Reducing Display Bottle Cooler Energy Consumption using PCM as Active Thermal Storage

By

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Introduction

- European Framework 7 Project acronym iCool
- Minimize total energy consumption of a bottle cooler
- Target > 75% energy consumption reduction compared to state of the art bottle cooler (2010 figures)
- Applying standard energy reducing options
- Using PCM to overcome peak demands (warm product) & to minimize temperature lift
- Applying a very small and efficient cooling system just coping with the time averaged cooling demand
  » Design for small temperature lift through using a highly efficient compressor developed for the domestic market
Bottle cooler

Characteristics

- Glass door cooler
- Volume = 386 dm³
- Load = 492 cans (0.33 dm³)
- Internal lighting
- Canopy lighting
- Energy consumption (benchmark 2010) = 5.7 kWh/24h (Lot 12 results)
- Energy consumption target < 1.4 kWh/24h (75% reduction)
- Half Reload Recovery (HRR) within 16 h at an ambient of 32 °C (110 HRR /y).
Appliance design

Heat load distribution

- Glass door: triple layer krypton filled glass. \((UA = 1.1 \text{ WK}^{-1})\)
- Insulation: 49 mm PUR + Vacuum panels fitted into the side walls \((UA = 1.35 \text{ WK}^{-1})\)
- Internal fan \((140 \text{ m}^3\text{h}, 6 \text{ W})\)
- Internal lighting \((7 \text{ W LED})\)
- Total reduction in heat load from 135 to 68 W (50%)
Appliance design
Cooling system

Design

- 8.7 kg of PCM (water)
- Product temperature spread < 3 K
- Compressor size 5.19 cm³ (R-600a)
- Compressor COP = 1.88 @ ASHRAE LBP
  - COP 3.8 at design condition (Te = -2.5 °C, Tc = 33 °C, Tsub = 2 K, Tsup = 0 °C, Tsuc = 25 °C)
- Condenser fan 200 m³h, 3.7 W
- Fin & Tube Evaporator UA = 40 WK⁻¹
- PCM evaporator UA = 25 WK⁻¹
- Condenser UA = 37 WK⁻¹
- Evaporation temperature at steady state -2.5 °C (ambient 25 °C)
- Condensation temperature at steady state 33 °C (ambient 25 °C)
PCM evaporator

- Evaporator plate fitted in center of casing
- Air passes at front and back wall
- Small thermal resistance between the refrigerant and the ice / water due to the use of an extended surface
Control

- During Steady State; Refrigerant flows through both evaporators
- During HRR the PCM evaporator is bypassed
  - PCM cold capacity is used for cooling the air / product
  - Active cooling through Fin & Tube only
- Compressor controlled by the internal temperature & state of the PCM
  - Layer thickness through electric conductivity measurement
- Product temperature control through internal fan
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Modelling

- Based on 72 h period, starting with HRR and solid PCM.
- Based on PCM phase change temperature of 4 and 0 °C
- UA values of condenser and evaporator as designed
- UA value evaporator / PCM of 200 WK\(^{-1}\) for ice and 20 WK\(^{-1}\) for 4 °C PCM
- Appliance heat load (UA) as designed
- Including valve control (i.e. valve switch)
- Compressor variation through proportional scaling of a commercially available compressor (3 cm\(^3\), R-600a)
- Business / non Business operation (8 h lighting on / 16 h lighting off)
- Lighting off during HRR
- HRR end @ average product temperature = 2.5 °C.
- Model does not yet include fan switch and PCM state sensor
Modelling

HRRT vs. Swept Volume

TEC vs. Swept Volume

Too long HRRT
No cooling time reduction with 4 °C PCM
   » Initial reduction in cooling time is negated by the increase in cooling time after reaching an air temperature equal to the phase change temperature.

Cooling time reduction with 0 °C PCM
   » Possible to apply smaller compressor size (i.e. from 6 to 4.5 cm$^3$) to reduce appliance TEC with approximately 4%
Modelling

TEC vs. PCM Mass

Calculations based on a 4.5 cm³ compressor and PCM of 0 °C
Modelling

- For the evaluated design the HRRT does not further reduce for a PCM mass above 10 kg
  - above 10 kg, ice is present after completion of the HRR
- TEC reduces with increasing PCM mass
  - Larger PCM mass results in a longer period with efficient operation of the evaporator.
  - Model does not include PCM state sensor and fan switch, therefore the results with large PCM mass give too positive results (no proper refreezing)
- Small dependency of TEC on UA value between PCM evaporator and air
  - Due to the use of PCM (0 °C), the coupling between the evaporator temperature and the air side heat transfer of the PCM evaporator is weak
- With increasing UA more PCM can contribute in cooling down the warm product, which opens the possibility to apply even smaller compressors.
Test Results

HRR and TEC according to the Heineken test protocol

- Includes appliance lighting during business hours
- Includes a HRR every 72 h (110 HRR / y)
- Ambient 25 and 32 °C
- Average product temperature of 2.5 °C
- Product temperatures within -1 and 6 °C
- HRR within 16 h
- No opening of the door
# Test Results

<table>
<thead>
<tr>
<th></th>
<th>Ambient 25 °C / 60% Rh</th>
<th>Ambient 32 °C / 65 %Rh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half reload recovery time</td>
<td>10.46 h</td>
<td>15.8 h</td>
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<tr>
<td>Average product temperature</td>
<td>1.2 °C</td>
<td>1.3 °C</td>
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<tr>
<td>during steady state</td>
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<td></td>
</tr>
<tr>
<td>Product temperature spread</td>
<td>2.1 K</td>
<td>3.0 K</td>
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<td>during steady state</td>
<td></td>
<td></td>
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<tr>
<td>Compressor run time</td>
<td>29.7%</td>
<td>46.4%</td>
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<tr>
<td>during steady state</td>
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<td></td>
</tr>
<tr>
<td>Compressor operating period</td>
<td>4.8 h</td>
<td>11.1 h</td>
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<tr>
<td>during steady state</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total appliance energy</td>
<td><strong>0.89 kWh/24h</strong></td>
<td><strong>1.24 kWh/24h</strong></td>
</tr>
<tr>
<td>consumption</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Discussions

- For further design optimization the model needs to be improved to include state sensor and fan control.

- During the tests the appliance was operating 1.3 K below specification.

- The power consumption of the current prototype controller can be reduced from 3 to 1 W.

- Implementation of an offset temperature during off business hours can further reduce TEC.
Conclusions

- Project is concluded with a demonstrator appliance having a TEC of 0.89 kWh/24 h (84% reduction compared to the benchmark)
- > 90% results from the heat reducing options applied
- 4-10% results from the use of active PCM
- Applying active PCM is only seen as an energy reduction option after minimizing appliance heat load and optimizing the cooling system
Thank You

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