Seminar outline

- Basics for Radiant systems
  - System types, Comfort
- Standards for Radiant Heating and Cooling Systems
  - Determination of Heating and Cooling Capacity
- Control of radiant cooling systems
- Construction and Installation Technologies
  - Examples
- Q&A

HISTORY

Frank Lloyd Wright's Usonian Houses 1930's

A lightweight floor slab was used and the traditional basement was dispensed with. By using steam or hot water piping, it became possible to heat the floor, therefore eliminating the need for radiators. The overall result was heat without a draft or temperature variation of the most comfort - cool head and warm feet.

c. 10,000 B.C., China

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Evidence of baked floors are found foreshadowing early forms of “kang” and “dikang” (heated floor) later “ondol” (warm stone) in China and Korea, respectively.

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c. 1904, Liverpool Cathedral

Heated with system based on the hypocaust principles.

Hypocausts were used from the third century B.C. in ancient Europe.
What is Low Temperature Heating/High Temperature Cooling?

- Heat exchange through large surfaces (floor, ceiling, walls)
- Supply water temperatures:
  - Heating: 25 – 40 °C (77 – 104 F)
  - Cooling: 16 – 23 °C (61 – 74 F)
    - temperature limited by dew-point to avoid condensation
- Wide range of systems, solutions both for residential and non-residential buildings

CONCEPTS OF RADIANT HEATING AND COOLING SYSTEMS

- Heating - Cooling panels
- Surface systems
- Embedded systems

COMBINATION WITH LOW ENERGY SOURCES

- Heating supply temp.: 25 - 40°C
  - heat pumps
  - condensing boiler
  - ground coupling
  - waste heat
  - solar energy
- Cooling supply temp.: 16 - 23°C
  - reversible heat pump
  - ground coupling
  - free cooling
  - air cooled chillers

Suspended cooled ceilings
GENERAL THERMAL COMFORT

• Personal factors
  – Clothing
  – Activity

• Environmental factors
  – Air temperature
  – Mean radiant temperature
  – Air velocity
  – Humidity
GENERAL THERMAL COMFORT
FLOOR TEMPERATURE

- OPERATIVE TEMPERATURE
  \[ t_o = \frac{(h_c t_a + h_r t_r)}{(h_c + h_r)} \]
  \[ t_o = 0.5 t_a + 0.5 t_r \] (low air velocity)

  - \( t_a \) = Air temperature
  - \( t_r \) = Mean radiant temperature
  - \( h_c \) = Convective heat exchange coefficient
  - \( h_r \) = Radiative heat exchange coefficient

- 1 (1.8F) degree change of floor temperature will change operative temperature 0.2 (0.4F) degree

MODERATE ENVIRONMENTS

- GENERAL THERMAL COMFORT
  - PMV / PPD, OPERATIVE TEMPERATURE

- LOCAL THERMAL DISCOMFORT
  - Radiant temperature asymmetry
  - Draught
  - Vertical air temperature difference
  - Floor surface temperature

DOWN DRAUGHT

<table>
<thead>
<tr>
<th>Category</th>
<th>CR (Draught Rate)</th>
<th>Maximum Air Velocity</th>
<th>Vertical Air Temperature Difference</th>
<th>Range of Floor Temperature</th>
<th>Radiant Temperature Asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[W/m²K]</td>
<td>[m/s]</td>
<td>[°C]</td>
<td>[°C]</td>
<td>[°C]</td>
</tr>
<tr>
<td>Category I</td>
<td>10</td>
<td>0.15</td>
<td>3</td>
<td>15</td>
<td>5</td>
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<tr>
<td>Category II</td>
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<td>0.15</td>
<td>5</td>
<td>15</td>
<td>5</td>
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<tr>
<td>Category III</td>
<td>50</td>
<td>0.25</td>
<td>10</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>

*Assuming air velocity of 0.3 m/s, turbulence intensity of 4% and an air temperature equal to the operative temperature of around 20 °C in winter and 23 °C in summer
DOWN DRAUGHT
With perimeter heating

