# Operative temperature in the sun

Line Røseth Karlsen[*,**], Per Heiselberg[**], Ida Bryn[*]

*Oslo and Akershus University College

**Aalborg University

OSLO AND AKERSHUS UNIVERSITY COLLEGE OF APPLIED SCIENCES

AALBORG UNIVERSITY DENMARK

## 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**

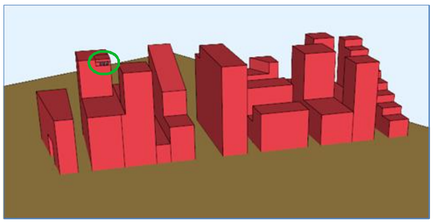

**Figure 1:** Sketchup model of the office building in its surrounding environment

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


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

# Case study

## IDA ICE model

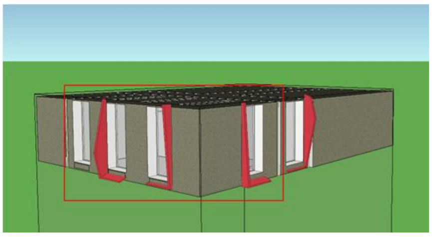

**Figure 3:** Simulation model for IDA ICE

## 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 |
| τ, 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

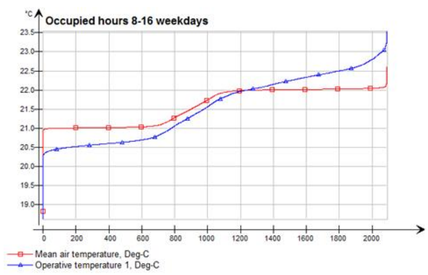


**Figure 4:** Duration mean air temperature and operative teperature in position 1, no solar shading, weather data NS3031

Total energy demand: 135 kWh/m²

## Comparison no solar shading – internal blinds

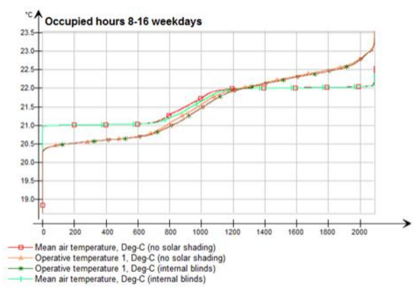


**Figure 5:** Comparison duration mean air temperature and operative teperature in position 1, no solar shading vs. Internal blinds, weather data NS3031

Total energy demand: 136 kWh/m²

# 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:

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

$T_{mrt}$ : mean radiant temperature of irradiated person
$T_{umrt}$ : mean radiant temperature of unirradiated person
const : $\frac{1}{\varepsilon_p \cdot \sigma}$
$\varepsilon_p$ : emittance (0,97)
$\sigma$ : Stephan Boltzmanns constant
$f_p$ : projected area factor (0.25 for the sphere)
$\alpha_{ir}$ : absobtance 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

$$q_{ir} = (I_{bn} \cdot cos\theta + \frac{3}{4} I_{dh} + \frac{\rho}{4}(I_{bh} + I_{dh})) \cdot \tau$$

$q_{ir}$ : solar radiation
$I_{bn}$ : beam normal radiation
$I_{dh}$ : diffuse horizontal radiation
$I_{bh}$ : 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

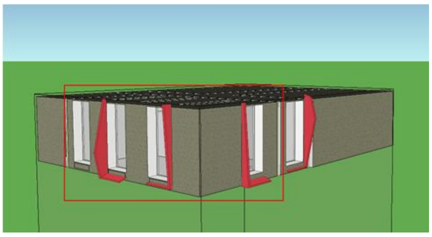

**Figure 6:** Simulation model for IDA ICE

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| Active beam cooling | | 60 W/m² |
| Set point heating | | 20.3 |
| Set point cooling | | 21.5 |
| | light | 12 W/m² |
| Internal gains | Equipment | 9 W/m² |
| | People | 6 W/m² |

