FIELD STUDY OF THE THERMAL ENVIRONMENT CREATED BY A RADIANT HEATING SYSTEM IN A DETACHED HOUSE FOR SLEEP THERMAL COMFORT
INTRODUCTION

- We sleep a significant portion of our lives
- But sleep thermal comfort have not really been investigated or defined
Established Standards

- ASHRAE 55: Thermal environmental conditions for human occupancy
  - Definition of thermal comfort: The condition of mind that expresses satisfaction with the thermal environment
- ISO 7730: Ergonomics of the thermal environment
- Both radiant thermal condition criteria is based on P.O. Fanger’s Work
Definition of Thermal Comfort

- ASHRAE 55 especially excludes the sleep condition
- What is sleep thermal comfort:
  - Sleep is unconscious, how can the mind express or how do we record satisfaction?
- Existing research in thermal comfort: neutral heat balance method (Fanger, Gagge)
## Comparison Between Asleep and Awake

<table>
<thead>
<tr>
<th>Asleep</th>
<th>Awake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reclined or laid down</td>
<td>Standing or seated</td>
</tr>
<tr>
<td>Reduced metabolism rate &lt; 40 W/m²</td>
<td>Varied metabolism rate &gt; 60 W/m²</td>
</tr>
<tr>
<td>Generally higher clothing value - blanket</td>
<td>Generally lower clothing value</td>
</tr>
<tr>
<td>Unconscious thermal regulation and incapable of controlling the environment</td>
<td>Conscious thermal regulation and active participation in controlling the environment</td>
</tr>
</tbody>
</table>
Given the differences between sleep and awake conditions, existing thermal comfort research is not entirely applicable.

Some research into thermal comfort of sleeping bags is applicable:

This current research will borrow from psychology: Sleep Quality and Sleep Efficiency – function of sleeping time, REM, S3 and S4 of sleep
Why – Radiant Heating and Sleep?

- Working as a HVAC designer/consultant, several client asked: Why did they wake up in the middle of the night with a cold sweat?
- HVAC systems were radiant heating
- Only males responded to having this issue
- Only occurs when it is near the design conditions outdoors – i.e. HVAC system operating at maximum capacity
RESEARCH OBJECTIVE AND METHODOLOGY

• Research objective:
  – Focus is on establishing sleep thermal comfort from a radiant ceiling heating system
  – Secondary focus is on potential energy savings of operating the system in reduced output mode during the hours of sleep

• Research Methodology
  – Development of a simple model for sleep thermal comfort
  – Experimental data collection in a building where the occupant have complained about sleep thermal comfort
  – Comparison of model and experimental data
DEVELOPMENT OF SLEEP THERMAL MODEL

- Two types of thermal model are widely used:
  - Single node model
    - Treat body as a single mass of flesh
    - Was used to model people whom are awake and for sleeping bags (Goldman 1988, Holland 1999, McCullough 1994, Hartog et al 2001)
    - Suggested and used by ASHRAE Fundamentals 2009 and ISO 11079
  - Two node model
    - Treat body as two concentric mass of flesh
    - Widely used to model awake people
    - Used by researcher like: KSU, Pierces and Gagge
Model for this research is based on the single node model:

- Radiant: Stefan-Boltmann’s law
- Convection: ASHRAE Fundamentals for free convection over a cylinder
- Conduction: Fourier’s law
- Latent heat loss: Respiration at 8.7 L/min @ 34°C leaving (Cain et al, 1990)
THE ASSUMPTIONS FOR THIS HEAT BALANCE MODEL

• Existing Literature
  – Sleep is complex, 4 stages of sleep, vasculatory rhythms, thermal regulatory cycles
  – No direct research into the “average” person; existing research focus on sleep disorders, elderly, soldiers and athletes
  – Simplified documentation of thermal environment, i.e. only a simple air temperature measurement

• Assumptions
  – Steady state for the entire period of sleep – unless the thermal environment is for one person and that there is a monitoring system on that person, the HVAC system have to one condition
BOUNDARY CONDITIONS