- Test conditions
  - Outside air = -12 °C  Room = 20 °C
  - Window = 12 °C,  Floor = 28 °C

<table>
<thead>
<tr>
<th></th>
<th>Floor heating 0,6m</th>
<th>0,9m</th>
<th>Without 0,6m</th>
<th>0,9m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air velocity m/s</td>
<td>0,10</td>
<td>0,12</td>
<td>0,18</td>
<td>0,15</td>
</tr>
<tr>
<td>Air temperature °C</td>
<td>21</td>
<td>22</td>
<td>18,5</td>
<td>19,5</td>
</tr>
<tr>
<td>Draught rate %</td>
<td>8</td>
<td>9</td>
<td>18</td>
<td>14</td>
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</table>

Determination of Heating and Cooling Capacity

SURFACE HEATING AND COOLING
Heat transfer coefficient

<table>
<thead>
<tr>
<th></th>
<th>Heating</th>
<th>Cooling</th>
<th>Floor</th>
<th>Ceiling</th>
<th>Wall</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>W/m²K</td>
<td>W/m²K</td>
<td>W/m²K</td>
<td>W/m²K</td>
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<td>1</td>
<td>11,0</td>
<td>8,0</td>
<td>11,0</td>
<td>8,0</td>
<td>6,0</td>
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<tr>
<td>2</td>
<td>7,0</td>
<td>6,0</td>
<td>6,0</td>
<td>5,5</td>
<td>5,5</td>
</tr>
<tr>
<td>3</td>
<td>5,5</td>
<td>5,5</td>
<td>5,5</td>
<td>5,5</td>
<td>5,5</td>
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<tr>
<td>4</td>
<td>4,0</td>
<td>4,0</td>
<td>4,0</td>
<td>4,0</td>
<td>4,0</td>
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<tr>
<td>7</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
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<tr>
<td>8</td>
<td>0,9</td>
<td>0,9</td>
<td>0,9</td>
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</table>

Max. - Min. Surface temperature

<table>
<thead>
<tr>
<th></th>
<th>Heating</th>
<th>Cooling</th>
<th>Floor</th>
<th>Ceiling</th>
<th>Perimeter</th>
<th>Wall</th>
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<tbody>
<tr>
<td>5°C</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>10°C</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>15°C</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>20°C</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>5</td>
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MAXIMUM HEATING AND COOLING CAPACITY

<table>
<thead>
<tr>
<th>Floor</th>
<th>Ceiling</th>
<th>Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.2</td>
<td>16.9</td>
</tr>
<tr>
<td>20</td>
<td>6.3</td>
<td>4.2</td>
</tr>
<tr>
<td>30</td>
<td>9.5</td>
<td>9.9</td>
</tr>
<tr>
<td>40</td>
<td>12.7</td>
<td>21.6</td>
</tr>
<tr>
<td>50</td>
<td>15.8</td>
<td>24.6</td>
</tr>
<tr>
<td>60</td>
<td>19.0</td>
<td>29.4</td>
</tr>
<tr>
<td>70</td>
<td>22.2</td>
<td>31.7</td>
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<tr>
<td>80</td>
<td>25.4</td>
<td>31.7</td>
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<tr>
<td>90</td>
<td>28.5</td>
<td>31.7</td>
</tr>
<tr>
<td>100</td>
<td>31.7</td>
<td>31.7</td>
</tr>
</tbody>
</table>

ALUMINUM HC device: Floor Heating & Cooling (type B), R=0.01~0.1, T=150 & 300

Heating/cooling medium differential temperature ΔθH=θH-θi [°C]

<table>
<thead>
<tr>
<th>Heating</th>
<th>Cooling</th>
<th>ΔθH=θH-θi [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.2</td>
<td>16.9</td>
</tr>
<tr>
<td>20</td>
<td>6.3</td>
<td>4.2</td>
</tr>
<tr>
<td>30</td>
<td>9.5</td>
<td>9.9</td>
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<td>12.7</td>
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<td>80</td>
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<td>28.5</td>
<td>31.7</td>
</tr>
<tr>
<td>100</td>
<td>31.7</td>
<td>31.7</td>
</tr>
</tbody>
</table>

