Review of the sky temperature and solar decomposition and their impact on thermal modeling

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Performing accurate hourly building energy modeling requires the presence of reliable boundary conditions. The required data for energy simulation model entries are exterior air temperature, exterior air relative humidity, solar radiation, sky temperature, wind velocity, and cloud cover. Unfortunately, most available measured solar energy data is in the form of global horizontal radiation. Moreover, measured night sky temperature is normally not available. Proper energy modeling of a full building requires having accurate solar radiation intensity on angled building envelope surfaces as well as precise sky temperature data available. In this study, among several available models, three hourly horizontal global solar radiation decomposition models, four hourly diffuse radiation models on an inclined surface, and five sky temperature estimation models are studied for the Vancouver, Canada, climate. For the purpose of solar radiation validation, 2013 1-year measured total solar radiation on a southeast-oriented wall located at the British Columbia Institute of Technology Burnaby Campus is compared with the results from selected solar models. For both solar radiation and sky temperature models, the impact of using different models on transient heat transfer results of lightweight and mass-type walls (two walls) are reviewed. Results reveal the high impact of both solar and sky temperature models on hourly heat transfer simulation results.

Introduction

Of the total energy spent in 2013 within Canada, 17% was found in the residential sector, and 10% in the commercial and institutional sectors (Natural Resources Canada 2016). Energy consumption for space heating was found to be 63% of total energy spent in the residential sector, and 55% of total energy spent in the commercial and institutional sectors. This proves that space heating energy consumption is a significant portion of energy use in residential, commercial, and institution sectors; therefore, any attempts to improve the energy consumption in this category would be a vital effort.

To better understand building energy consumption, it is important to thoroughly understand the interaction between energy consuming elements within a building, which requires dynamic energy simulation (Kosny and Kossecka 2002; Martin et al. 2011). Dynamic energy simulation takes into account the dynamic impact of boundary condition on the construction’s assemblies. Performing an accurate dynamic energy simulation requires having correct input boundary conditions available. Two important boundary conditions that could highly impact the simulation results are solar radiation and sky temperature values. Both solar radiation and sky temperature could highly impact the exterior surface temperature, which results in additional/less transient heat loss through the assembly.

Solar radiation

Typical available solar radiation data from weather stations (Burlon et al. 1991) include total global solar radiation on a horizontal surface as per Equation 1:

\[ I_{GH} = I_{BH} + I_{DH} \]  

(1)

Once global solar radiation on horizontal surface is decomposed into beam and diffuse components, total solar radiation on inclined surfaces could be calculated as per Equations 2 and 3 by having the ratio between solar radiation on inclined and horizontal surfaces:

\[ I_{T} = I_{BT} + I_{DT} + I_{RT} \]  

(2)

\[ I_{T} = I_{BH} \cos \theta / \cos (Z) + r I_{DH} + I_{GH} \rho_s \]  

(3)

Therefore, calculation of total solar radiation on a tilted surface requires decomposition of global solar radiation on a horizontal surface, and calculation of the ratio between solar radiation on inclined and horizontal surfaces. Many decomposition models for calculation of diffuse solar radiation are
developed based on the terminology first studied by Liu and Jordan (1960). The models are selected according to the climatic data that the models are calibrated on. Performance of several previous solar radiation models is reviewed in this study, and results are compared with the measured data for validation. Lastly, the impact of different solar radiation models on transient thermal modeling is reviewed.

Sky radiation

Heat transfer caused by long-wave radiation between a surface and sky is calculated as per Equation 4:

\[
q = εσF\left(T_{\text{sky}}^4 - T_{\text{surface}}^4\right)
\]  

(Measured sky radiation is not always available (Berdahl and Martin 1984). Therefore, approximation models are being used to estimate the values.

There are several studies performed on sky radiation estimation. Most of the models are based on the clear sky condition (Algarni and Nutter 2015), while climates with high cloud coverage (i.e., Vancouver, Canada) require more complex correlation to account for sky condition. This study focuses on different models for cloudy sky temperature estimation. Since no measured sky temperature values are available, only the impact of using different sky temperature models is reviewed on transient thermal modeling.

Overall, in this study, performances of different sky temperature models, solar decomposition modes, and diffuse radiation on inclined surface models are reviewed, and the impact of these models on transient thermal modeling is studied. The goal is to understand how much error could be expected when using inappropriate sky and solar radiation models for transient thermal modeling.

Methods

In this study, in total three hourly horizontal global solar radiation decomposition models, four hourly diffuse radiation models, and five sky temperature estimation models are reviewed. The impact of different models is reviewed on one lightweight and one mass-type assembly. The details of models and simulations setup are in this section.