# Experimental setup

## Measurement points

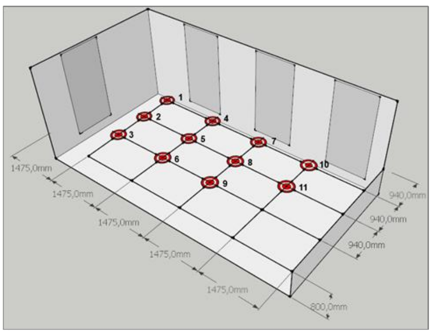


**Figure 7:** Illustration of location of measurement points.

## Instrumental setup

**Figure 8:** Photo of instrumental setup, illuminance meter (0,85 m) globe thermometer (1,1 m). Photo: Silje Bjørkeng

# Thermal environment
## measurements

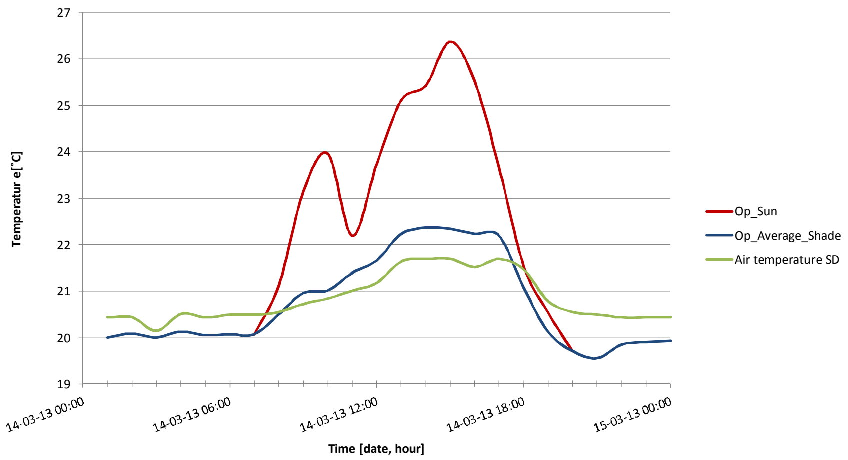


**Figure 9:** Measurement results for a sunny day, 14.03.2013. Measurement intervals of 5 and 15 minutes are averaged on an hourly basis. The red line represent measurement points exposed to solar radiation, blue line represent the average of measurement points located in the shade and the green line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

# Thermal environment
## measurements and simulations

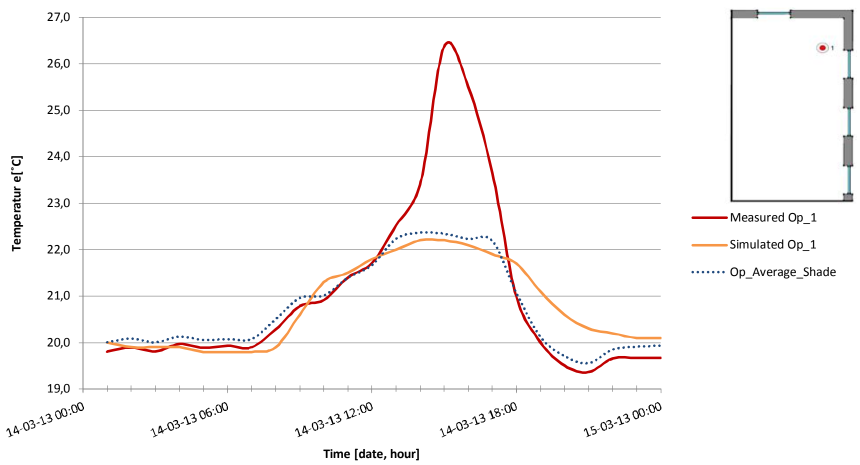


**Figure 10:** Measurement and simulation results for a sunny day, 14.03.2013. Measurement intervals of 5 minutes are averaged on an hourly basis. The red line represent measurement in position 1, blue doted line represent the average of measurement points located in the shade and the orange line represent 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

