Solar Heat Gain Modelling for Urban Environment

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Introduction

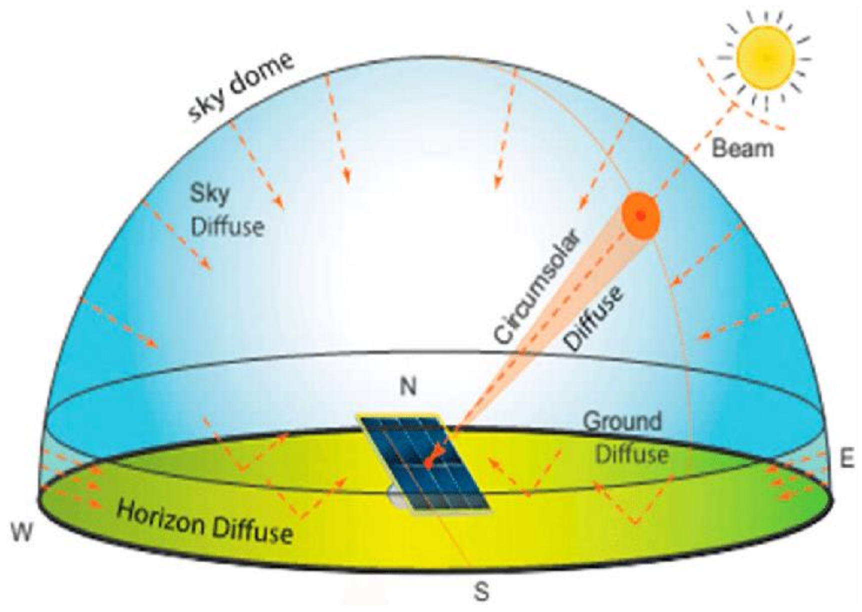
Solar Irradiance

Direct Irradiance
Solar irradiance incident per unit area that comes in a straight line from the Sun.

Diffuse Irradiance
Solar irradiance received per unit area that has been scattered by molecules and particles in the atmosphere.

A sky model focuses more on diffuse irradiance as seen from the figure on the right.

Perez Sky Model



Advantages of Perez Sky Model

- Perez Sky Model introduces 3 distinct diffuse irradiance zones in the sky dome as seen above
- The 3 zones are **isotropic sky zone**, **circumsolar zone** & **horizon band zone**
- Perez Sky Model also introduces **Sky Brightness Δ** and **Sky Clearness ε**
- The **Sky Clearness ε** categorises the sky into 8 different categories from clear to overcast

The basic form of Perez Sky Model to determine diffuse irradiance on a tilted surface is:

$$DI_{tilt} = DHI\,[\underbrace{0.5(1+\cos(\theta_{tilt}))(1-F_1)}_{\text{Sky}} + \underbrace{F_1(a/b)}_{\text{Circumsolar}} + \underbrace{F_2.\sin(\theta_{tilt})}_{\text{Horizon}}]$$

$$\frac{a}{b} = \frac{max[0, \cos(AOI)]}{\max[\cos(85^o),\ \cos(\theta_Z)]}$$

$$F_1 = f_{11} + f_{12}.\Delta + f_{13}.\theta_z$$
$$F_2 = f_{21} + f_{22}.\Delta + f_{23}.\theta_z$$

DI_{Tilt} : Diffuse Irradiance at tilt surface
DHI : Diffuse Horizontal Irradiance
θ_{tilt} : Surface Tilt Angle
AOI : Solar Incidence Angle on Surface
θ_Z : Solar Zenith Angle
F_1 : Circumsolar coefficient function
F_2 : Horizon Brightness coefficient function
f : coefficients defined for each category of ε

Objective

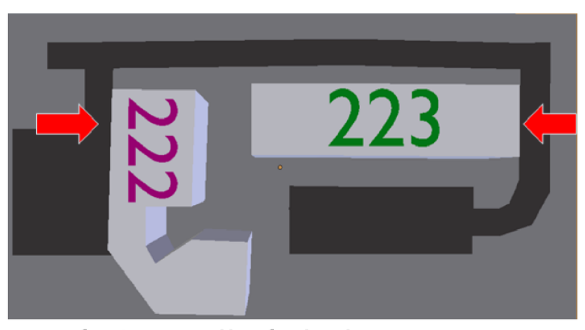
In an Urban Environment, building orientation plays a major role in a building's envelop heat gain. As such, the Perez Sky Model is often used in simulations so as to predict the solar irradiance incident on the building's surfaces. However, the *f* coefficients in the Perez Sky Model was determined from data over 8 different locations that do not have the exact same tropical climate as in Singapore. As such, the objectives of this study are as follows:

