Thermal Insulation of Household Refrigerators: Perspectives and Evaluation Methods

Cláudio Melo | Federal University of Santa Catarina
Historical Aspects
Design Requirements
Cabinet Thermal Load
Thermal Insulation
Evaluation Methods
Final Remarks
Q) How did our ancestors live without refrigerators?
A) They simply made use of natural ice.

The trading of natural ice on a commercial scale was initiated by Frederic Tudor (1783-1864) who, in around 1806, cut ice from the Hudson River in the United States and sold it.
At the beginning of the 20th century wooden boxes insulated with various materials, including cork and sawdust, were used to hold blocks of ice and refrigerate food.
The introduction of CFCs, in the 30’s, allowed the widespread use of household refrigerators, which had evolved from being seen as a luxury into a necessity.
The **Coefficient of Performance (COP)** represents the ratio

\[
\text{magnitude of desired commodity} \quad \frac{\text{magnitude of expenditure}}{
\]

or,

\[
\text{useful refrigeration} \quad \frac{\text{net work}}{
\]

\[
COP = \frac{\dot{Q}_E}{\dot{W}_C}
\]
Design Requirements

In 1974 it was found that the CFCs would reach the stratosphere and there deplete the ozone layer. Later, these substances were also found to contribute to the greenhouse effect. Thus, ecological appeal became an additional design requirement in the refrigeration industry.
The thermal load imposed on the refrigerating system comes from both **external** and **internal** heat sources.

The heat gain through the walls and magnetic door gasket can potentially reach about **55%** and **30%** of the thermal load of a refrigerator, respectively.

\[
\dot{Q}_{tot} = \dot{Q}_{walls} + \dot{Q}_{gasket} + \dot{Q}_{miscellaneous} = \dot{Q}_{E}
\]
Cabinet Thermal Load

- Research efforts on gasket and flange designs are needed in order to reduce the energy losses in the gasket region.

- Future reductions in cabinet thermal load must come from advanced insulations or door gasket improvements.

- Reducing cabinet thermal load would lower the electrical power input to the compressor by an amount proportional to the reduction.
• In the 60’s, the insulation material was changed from mineral wool and cork to **polyurethane foam (PU)**. This change lowered the energy consumption by around 50%.

• Polyurethane foam insulation has been used in refrigerators for over 40 years, originally using **CFC-11**. Because of the ozone damage the Montreal Protocol began curtailing its use in 1994.

• Most US manufactures of refrigerators then converted to **HCFC-141b** as an interim blowing agent; those in other parts of the world move straight to **cyclopentane**.
Thermal Insulation

HCFC-141b
Was banned from the U.S. market in 2010 and will be banned from the Canadian market in 2014.

HFC-245fa
Its use will be restricted by 2016 and 2012 in the U.S. and Europe markets, respectively.

HFO-1234ze
HBA-2
AFA-L1
FEA-1100...
C-pentane

Pentane isomers, widely used in Europe and also in other regions of the globe, seems to be the most promising long-term alternative.

The insulation levels provided by synthetic blowing agents are comparable to that of CFC-11, but HC foams have generally slightly poorer insulation values (5-10%), which imposes an additional performance requirement on the new cooling systems.
Increasing the insulation thickness to reduce the cabinet thermal load is **limited** due to the manufacturers’ desire to provide **maximum internal volume** for their products.
Due to the impossibility of reducing the thermal conductivity or increasing the thickness of the polyurethane foam, the use of vacuum insulation panels (VIPS) seems to be a promising alternative to reduce the thermal load and therefore to improve the system performance.

**Polyurethane foams:** 20mW/mK

**VIPS:** 3 to 5mW/mK

VIP thermal conductivity versus temperature
Thermal Insulation

• A VIP (~1 mbar) consists of a low thermal conductance fill and an impermeable skin.

• Fine mineral powders such as silica and fiberglass are normally used as fillers.

• Metalized skins such as aluminum coated polyethylene (PE) are sufficient impermeable while causing minimal edge effect - heat conduction path from the warm to the cold side of the panel.
Thermal Insulation

The widespread use of vacuum insulation panels has always been limited because of their high cost. Besides, there is a view in the industry that they sometimes fail to achieve expected improvements.

However, the energy consumption targets have reached an order of magnitude such that even with a high cost some manufactures are using them on a regular basis, especially in high-end products.
• This is a **novelty in domestic refrigeration**, a field traditionally driven by cost reduction.

• However, there still a need for breakthrough **cost reduction** technology to enable wide scale use in domestic refrigerators.