Method for verification of FEM and FDM calculation programs

Figure 4.17 Heat exchange between the surface (with ceramic tiles, wooden parquets or carpet R=0.1 and no covering R=0) and the space when aluminium heat conductive device used
Radiant Floor Cooling

More than 100 W/m² or 32 Btu/ft² h

TABS
Thermo Active Building Systems

Control of radiant heating and cooling systems

Figure 2 – Example of peak-shaving (reducing the peak load) effect (time vs. cooling power [W].)
Control of a combined floor heating-cooling system with individual room control

SELF CONTROL

Radiant surface heating and cooling systems

Thermo Active Building Systems (TABS)

Window

Reinforcement

Concrete

Room

Floor

Wall

Ceiling

Pipes

Floor temperature Heat. level temp. tiles

Heat load

Floor

Wall

Ceiling

% decrease in heat output by 1 K room temperature increase

% decrease in heat output by 1 K room temperature increase

10 W/m²? 20 W/m²? 40 W/m²? 80 W/m²?

Floor temperature Heat. level temp. tiles

Heat load

Heat level temp. carpet

Heat level temp. tiles

Floor temperature at 20 °C Roomtemperature

Btu/hr/(ft²)

W/m²)

10 3.2
20 6.3
30 9.5
40 12.7
50 15.8
60 19.0
70 22.2
80 25.4
90 28.5
100 31.7

SELF CONTROL
The analysed building

Office building

- West room
- Office
- Office

Width of the room: 3.6 m
Window portion of the outside wall: 50%

Internal heat sources

Monday to Friday

* Heat production [W]

- 0
- 100
- 200
- 300
- 400
- 500
- 600

* Daytime [h]

- 1
- 3
- 5
- 7
- 9
- 11
- 13
- 15
- 17
- 19
- 21
- 23

Time of operation

- Four different schedules
  - 24 hour
  - 8:00-17:00
  - 18:00-06:00
  - 22:00-06:00
Intermittent operation of circulation pump

- Pump on for 1 hour – Pump off for 1 hour
- Pump on for ½ hour – Pump off for ½ hour
- Pump on for ¼ hour - Pump off for ¾ hour

Control of water temperature

- Supply water temperature equal to internal dew point temperature.

\[ T_{\text{supply}} = 1.3 \times 0.4 \times (T_{\text{external}} - 20) + 20 \]

- Average water temperature a function of outside temperature

\[ T_{\text{average}} = 1.3 \times 0.4 \times (T_{\text{average}} - 20) + 20 \]

- Supply water temperature constant equal to: 18 °C, 20 °C and 22 °C
- Average water temperature constant equal to: 18 °C, 20 °C and 22 °C

Evaluation parameters

- Range of operative temperatures
- Pump running time
- Energy consumption
Construction and Installation Technologies

Examples

Transportation of modules
Thermo active hollow-core slab
ThermoMax

- Produced in Denmark by Spæncom
- 1.2 m wide, thickness 220, 270, 320 and 400 mm
- 20 mm PEX-pipes
Radiant Floor Cooling

Airport Bangkok

Temperature contour plot

- Temperature values
- Legend
- Operating conditions
- Radiant cooling system

Airport Bangkok
Airport Bangkok

Comparison of Cooling loads entire Airport

Original Concept

- supply air latent: 39.3 GWh/a
- supply air sensible: 29 GWh/a
- total load: 275 GWh/a
- 739 kWh/m²a

Optimized Concept

- supply air latent: 39.3 GWh/a
- supply air sensible: 29 GWh/a
- total load: 191 GWh/a
- 513 kWh/m²a