| Time | Weateher conditions | Measured air temperature | Measured operative temperature in shadow | Diffus horisontal radiation (calculated based on Skartveit og Olseth 1998) | Direct normal radiation (calculated based on Skartveit og Olseth 1998) | calculated solar radiation | Calculated radiant temperature T_umrt | calculated mean radiant temperature, T_mrt | calculated operative temperature in the sun | measured operative temperature in the sun | Relative error in percentage with respect to measured values | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [°C] | [°C] | [W/m²] | [W/m²] | [W/m²] | [°C] | [°C] | [°C] | [°C] | [%] | |
| 12.03.2013 15:00 | sunny | 21,7 | 22,2 | 85 | 827 | 738,4 | 22,7 | 29,0 | 25,4 | 25,9 | 2,074 | |
| 12.03.2013 16:00 | | 21,7 | 21,9 | 129 | 707 | 656,8 | 22,2 | 27,8 | 24,7 | 25,1 | 1,447 | |
| 12.03.2013 17:00 | | 21,8 | 22,1 | 93 | 618 | 504,6 | 22,5 | 26,8 | 24,3 | 23,9 | -1,621 | Not sun the whole hour |
| 13.03.2013 15:00 | sunny | 22,0 | 22,4 | 120 | 819 | 870,2 | 22,7 | 30,1 | 26,1 | 26,4 | 1,265 | |
| 13.03.2013 16:00 | | 21,8 | 22,1 | 124 | 741 | 790,3 | 22,3 | 29,1 | 25,4 | 26,0 | 2,196 | |
| 13.03.2013 17:00 | | 21,8 | 21,8 | 100 | 654 | 640,5 | 21,9 | 27,5 | 24,6 | 23,9 | -2,922 | Not sun the whole hour |
| 14.03.2013 14:00 | sunny | 21,9 | 22,1 | 102,8 | 875,1 | 865,3 | 22,3 | 29,7 | 25,8 | 25,6 | -0,631 | |
| 14.03.2013 15:00 | | 22,0 | 22,4 | 121,7 | 825,5 | 876,0 | 22,8 | 30,2 | 26,1 | 26,3 | 0,966 | |
| 14.03.2013 16:00 | | 21,7 | 22,0 | 125,6 | 748,4 | 796,1 | 22,4 | 29,2 | 25,4 | 25,6 | 0,673 | |
| 18.03.2013 12:00 | Partly cloudy | 21,5 | 21,9 | 137 | 625 | 499,4 | 22,3 | 26,6 | 24,0 | 23,6 | -1,865 | Not sun the whole hour |
| 18.03.2013 13:00 | | 21,8 | 22,0 | 135 | 779 | 715,9 | 22,2 | 28,4 | 25,1 | 23,9 | -4,871 | Not sun the whole hour |
| 18.03.2013 14:00 | | 22,2 | 22,2 | 179 | 414 | 509,9 | 22,3 | 26,7 | 24,5 | 25,3 | 3,230 | |
| 18.03.2013 15:00 | | 22,0 | 22,1 | 118 | 614 | 664,8 | 22,3 | 28,0 | 25,0 | 25,7 | 2,710 | |
| 18.03.2013 16:00 | | 21,4 | 21,6 | 120 | 211 | 288,7 | 21,8 | 24,3 | 22,9 | 24,4 | 6,407 | Weather data from Ås |
| 21.03.2013 12:00 | Partly cloudy/ | 21,4 | 21,9 | 110 | 825 | 598,6 | 22,5 | 27,6 | 24,5 | 23,7 | -3,316 | Not sun the whole hour |
| 21.03.2013 13:00 | Sunny after noon | 21,6 | 22,2 | 92 | 894 | 766,1 | 22,7 | 29,2 | 25,4 | 24,9 | -2,250 | Not sun the whole hour |
| 21.03.2013 14:00 | | 22,0 | 22,0 | 75 | 911 | 860,3 | 22,0 | 29,4 | 25,7 | 25,7 | -0,234 | |
| 21.03.2013 15:00 | | 21,9 | 22,1 | 115 | 839 | 865,9 | 22,3 | 29,6 | 25,7 | 26,2 | 1,701 | |
| 21.03.2013 16:00 | | 21,7 | 21,8 | 147 | 764 | 808,5 | 22,0 | 28,9 | 25,3 | 25,5 | 0,926 | |
| 22.04.2013 10:00 | Partly cloudy | 22,1 | 22,1 | 187 | 454 | 532,4 | 22,0 | 27,3 | 24,7 | 24,0 | -2,766 | Not sun the whole hour |
| 22.04.2013 11:00 | | 22,3 | 22,4 | 182 | 537 | 537,4 | 22,5 | 27,8 | 25,1 | 26,7 | 6,175 | Weather data from Ås |
| 22.04.2013 12:00 | | 22,5 | 22,7 | 174,8 | 707,2 | 538,4 | 22,9 | 28,3 | 25,4 | 24,9 | -1,975 | Not sun the whole hour |
| 23.04.2013 13:00 | | 22,8 | 23,2 | 121,8 | 822,4 | 389,8 | 23,6 | 27,4 | 25,1 | 25,1 | -0,087 | |
| 23.04.2013 10:00 | Partly cloudy | 22,6 | 22,9 | 164 | 518 | 615,7 | 23,3 | 29,3 | 26,0 | 25,4 | -2,037 | Not sun the whole hour |
| 23.04.2013 11:00 | | 22,9 | 23,3 | 168 | 581 | 610,2 | 23,7 | 29,7 | 26,3 | 27,9 | 5,747 | Weather data from Ås |
| 23.04.2013 12:00 | | 23,2 | 23,2 | 169 | 712 | 596,3 | 23,1 | 29,0 | 26,1 | 24,5 | -6,448 | Not sun the whole hour |
| 23.04.2013 13:00 | | 22,9 | 22,8 | 226,0 | 57,1 | 205,6 | 22,6 | 24,7 | 23,8 | 23,1 | -3,077 | Not sun the whole hour |