• Finally, reliability is a concerns due to **performance degradation** over time.
Evaluation Methods

Reverse heat leakage

- The thermal load is calculated from the thermal conductances, $UA_{fz}$ and $UA_{ff}$.

$$
UA_{fz} (T_{fz} - T_{amb}) + UA_{ff} (T_{ff} - T_{amb}) = W_{ff} + W_{fz} + W_{fan}
$$

<table>
<thead>
<tr>
<th>Test</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh-food temperature, °C</td>
<td>31.3</td>
<td>35.0</td>
<td>39.4</td>
<td>43.6</td>
</tr>
<tr>
<td>Freezer temperature, °C</td>
<td>39.1</td>
<td>47.7</td>
<td>52.8</td>
<td>55.2</td>
</tr>
<tr>
<td>Ambient temperature, °C</td>
<td>24.9</td>
<td>24.9</td>
<td>24.9</td>
<td>24.9</td>
</tr>
<tr>
<td>Fresh-food heater, W</td>
<td>0.0</td>
<td>1.4</td>
<td>8.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Freezer heater, W</td>
<td>11.0</td>
<td>20.0</td>
<td>22.3</td>
<td>19.9</td>
</tr>
<tr>
<td>Fan power, W</td>
<td>6.3</td>
<td>6.3</td>
<td>6.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

$$
UA_{ff} = 1.30 \text{ W/K} \\
UA_{fz} = 0.64 \text{ W/K}
$$
Evaluation Methods

Heat flux meters
# Evaluation Methods

## Heat transfer paths

<table>
<thead>
<tr>
<th>Location</th>
<th>Taxa [W]</th>
<th>Fláuxo [W/m²]</th>
<th>Porcentagem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portas</td>
<td>13,4</td>
<td>9,7</td>
<td>22,6</td>
</tr>
<tr>
<td>Laterais</td>
<td>22,7</td>
<td>10,4</td>
<td>38,3</td>
</tr>
<tr>
<td>Posterior</td>
<td>14,7</td>
<td>11,3</td>
<td>24,7</td>
</tr>
<tr>
<td>Fundo</td>
<td>3,3</td>
<td>8,2</td>
<td>5,6</td>
</tr>
<tr>
<td>Topo</td>
<td>5,2</td>
<td>14,5</td>
<td>8,7</td>
</tr>
</tbody>
</table>

**Distribuição de carga térmica por macrorregiões**

- Blue: Taxa [W]
- Green: Fláuxo [W/m²]
- Red: Porcentagem
Evaluation Methods

CFD analysis

Thermal Insulation for the White Line
Evaluation Methods

EPA data (1993)

<table>
<thead>
<tr>
<th></th>
<th>VIP coverage area [%]</th>
<th>Drop in energy consumption [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>54</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>68</td>
<td>8</td>
</tr>
</tbody>
</table>

Fundamental question: where should the vacuum panels be applied, i.e., where will they be most effective?
Evaluation Methods

Reverse heat leakage measurements

Sample 1: 8 VIPs

\[ UA_{ff} = 0.59 \text{ W/K} \]
\[ UA_{fz} = 0.40 \text{ W/K} \]

Sample 2: 2 VIPs

\[ UA_{ff} = 0.61 \text{ W/K} \]
\[ UA_{fz} = 0.37 \text{ W/K} \]

The conventional reverse heat leakage method does not capture the effect of the VIPs!!!
Evaluation Methods

CFD analysis
Evaluation Methods

Prototypes

Sample 1
Thickness 8mm

Sample 2
Thickness 8mm

Thermal Insulation for the White Line
Evaluation Methods

Prototypes

Samples 3 and 4
Thickness 8mm and 16mm

Sample 5
Thickness 8mm

Thermal Insulation for the White Line
Final Remarks

In addition to the energy consumption requirements household refrigerators must have a low cost and be environmentally friendly, without leaving aside the indispensable requirements of low noise, safety, reliability, etc.

To design household refrigerators without penalties in terms of any of these requirements is the major challenge in current refrigeration engineering.
Thermal Insulation for the White Line

Laboratórios de Pesquisa em Refrigeração e Termofísica
Research Laboratories for Emerging Technologies in Cooling and Thermophysics

Cláudio Melo
melo@polo.ufsc.br
Federal University of Santa Catarina
Department of Mechanical Engineering
88040-900 – Florianópolis - SC - Brazil
phone +55 (48) 3234.2691   fax +55 (48) 3234.5166
http://www.polo.ufsc.br