Overview of Human Thermal Modeling, Thermoregulation, and Thermal Comfort at NASA

Hee Jong Song
Engineering Design and Analysis Branch
Crew & Thermal Systems Division
JSC/NASA
Overview/Objective

- History of Human Thermal Models
- Human Thermal Models Used at NASA/JSC
- Thermoregulation
- Testing/Correlation
- Core Body Temperature Measurement
- Thermal Comfort Criteria

Focus on applicability of Human Thermal Models to assess Thermoregulation Concepts for Thermal Comfort
### History

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1927</td>
<td>Bazett and McGlone</td>
<td>Measured temperature gradients in the arm</td>
</tr>
<tr>
<td>1934</td>
<td>Alan Burton</td>
<td>1st mathematical model of temperature distribution</td>
</tr>
<tr>
<td>1936</td>
<td>Burton and Bazett</td>
<td>1st transient conduction model for the body</td>
</tr>
<tr>
<td>1948</td>
<td>Pennes</td>
<td>Blood flow on tissue temperature</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>Wissler</td>
<td>1st multi-element human thermal model</td>
</tr>
<tr>
<td>1964</td>
<td>Wissler</td>
<td>Human thermoregulation model using finite difference method and solved on a digital computer</td>
</tr>
<tr>
<td>1966</td>
<td>Stolwijk and Hardy</td>
<td>Skin blood flow, sweating, and shivering</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Stolwijk</td>
<td>25 node model used for Apollo PLSS</td>
</tr>
<tr>
<td></td>
<td>Kuznetz</td>
<td>41 node &quot;metabolic man&quot;, LCG, EMU</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Wissler</td>
<td>15 segment, 225 node model modified by Nyberg, added LCVG for Constellation program</td>
</tr>
<tr>
<td>2009</td>
<td>Wissler</td>
<td>3780 node model (3D)</td>
</tr>
</tbody>
</table>
Wissler & METMAN

Wissler
- 225 Nodes
- 15 Segments with 15 Tissue nodes
- 2 Blood Nodes per Segment

METMAN
- 41 nodes
- 10 segments with 4 nodes
- 1 Central Blood Node
3780-node Wissler

- Can resolve lateral & circumferential differences
- May be need for some localized cooling techniques
Human Thermal Model

- **Simulation**
  - Linear conduction
  - Blood circulation
  - Vasoconstriction
  - Sweating
  - Shivering
  - Respiration
- **Heat Transfer Modes**
  - Respiratory dry heat
  - Respiratory water vapor exchange
  - Conduction through clothing
  - Convection & radiation from skin to ambient environment
  - Vapor loss from the skin
  - Heat exchange with fluid cooled garment
Input/Output

**Input**
- Mode (shirt sleeve, LCVG, IVA/EVA)
- Metabolic rate
- Height/weight
- Environment
  - Temperature
  - Humidity
  - Flow Velocity
- Respiratory quotient
- Work efficiency

**Output**
- Core body temperature
- Heat storage
- Skin temperature
- Sensible/latent heat
- Shiver rate
- Evaporation
Testing/Model Correlation

- Skin temperatures
- Core body temperature
- Oxygen Consumption (metabolic rate)
- Sweat
Core Body Temperature

- **SpotOn/Bair Hugger (3M)**

- **CorTemp (HQ Inc)**
  - CorTemp Sensor (pill)
  - Wireless Monitoring Data Recorder

- **Rectal Probe**
Thermal Comfort Criteria

- Objective vs. Subjective criteria
- Body thermal storage within comfort range
- Evaporative heat loss
- No thermogenic shivering
- Body core temperatures near normal resting values
- Skin temperatures near normal resting values
Thermal Comfort Criteria

- **Body thermal storage within comfort range**

<table>
<thead>
<tr>
<th>Energy Stored/Mass (BTU/lbm)</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>Hot Impairment</td>
</tr>
<tr>
<td>1.3</td>
<td>Hot Comfort</td>
</tr>
<tr>
<td>-0.8</td>
<td>Cold Comfort</td>
</tr>
<tr>
<td>-1.8</td>
<td>Cold Impairment</td>
</tr>
</tbody>
</table>

