Operative temperature in the sun
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Why is this important?

• Radiative heat exchange significantly affect the thermal sensation experienced by a person in a confined environment.

• In todays commercial buildings with large portions of glazing in the facade, solar radiation might play an important role in the indoor environment.
How is thermal comfort in the sun treated in building simulation tools?

SIMIEN
- Isothermal surface temperature.
  - Radiation heat gain is assumed to be distributed evenly on the different opaque surfaces in the room.
  - Direct sun on the human is not accounted for.

IDA ICE 4.5
- Mean radiant temperature is calculated based on view factors between the zone and an infinitely small cube.
  - Direct sun radiation through window before first reflection is not accounted for.
  - Do not take into account the contribution of solar radiation on the human body.

Case study

Office building Bjørvika Oslo 59N10E

Model of the team-office which is object for the case study

Figure 1: Sketchup model of the office building in its surrounding environment

Figure 2: Model of the team-office. Solar shading is not in use.
Case study

IDA ICE model

- **Building properties**
  - U-value wall: 0.17 W/m² K
  - U-value roof: 0.12 W/m² K
  - Normalised thermal bridge: 0.06 W/K m² floor area
  - U-value window: 1.1 W/m² K
  - g-value window: 0.27
  - t, solar transmittance: 0.24
  - VAV-ventilation: 2-3 l/s / 0.6 l/s
  - Active beam cooling: 60 W/m²
  - Set point heating (NS3031): 21/19
  - Set point cooling (NS3031): 22
  - Internal gains (NS3031): light 8 W/m², Equipment 11 W/m², People 4 W/m²

Case study

No solar shading

Comparison no solar shading – internal blinds

- Total energy demand: 135 kWh/m²
- Total energy demand: 136 kWh/m²

Figure 3: Simulation model for IDA ICE

Figure 4: Duration mean air temperature and operative temperature in position 1, no solar shading, weather data NS3031

Figure 5: Comparison duration mean air temperature and operative temperature in position 1, no solar shading vs. internal blinds, weather data NS3031
Calculation of operative temperature in the sun

Mean radiant temperature of an object exposed to directional irradiation from a high-intensity radiant source according to P.O. Fanger:

\[ T_{\text{mrt}} = \sqrt{\left(T_{\text{wrrt}}^4 + \left(\text{const} \cdot f_p \cdot a_{ir} \cdot q_{ir}\right)\right)} \]

- \( T_{\text{mrt}} \): mean radiant temperature of irradiated person
- \( T_{\text{wrrt}} \): mean radiant temperature of unirradiated person
- \( \text{const} \): \( \frac{1}{\varepsilon_p} \) (0.97)
- \( \varepsilon_p \): emittance
- \( \sigma \): Stephan Boltzmanns constant
- \( f_p \): projected area factor (0.25 for the sphere)
- \( a_{ir} \): absorptance of outer surface of the object (assumed to be 0.85 for this case)
- \( q_{ir} \): irradiation from the source

Calculation of operative temperature in the sun

\[ q_{ir} = \left(l_{bn} \cdot \cos \theta + \frac{3}{4} l_{dh} + \rho \left(l_{bh} + l_{dh}\right)\right) \cdot \tau \]

- \( q_{ir} \): solar radiation
- \( l_{bn} \): beam normal radiation
- \( l_{dh} \): diffuse horizontal radiation
- \( l_{bh} \): beam horizontal radiation
- \( \theta \): angle of incidence
- \( \rho \): outdoor reflectance (assumed 0.2 for this case)
- \( \tau \): direct solar transmittance of window (0.24 in this case)

• Ida Bryn and Marit Smitsrød tried to test this model in 2001
  – restricted data with sunny weather
  – promising results.
Case study

IDA ICE model

<table>
<thead>
<tr>
<th>Building properties</th>
<th></th>
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</thead>
<tbody>
<tr>
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Figure 6: Simulation model for IDA ICE

Experimental setup

Measurement points

Instrumental setup

Figure 7: Illustration of location of measurement points.

Figure 8: Photo of instrumental setup, illuminance meter (0.85 m) globe thermometer (1.1 m). Photo: Silje Bjørckeng
Thermal environment measurements

Figure 9: Measurement results for a sunny day, 14.03.2013. Measurement intervals of 5 and 15 minutes are averaged on an hourly basis. The red line represents measurement points exposed to solar radiation, blue line represents the average of measurement points located in the shade and the green line represents the measured air temperature.

Thermal environment measurements and simulations

Figure 10: Measurement and simulation results for a sunny day, 14.03.2013. Measurement intervals of 5 minutes are averaged on an hourly basis. The red line represents measurement point in position 1, blue dotted line represents the average of measurement points located in the shade and the orange line represents the simulated operative temperature by IDA ICE 4.5.
Operative temperature in the sun calculations

Table 1: Calculation of operative temperature for sunny conditions during the experiment period

<table>
<thead>
<tr>
<th>Time [date, hour]</th>
<th>Measured Op_1</th>
<th>Simulated Op_1</th>
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</table>

Figure 11: Comparison of measured operative temperature averaged over an hour and simulated operative temperature with IDA ICE 4.5.

Figure 12: Comparison of measured operative temperature and simulated operative temperature with IDA ICE 4.5 supplemented with calculated operative temperature in the sun with a time step of 5 min.
Operative temperature in the sun measurements and calculations

Figure 13: Scatter plot of measured predicted $T_{op}$ against measured $T_{op}$. Measurement interval = 5 min. Observations $n=200$, correlation coefficient $r=0.82$

Uncertainty

- Uncertainty stem from
  - Use of climatic data of global solar radiation from Ås, 30 km outside Oslo
  - Modelling diffuse and direct radiation
  - Assumption of absorption of the globe thermometer
  - Measurement errors
Summary & Preliminary conclusion

• Simulation tools for prediction of thermal comfort and energy use should implement assessment of how direct sun influence thermal comfort.
  – On-going process by Equa for IDA ICE 5

• The present validation indicate that the theory of Fanger work rather well for an object exposed to direct solar radiation.
  – Shorter time-step than 1 hour might be preferable.
  – Simplification: the sphere represent the human body
  – The “whole” body is irradiated
    • Future studies might have measurements in different heights
  – Simple calculation useful in the initial design of a building.

Acknowledgement

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• Building owners of case study.
Thank you for your attention!

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