Terminal building

Installation of PEX pipes

- $T_a = 16^\circ C$
- $T_d = 10^\circ C$
- $T_{sup} = 13^\circ C$
- $T_{inf} = 0^\circ C$
ART MUSEUM IN BREGENZ

- Design requirements
  - Air temperature variations during a day within 4 K
  - Relative humidity variations less than 6% during a day.
  - Seasonal variations between 48 and 58%
  - Room temperature in winter 18°C to 22°C
  - Room temperature in summer 22°C to 26°C, occasional up to 28°C

- Design load 250 persons pr. day, 2 hours
- Displacement ventilation < 0,2 h⁻¹
- Floor area 2,800 m², 4 floors
- 28,000 m plastic pipes embedded in walls and floor slabs

ART MUSEUM IN BREGENZ

- 3,750 m² floor area
- 4,725 m² embedded pipes
- Condensing boiler
- Ventilation 750 m³/h per floor (first design was 25,000 m³/h)
Balanced Office Building (BOB.1)
Aachen, Germany

- Gross floor area 2,151 m²
- 4 storeys
- Efficiently insulated external envelope
- Ground-coupled heating and cooling with TABS
- Ventilation system with heat recovery
- Daylight-controlled lighting
- Rainwater collection for use in toilet flushing
cooling period in BOB.1

IDOM Company Headquaters, Madrid, Spain

- 16 000 m²
- Natural & Mechanical ventilation
- External solar shading & green facade
- TABS combined with free cooling (covers 40-50 kWh/m²)

Energy use

<table>
<thead>
<tr>
<th>(kWh/m²y)</th>
<th>IDOM HQ</th>
<th>CTE - MADRID</th>
<th>%</th>
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<tbody>
<tr>
<td>Heating + DHW</td>
<td>27,35</td>
<td>77,00</td>
<td>-64,5</td>
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<tr>
<td>Cooling</td>
<td>12,58</td>
<td>85,00</td>
<td>-85,2</td>
</tr>
<tr>
<td>Lighting</td>
<td>11,37</td>
<td>34,00</td>
<td>-66,6</td>
</tr>
<tr>
<td>Total</td>
<td>51,30</td>
<td>196,00</td>
<td>-73,8</td>
</tr>
</tbody>
</table>

Radiant Floor Cooling

IDOM Company Headquaters, Madrid, Spain
Yearly indoor comfort evaluation and energy consumption, and assessment of thermal activated building systems in Middelfart Sparekasse.

Opera House in Copenhagen
Summer indoor climate in Foyer

- Radiant floor cooling with stone cover down the structural slabs to reduce peak cooling load
- High air change by displacement ventilation system.
- Humidity control prevents condensation on floor.

References / South, West Europe

- Modern Old Port of Savona, NW coast of Italy
  - Underfloor heating for 140 high-end residential apartments and shopping area at ground level
- Dolce Vita Tejo, Lisbon, Portugal
  - One of Europe’s largest shopping centres to be built, heating and cooling by Uponor
Industrial heating/cooling application: BWM World Munich, Germany - 2007

- 16,500 m² of floor, glass and steel, architecture in the BWM museum
- 5,000 m² of industrial radiant cooling and heating with PE-Xa pipes integrated into the hall floor – massive invisible cooling or heating panel
- Full architectural freedom provided: An experience which appeals to all senses, allowing visitors to experience the fascination of mobility
- Energy-saving and environmentally friendly operation

Sun shading and daylight penetration

| RADIANT | VAV |

Energy

Radiant Cooling – Third Party Evaluation

- Evaluation Infosys – Hyderabad, India
  2. Analysis of Energy Consumption

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Radiant</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC consumption (kW/kWp/m²)</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>Energy savings</td>
<td>5%</td>
<td>32%</td>
</tr>
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</table>

Figure 1 - Infosys SDB-1 Hyderabad - 125,000 sf of radiant cooling and 125,000 sf of VAV cooling
Thermal Comfort