$$rE = \frac{T_{op,i} - T_{op,est,i}}{T_{op,i}} \cdot 100\ \%$$

# Thermal environment

## measurements and calculations

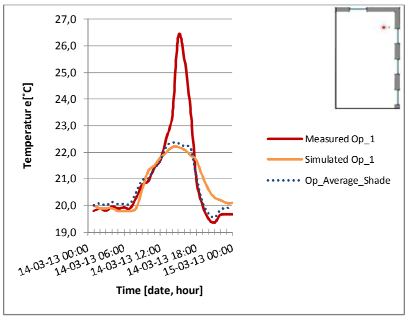


**Figure 11:** Compearison of measured operative temperature averaged over an hour and simulated operative temperature with IDA ICE 4.5.

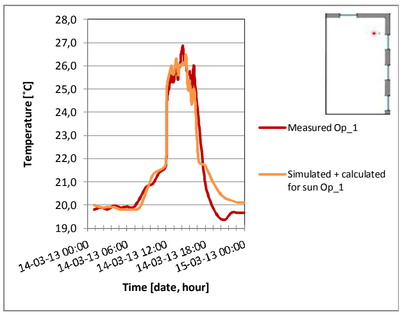


**Figure 12:** Compearison of measured operative temperature and simulated operative temperature with IDA ICE 4.5 supplemented with calculated operative temperature in the sun with a time step of 5 min.

# Operative temperature in the sun

## measurements and calculations

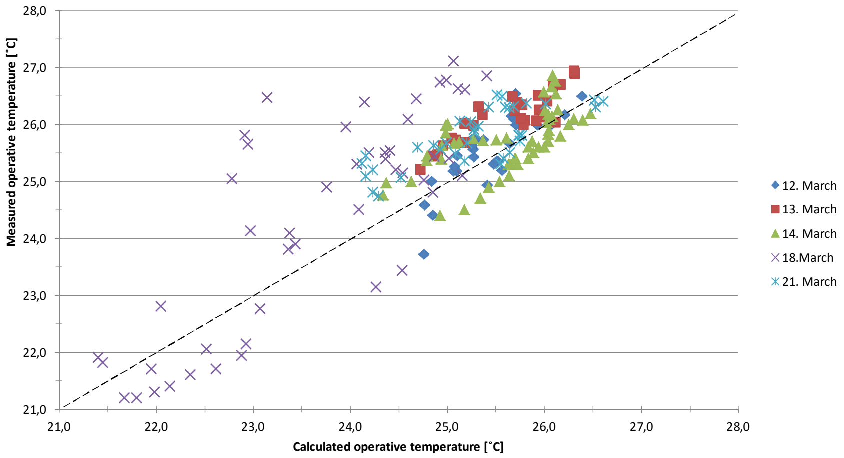


**Figure 13:** Scatter plot of measured predicted $T_{op}$ against measured $T_{op}$. Measurement interval = 5 min. Observations n= 200, correlation coefficient r=0,82

# 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


- Silje Bjørkeng and Silje Navekvien (Master students HiOA spring 2013) for cooperation with conducting the measurements.
- Building owners of case study.


Thank you for your attention!
Line-roseth.karlsen@hioa.no
OSLO AND AKERSHUS
UNIVERSITY COLLEGE
OF APPLIED SCIENCES
AALBORG UNIVERSITY
DENMARK