1) To determine the *f* coefficients of the Perez Sky Model based on the local climate of Singapore

2) To study the relationship between incident solar irradiance on a surface at different tilt angles and its surface temperature

Experimental Methods

Location

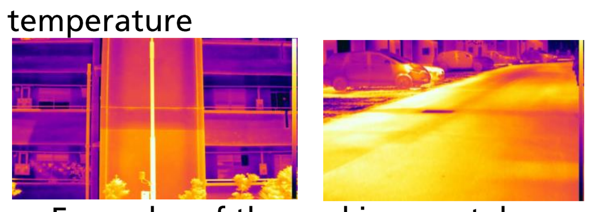


East facing wall of Block 223 & West facing wall of Block 222 @ Yuhua HDB

Equipment

Pyranometer to measure vertical irradiance

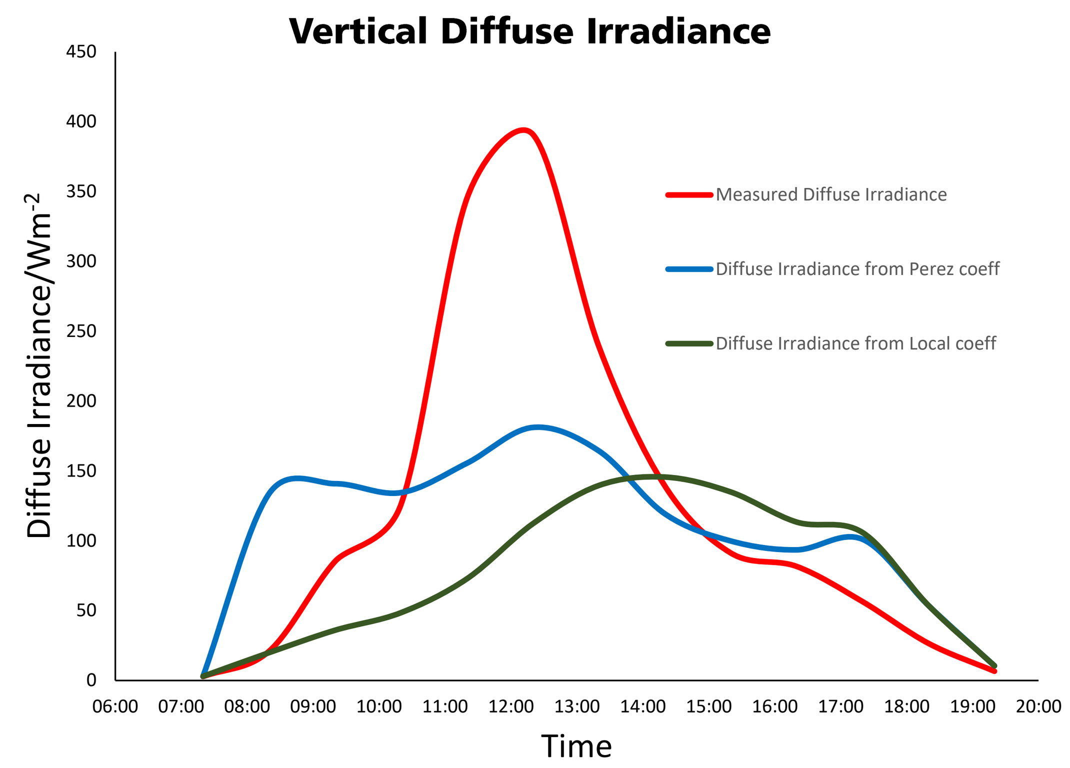
Pyranometer and temperature sensor to measure horizontal irradiance and roof temperature



Examples of thermal images taken

- Solar irradiance data was taken from the vertical and horizontal plane every 5 seconds and 5 minutes respectively
- Surface temperature of the East facing wall and roof were measured every 10 minutes using a temperature sensor probe
- Thermal images of concrete floor, road, West facing wall, East facing wall and grass were taken every 20 minutes