• Skin temperature:
  – Neutral heat balance: 32°C for soldiers’ sleeping bags (Goldman)
  – Neutral heat balance: 31.5°C for athletes’ sleeping bags (KSU)
  – Neutral heat balance Europe: 32.8°C for athletes’ sleeping bags (EN13573)
  – Sleep quality study: 32.5°C (Bischof et al)

• Body heat loss rate:
  – 34.9 W/m² to 43.5 W/m² with body heat deficit (Goldman)
  – 36 W/m² with body heat gain (Bischof et al)
HEAT BALANCE MODEL DIAGRAM

SLEEP THERMAL COMFORT
TUESDAY MAY 31, 2011
Heat Balance Calculation Results

- 1 Clo = 1.55 Tog
- All season blanket = 3 to 5 Tog
- Suggest overheating if operative temperature (average of air temperature and MRT) > 16 °C
EXPERIMENT SITE

- Site is single family home located in Caledon Ontario Canada
- Floor area is around 560 m², volume is around 2,400 m³
- Sprayed concrete hydronic radiant heating system
- Triple low-E Argon RSI 1.2 windows
- RSI 6.2 walls.
Simplified HVAC Heat Flow Schematic

- Well Source Heat Pump
- Backup Wood Boiler
- Thermal Storage Tank 4100 L
- Radiant Heating Panel
EXPERIMENT SETUP

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Air Temperature Stratification Array
Black Globe and Hot Sphere Anemometer
## Sensors and Measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sensors</th>
<th>Deployed Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Radiant Temperature</td>
<td>Black Globe Thermometer and Hot Sphere Anemometer</td>
<td>1</td>
</tr>
<tr>
<td>Surface Temperatures</td>
<td>Type T thermocouple surface temperature sensors</td>
<td>19</td>
</tr>
<tr>
<td>Air Temperature Stratification</td>
<td>Type T thermocouple radiant shielded temperature sensor</td>
<td>5</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Relative humidity probe</td>
<td>1</td>
</tr>
<tr>
<td>Outdoor relative humidity and temperature</td>
<td>Micro weather station</td>
<td>1</td>
</tr>
</tbody>
</table>
WALL SURFACE TEMPERATURE COMPARISON

Radian Panel
Free Ceiling, Walls and Floor
Windows

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Everyone Makes a Mark
WALL SURFACE TEMPERATURE COMPARISON

Hydronic Supply

Radiant Panel

Top: MRT
Middle: T-opr
Bottom: T-air

Outdoor Air

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RYERSON UNIVERSITY
Everyone Makes a Mark
Maximum rate of change for operative temperature is approximately 1 °C/6 hours: less than ASHRAE 55 limit of 3.3 °C/4 hours
- Radiant asymmetry within ASHRAE 55 requirements
- The operative temperature was between 19 °C and 25 °C, regardless of outdoor temperature -24 °C to 10 °C
- Higher than the operative temperature calculated for comfortable sleep
- The mean air velocity is measured at 0.021 m/s.
- Relative humidity is between 21% to 37%
- The air temperature did not lag the MRT significantly and is approximately 1 °C lower than the MRT
This radiant heating system considered comfortable under existing standards for an awake person.

The operative temperature recorded is higher than what is calculated for comfortable sleep.

Possible reduction of operative temperature down to 16°C with a 5 TOG blanket. – Potential energy savings?
Limitations

- Limitations
  - Existing system is radiant ceiling system in heating (during winter), research may not apply to wall and floor system; or as in cooling
  - The test building have a superior envelope to typical buildings and will not be representative of other buildings
  - Small scale experiment will not produce concrete comprehensive results
CONCLUSION AND FUTURE WORK

• Conclusion
  – Existing knowledge have significant gaps in sleep thermal comfort
  – Developed a simple model to determine the desired thermal environment for sleep
  – Field measurement shows that recorded operative temperature is higher than desired

• Future Work
  – Experimental studies with statistically significant demographic to establish sleep thermal comfort criteria.
  – Controlled lab test with volunteers and thermal manikin
  – Bridging scientific knowledge from psychology, physiology and engineering with multidiscipline research teams
  – Calculation of potential energy savings of reduction of operative temperature during sleep