Radiant Cooling – Third Party Evaluation

DOE-USA

Table 4-1: Energy Savings Potential Summary for 15 Options

<table>
<thead>
<tr>
<th>Technology Option</th>
<th>Technology Status</th>
<th>Technical Energy Savings Potential (quads)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated Outdoor Air Systems</td>
<td>Current</td>
<td>0.45</td>
</tr>
<tr>
<td>Displacement Ventilation</td>
<td>Current</td>
<td>0.20</td>
</tr>
<tr>
<td>Electronically Commutated Permanent Magnet Motors</td>
<td>Current</td>
<td>0.15</td>
</tr>
<tr>
<td>Enthalpy/Energy Recovery Heat Exchangers for Ventilation</td>
<td>Current</td>
<td>0.55</td>
</tr>
<tr>
<td>Heat Pumps for Cold Climates (Zero-Degree Heat Pump)</td>
<td>Advanced</td>
<td>0.1</td>
</tr>
<tr>
<td>Improved Duct Sealing</td>
<td>Current/New</td>
<td>0.23</td>
</tr>
<tr>
<td>Liquid Desiccant Air Conditioners</td>
<td>Advanced</td>
<td>0.24 / 0.09</td>
</tr>
<tr>
<td>Microenvironments / Occupancy-Based Control</td>
<td>Current</td>
<td>0.07</td>
</tr>
<tr>
<td>Microchannel Heat Exchanger</td>
<td>New</td>
<td>0.11</td>
</tr>
<tr>
<td>Novel Porous Stomach</td>
<td>Current</td>
<td>0.2 / 0.06</td>
</tr>
<tr>
<td>Radiant Cooling Cooling / Chilled Beam</td>
<td>Current</td>
<td>0.6</td>
</tr>
</tbody>
</table>

DOE-USA

COOPER UNION NEW YORK

First costs

| Overhead VAV lab + Fan Coils                           | $4,107,200        |
| Radiant cell                                          | $3,676,279        |
| VAV lab + Fan Coil                                    | $220,000/year utility savings |
**Shogakukan Building**

- **DOE-USA**

  - **Height Limitation**
    - Conform to the strict rules of the site. (urban design regulations)
    - Allocation of the areas in accordance with height limitation.
    - **Integration of Architecture, Structure and MEP**
Radiation Cooling and Heating

- Surface temp. = 20°C (cooling)
- Room temp. = 26°C (cooling)

Healthy and comfortable
- Improvement in quality of room air by increasing supply rate of fresh air.

Energy Conservation
- Reduction in heat transfer energy by converting heating medium

TABS

With the situation that nuclear power plants remain inoperable, the electricity in Japan is still tight.
⇒ Reduce power demand

Comparison of the cooling loads

An ordinary building
Shogakukan Bldg. (High heat insulation, external wall in: Shogakukan Bldg. (TABS)

Run radiant operation at night ⇒ 20W/m² is decreased

Integration of Architecture, Structure and MEP

- Ceiling height: 2,800mm
- Floor height: 3,750mm

Reduction in floor height: space beside girders is used for “air passage” and “pipe passage”
⇒ Ceiling with less space

Indoor thermal environment in winter

Measurement

Shinichi Tanabe
(Prof. WASEDA Univ.)
On the 10th floor (with radiant panels), the PMV difference was ±0.5.
On the 4th and 7th floor, (TABS adopted), the PMV difference in the daytime was sometimes more than +0.5.
⇒ It seems that it was due to higher indoor temperature.

Questionnaire about thermal comfort in winter

The number of the answerers who felt the room hot was slightly higher.
⇒ This is similar results of PMV.

Low Exergy Hydronic Radiant Heating and Cooling

Why?

- Water based systems
- Low temperature heating - High temperature cooling
- More economical to move heat by water:
  - Greater heat capacity than air
  - Much smaller diameter pipes than air-ducts
  - Electrical consumption for circulation pump is lower than for fans
- Lower noise level
- Less risk for draught
- Lower building height
- Higher efficiency of energy plant
- But
  - Reduced capacity?
  - Acoustic?
  - Latent load?