Results

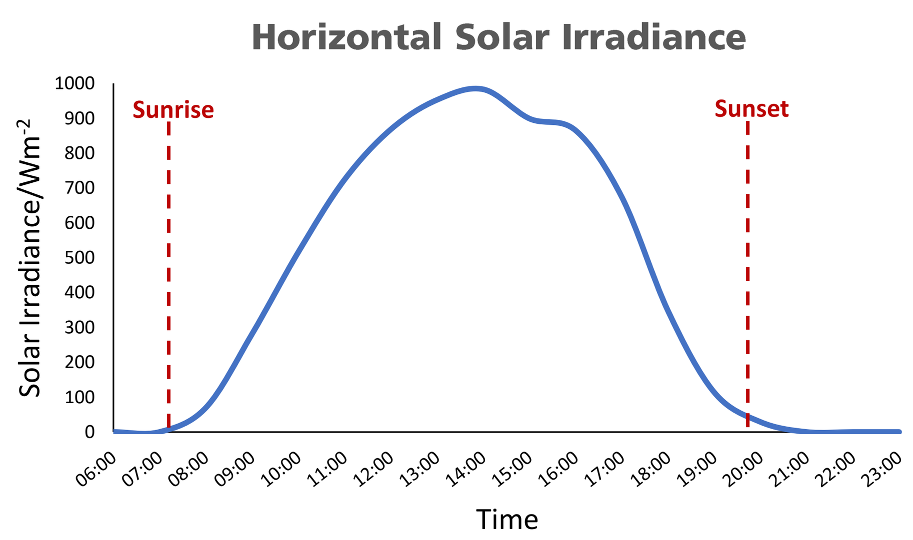


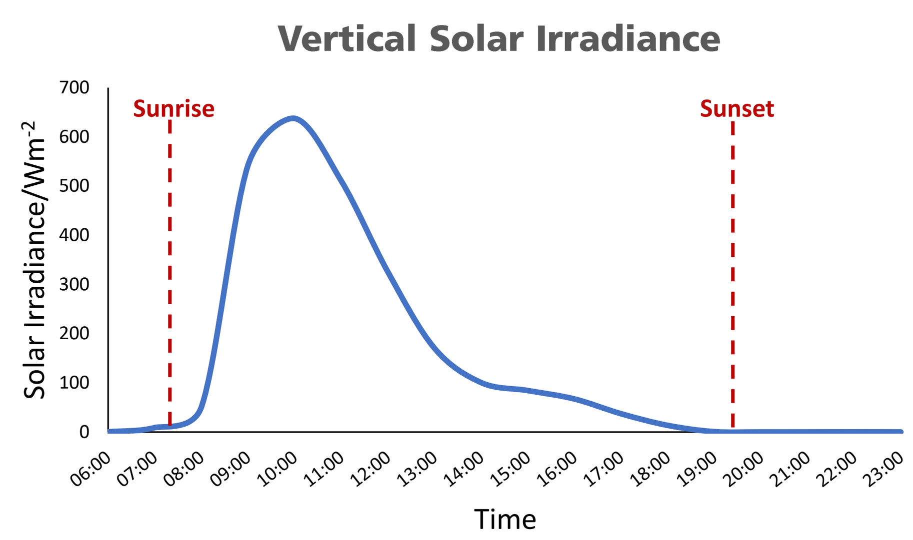
Perez Coefficients

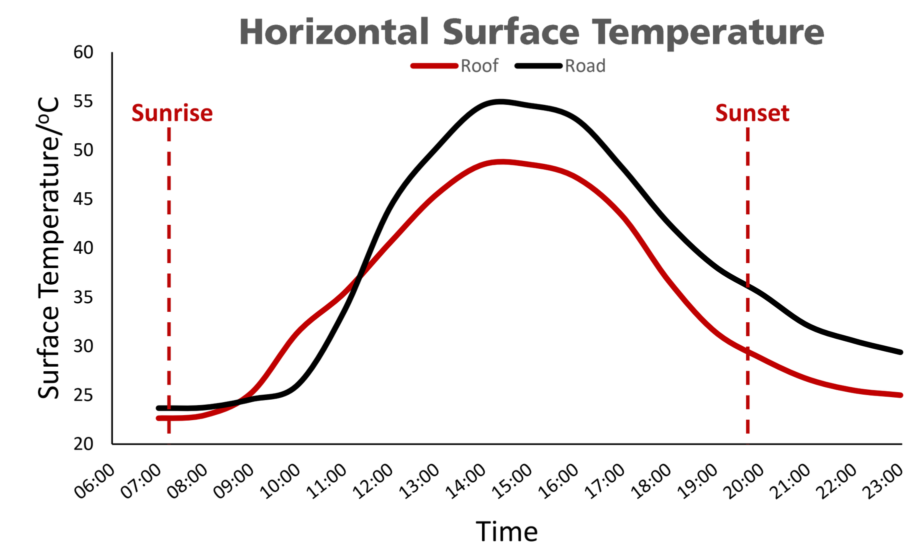
ε category	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{23}
1	-0.008	0.588	-0.062	-0.060	0.072	-0.022
2	0.130	0.683	-0.151	-0.019	0.066	-0.029
3	0.330	0.487	-0.221	0.055	-0.064	-0.026
4	0.568	0.187	-0.295	0.109	-0.152	-0.014
5	0.873	-0.392	-0.362	0.226	-0.462	0.001
6	1.132	-1.237	-0.412	0.288	-0.823	0.056
7	1.060	-1.600	-0.359	0.264	-1.127	0.131
8	0.678	-0.327	-0.250	0.156	-1.377	0.251