- Evaporative heat loss
- No thermogenic shivering
- Body core temperatures near normal resting values
- Skin temperatures near normal resting values
Thermal Comfort Criteria

- **Body thermal storage within comfort range**
- **Evaporative heat loss**
  - Insensible evaporation only
    - Respiration
    - Diffusion
  - No active sweating
- **No thermogenic shivering**
  - Shivering helps the body create heat. The skeletal muscles create the shivering. There’s a little muscle on each hair that helps to create a better blanket for us. The shivering heats up the body. The non-shivering thermogenesis fits into a classification, which is called diet-induced thermogenesis
- **Body core temperatures near normal resting values**
- **Skin temperatures near normal resting values**
Thermal Comfort Criteria

- Body thermal storage within comfort range
- Evaporative heat loss
- No thermogenic shivering
- **Body core temperatures near normal resting values**
  - Approximately 37 °C (99 °F)

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;102.2</td>
<td>Pyrexia-severe sweating, fainting, dehydration, weakness</td>
</tr>
<tr>
<td>&gt;100.4</td>
<td>Moderate to severe sweating, flushed and very red</td>
</tr>
<tr>
<td>&gt;99.5</td>
<td>Mild to moderate sweating</td>
</tr>
<tr>
<td>96.8-99.5</td>
<td>Normal Body Temperature</td>
</tr>
<tr>
<td>&lt;96.8</td>
<td>Mild to moderate shivering</td>
</tr>
<tr>
<td>&lt;94.9</td>
<td>Hypothermia-intense sweating, numbness and blue/grey skin</td>
</tr>
<tr>
<td>&lt;93.2</td>
<td>Severe Shivering, loss of finger movement, blueness and confusion</td>
</tr>
</tbody>
</table>

- **Skin temperatures near normal resting values**
Thermal Comfort Criteria

- Body thermal storage within comfort range
- Evaporative heat loss
- No thermogenic shivering
- **Body core temperatures near normal resting values**
- **Skin temperatures near normal resting values**
  - Approximately 32.8 °C to 34.4 °C (91 °F to 94 °F)
Conclusions/Q&A

- As Human Thermal Models have evolved, they have proven useful tools to predict human thermal response
- NASA has refined and used Human Thermal Models to design, develop, and test ECLSS (Environmental Control and Life Support Systems)
- Human Thermal Models could be used with Thermal Comfort Criteria may be used to assess effectiveness of Local Thermal Management Systems

- Questions/Comments?

Durrant and Fricker; “Exploration EVA Suit Thermal Performance in a Variety of Environments”; 44th International Conferences on Environmental Systems; ICES-2014-271

Cognata and Durrant; “3D Modeling of the Human Thermal Interaction in Complex Environments using the Wissler Human Thermal Model”; 44th International Conferences on Environmental Systems; ICES-2014-266

Wissler; “A New Human Thermal Model”; Proc. 13th Int’l Conf. on Environmental Ergonomics, Aug 2-9, 2009, Boston, MA

Bue; “Computer Program Documentation, 41-node Transient Metabolic Man Program”; CTSD-0425
### Thermal Comfort Criteria

#### The Borg Scale

<table>
<thead>
<tr>
<th>Colour</th>
<th>BORG</th>
<th>Explanation/perceived exertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>GREEN</td>
<td>6</td>
<td>Zero exertion</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Very easy</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Minimal recognition of effort</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Very light (Comfortable walking pace)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Can just start to hear your breathing</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Conversation is easy and you feel you could run for a while at this pace</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Light exertion - This is where you are developing your aerobic system</td>
</tr>
<tr>
<td>YELLOW</td>
<td>13</td>
<td>Somewhat hard</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>You can hear your breathing but you're not struggling</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>You can talk but not in full sentences - You are still developing the aerobic system here but getting towards its top end</td>
</tr>
<tr>
<td>ORANGE</td>
<td>16</td>
<td>Hard work - This is probably just below your anaerobic threshold</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>Very hard - Starting to get uncomfortable and you're getting tired - This probably represents your anaerobic threshold</td>
</tr>
<tr>
<td>RED</td>
<td>18</td>
<td>You can no longer talk because your breathing is heavy</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>Extremely hard. Your body is screaming at you to stop</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Max exertion</td>
</tr>
</tbody>
</table>