707</td>
<td>514</td>
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4.75 ft bent long throw adapter

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<tr>
<td>[m/s]</td>
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<tr>
<td>[fpm]</td>
<td>705</td>
<td>490</td>
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</table>
5 ft bent long throw adapter

<table>
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<th>Average Velocity</th>
<th>Spiral [m/s]</th>
<th>Coils [fpm]</th>
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<tr>
<td>[m/s]</td>
<td>3.74</td>
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<td>[fpm]</td>
<td>736</td>
<td>474</td>
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6 ft bent long throw adapter

<table>
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<td>[m/s]</td>
<td>3.30</td>
<td>2.54</td>
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<tr>
<td>[fpm]</td>
<td>650</td>
<td>500</td>
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5 ft bent & chamfered long throw adapter

<table>
<thead>
<tr>
<th>Average Velocity</th>
<th>Spiral [m/s]</th>
<th>Coils [fpm]</th>
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<tbody>
<tr>
<td>[m/s]</td>
<td>3.69</td>
<td>2.48</td>
</tr>
<tr>
<td>[fpm]</td>
<td>727</td>
<td>488</td>
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</table>
5 ft bent & chamfered LTA with additional baffing

<table>
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<th>Spiral</th>
<th>Coils</th>
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<tbody>
<tr>
<td>[m/s]</td>
<td>3.33</td>
<td>2.48</td>
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<tr>
<td>[fpm]</td>
<td>656</td>
<td>488</td>
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</table>
Are the CFD model results believable?
Surrogate product – “phantom”

Air temperature sensor

Heat flux sensor – top and bottom

Embedded “product” center temperature sensor & heater

Make sure model matches reality

Step 3
Data logging equipment
DC battery to power heater and equipment

mV DC to 4-20 mA transmitters

Various data loggers
The Phantom is an instrument that simulates the product being frozen for the purpose of gathering heat transfer data within the operating blast freezing system.
Preparing to run the Phantom
Dry run of the phantom in a spiral freezer
Phantom running during production
Comparing CFD with Phantom results
What about the product itself?
Thermal model of food product being frozen

Needed Properties
1. Density ($\rho$)
2. Thermal conductivity ($k$)
3. Heat capacity ($c$)
4. Water content
5. Air voids

\[ \frac{dU}{dt} = \dot{q}_{\text{conv}} = h(t)A_c (T_\infty - T_N) \]

\[ h(t) \text{ (heat transfer coefficient)} \]
Product thermal properties

Density ($\rho$) = constant = 533.8 kg/m$^3$

\[
c = \frac{1}{\sigma \sqrt{2\pi}} e^{\left(\frac{1}{2}\left(\frac{T-\mu}{\sigma}\right)^2\right)} 113100 \left[ \frac{J}{kg} \right] + 2460 \left[ \frac{J}{kg} \right]
\]
Product thermal model results

Velocity from CFD

Thermal model

Temperature [°F] vs. Time [s]

- \( x/L = 0 \) (bottom)
- \( x/L = 0.25 \)
- \( x/L = 0.5 \) (center)
- \( x/L = 0.75 \)
- \( x/L = 1 \) (top)
- Velocity (m/s)
Effect of velocity on product

4.2% improvement
Exiting temperature vs belt speed

Temperature as a Function of Belt Speed

Exiting temperature of product (F)

Belt speed (units/min)
Optimizing freezing process

Step 1-A
Initial velocity distribution

Step 1-B
Adjust belt speed that achieves temperature set point (ΔT) at exit. Output is velocity profile and belt speed

Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1453.6273 seconds
Elapsed time is 2.391258 seconds.
Temperature delta T: 10.4441 @ a belt speed of 164.8625
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1535.9025 seconds
Elapsed time is 2.705465 seconds.
Temperature delta T: 6.7566 @ a belt speed of 135.8625
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1571.7726 seconds
Elapsed time is 2.586108 seconds.
Temperature delta T: 2.7032 @ a belt speed of 142.8406
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1605.9942 seconds
Elapsed time is 2.509586 seconds.
Temperature delta T: 0.62127 @ a belt speed of 146.3977
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1571.7726 seconds
Elapsed time is 2.554558 seconds.
Temperature delta T: 2.7032 @ a belt speed of 142.8406
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1616.0127 seconds
Elapsed time is 2.485224 seconds.
Temperature delta T: 0.43622 @ a belt speed of 148.1932
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1596.6667 seconds
Elapsed time is 2.450556 seconds.
Temperature delta T: 0.022483 @ a belt speed of 147.4904
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1606.0127 seconds
Elapsed time is 2.505074 seconds.
Temperature delta T: 0.62118 @ a belt speed of 146.3977
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1612.8954 seconds
Elapsed time is 2.501893 seconds.
Temperature delta T: 0.17078 @ a belt speed of 147.7432
Velocity profile: spiral_midlane_existing_revEA.csv
Freezing time (Mid temp <= 10°F): 1614.3259 seconds
Elapsed time is 2.552271 seconds.
Temperature delta T: 0.022483 @ a belt speed of 147.4904

Optimization strategy:
- **Iteration #1**
- **Iteration #2**
- …3
- …4 etc.

Optimum belt speed
Monte Carlo simulation with varying velocity distribution (two step/regime) across product

- Random velocity 1
- Random time duration 1
- Random velocity 2
- Random time duration 2
Monte Carlo Pareto front simulation to identify efficient velocity profile regime values with constrained mean and limits that maximizes belt speed

Step 1-A
Generate random velocity distribution

Step 1-B
Adjust belt speed that achieves temperature set point ($\Delta T$) at exit. Output is velocity profile and belt speed

Repeat 1000+ times, establish Pareto front
Pareto front

![Graph showing the relationship between Belt Speed and Average Velocity with different performance categories: Existing Distribution, Reverse of Existing, High Performing, and Low Performing.](image)
Pareto front – deep dive
Refinement

- 10 regimes
- Same time duration
- Random velocities with constraints
- Thousands of unique distributions

...+Randomization
Optimized air velocity Pareto front

![Graph showing the relationship between Belt Speed [products/min] and Average Velocity [m/s]. The graph includes data points for Existing Distribution, Reverse of Existing, High Performing, Low Performing, and Optimized air velocity. The optimized solution is indicated by a green triangle.](image-url)
Model results

11% improvement in throughput with identical average velocity through the spiral, just a better distribution
Future work

• Field evaluate different blast freezer configurations
  • Phantom can serve as a benchmarking tool
  • Measure air infiltration rate vs. best practice
• CFD model to establish baseline performance and evaluate strategies to improve air-flow
• Build optimization algorithms that account for energy cost, fan power, etc., that can be calibrated to many systems
• Validate results from facility modifications
• Transplant knowledge to end-users and freezer manufacturers
Airflow optimization - existing and new builds

- Use optimal velocity distributions to guide baffling modifications and hypothetical designs
New build design

- Same fans currently used by Plant A
- Opposing fans creates a “tornado” effect

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<tr>
<td>Spiral</td>
<td>1,157 {5.88}</td>
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<tr>
<td>Coils</td>
<td>579 {2.94}</td>
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<table>
<thead>
<tr>
<th>Energy Per Product [Btu/prod]</th>
<th>Throughput [prod/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>139 (new design)</td>
<td>207</td>
</tr>
<tr>
<td>173 (Plant A)</td>
<td>145</td>
</tr>
</tbody>
</table>

| Percent Change | 19.4% | 43.3% |

Drawback: Area 24.3% larger, however Volume 5.6% smaller
New build design (four fans)

- Same fans currently used by Plant A
- Even greater energy savings

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<tr>
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</tr>
<tr>
<td>907 {4.61}</td>
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<tr>
<td>Coils</td>
</tr>
<tr>
<td>394 {2.00}</td>
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<table>
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<th>Energy Per Product [Btu/prod]</th>
<th>Throughput [prod/min]</th>
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<tbody>
<tr>
<td>131 (four fans)</td>
<td>171</td>
</tr>
<tr>
<td>173 (Plant A)</td>
<td>145</td>
</tr>
</tbody>
</table>

Percent Change

-24.1%          18.5%

Drawback: Area 24.3% larger, however Volume 5.6% smaller
Future Work

• Gather performance data for more blast freezers
• Find baffling configurations for a wider range of blast freezer designs
• Finding optimal flow angle for maximum heat transfer with minimal flow resistance
• Optimize “new build” configurations
Questions?