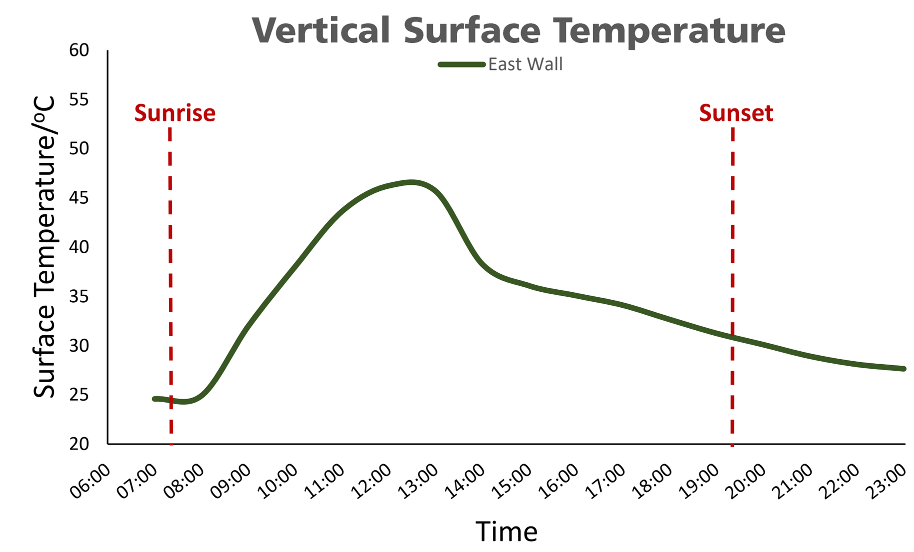
Local Coefficients

ε category	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{23}
1	0.062	0.417	-0.041	0.154	26.200	-0.066
2	0.130	0.683	-0.151	-0.019	0.066	-0.029
3	0.330	0.487	-0.221	0.055	-0.064	-0.026
4	0.568	0.187	-0.295	0.109	-0.152	-0.014
5	-341	-12300	30.7	-116	-10100	-30.2
6	2.18	-531	1.42	0.251	-195	1.74
7	-1.55	-197	8.43	8.96	-589	-11.6
8	0.678	-0.327	-0.250	0.156	-1.377	0.251









Discussion

- The Perez Sky Model performed noticeably better when Perez original coefficients were used as compared to the determined local coefficients. This could be due to 2 reasons.

  1) The local *f* coefficients for the Perez Sky Model were not determined for sky clearness category 2, 3, 4 and 8. This was due to only having 2 data points at most that fell into these categories of sky clearness. As such, the original Perez coefficients were adopted instead.

  2) The Perez coefficients were determined from data collected from a time span of at least 6 months from irradiance data collected from all four cardinal directions.

- The surface temperature of the roof increases at an earlier time as compared to the road due to its altitude. This is because the scattering effect is less at higher altitudes. Therefore, there would be more diffuse irradiance incident on the roof as compared to the road.

- The road eventually peaks at a higher temperature than the roof due to its lower albedo value. A low albedo value indicates that the material absorbs more incident solar irradiance.

- The horizontal surfaces have an approximate time lag of 2 hours while the vertical surface has a time lag of 1 hour before an increase in temperature is observed. This can be easily explained as the vertical surface (East facing wall) receives a greater component of direct irradiance from the Sun as compared to the horizontal surfaces.

Conclusion

- The *f* coefficients of the Perez Sky Model were determined based on local climate of Singapore for four categories of sky clearness.
- The Perez Sky Model performed noticeably better when Perez original coefficients were used as compared to the determined local coefficients.
- The surface temperature of various surfaces at different tilt angles depends on the incident solar irradiance at that tilt angle as well as its albedo value.

References
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[4] Mohammad Sameti & Mohammad Ali Jokar, 2017. "Numerical modelling andoptimization of the finite-length overhang for passive solar space heating". Intelligent Buildings International