Solar radiation

The selected hourly horizontal global solar radiation decomposition models are from Erbs et al. (1982), Reindl et al. (1990a), and Orgill and Hollands (1977). Studied hourly diffuse radiation models on an inclined surface are Reindl et al. (1990b), Skartveit and Olseth (1986), Hay (1979), and Perez et al. (1990). These models are selected based on the climates that they have been developed based on, and extent of their use in energy modeling industry. Therefore, the combination of decomposition models and diffused radiation on tilted surface models would result in total of 12 models.

The already-mentioned models require extraterrestrial solar radiation, global solar radiation, cloud index, temperature and relatively humidity, and sun position as inputs. Model inputs are imported from Engineering Climate Datasets (Government of Canada n.d.-a). The model results (total of 12 combined models) are compared with 2013 1-year measured total solar radiation on a southeast-oriented wall located at BCIT Burnaby Campus. Global solar radiation (Government of Canada n.d.-b) is decomposed into direct and diffuse components using the selected three models. Fraction of diffuse solar components on south-east wall is then calculated using the four selected models. Lastly, results for total tilted solar radiation on southeast orientation wall (12 models) are compared with 2013 measured data from BCIT Burnaby Campus.

In order to review the impact of different solar radiation models on hourly thermal modeling, solar radiation from different models is used to simulate the transient heat transfer in one-dimensional lightweight and mass-type walls (total of two walls). Errors caused by utilizing different models are presented.

Sky temperature

In this study, selected sky emissivity models are from Melchor (1982), Clark and Allen (1978), Daguenet (1985) (both England and Sweden), and Aubinet (1994). All these models were developed according to climates with a relatively high chance of rain; therefore, they would be potential candidates for climates such as in Vancouver.

The already-mentioned models require relative humidity, ambient temperature, atmospheric pressure, site elevation, sky cover, and clearness index as inputs. Model inputs are imported from Engineering Climate Datasets (Government of Canada website).

Since measured data were not available for sky temperature, only the impact of using different sky temperatures on hourly thermal modeling is reviewed. Sky temperature results from different models are used to simulate the transient heat transfer in one-dimensional lightweight and mass-type walls (total of two walls). The 2005 hourly Vancouver International Airport weather data are used for the purpose of this simulation. Deviation of the results from the reference case of “no sky temperature” is reviewed for each model.

Simulation setup

For both solar radiation and sky temperature one lightweight wall and one mass-type wall are simulated in order to review the impact of different sky and solar radiation models on both light and mass-type assemblies. Due to thermal mass, lightweight assemblies tend to show the impact of boundary condition on resultant heat flux more quickly than mass-type assemblies. A typical lightweight wall assembly in Vancouver consists of 1/2 inch drywall, 5½ inches of batt insulation, 1/2 inch plywood sheathing, 1/2 inch air cavity,
and 1/2 inch fiber-cement board, and a typical mass-type wall consists of 1/2 inch drywall, 3 inches of XPS insulation, and 8 inches of concrete structural wall (material properties are shown in Table 1). One-year exterior boundary conditions are imported from Engineering Climate Datasets (Government of Canada n.d.-a). Material properties are selected from 2013 ASHRAE Handbook—Fundamentals. The interior air film coefficient is assumed to be 8.33 W/m²·K and the exterior air film coefficient is assumed to be 33 W/m²·K. No sky temperature radiation is considered for solar radiation simulation cases, and no solar radiation is considered for sky temperature simulation cases. Ground reflectivity is assumed to be 0.2 (dimensionless).

For all transient numerical simulations, COMSOL Multiphysics Modeling Software has been used. A conduction heat transfer equation is used for numerical simulation as follows:

\[
\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q \tag{5}
\]

The software results are validated using the four benchmark cases from ISO 10211 (ISO2007). For illustration purposes, simulation results for case 3 of the ISO standard (geometries shown in Figure 1) are presented in this section. Boundary conditions, material properties, and model assumptions are given in the standard. The calculated results are in good agreement with the results from ISO (Table 2).

**Table 1. Material properties.**

| Number | Component                        | Thickness, mm (inches) | Thermal conductivity, W/m·K (btu/h·ft²·°F) | Density, kg/m³ (lb/ft³) | Heat capacity, J/kg·K (Btu/lb·°F) |
|--------|----------------------------------|------------------------|-------------------------------------------|--------------------------|----------------------------------|
| 1      | Gypsum board                     | 12.7 (1/2)             | 0.16 (0.093)                              | 640 (40)                 | 1150 (0.27)                      |
| 2      | Glass fiber Insulation board     | 139.7 (5.5)            | 0.043 (0.025)                             | 14 (0.87)                | 840 (0.20)                       |
| 3      | Extruded polystyrene insulation | 76.2 (3)               | 0.0288 (0.017)                           | 28 (1.74)               | 1220 (0.29)                      |
| 4      | 2 x 6 SPF wood stud              | 139.7 (5 1/2)          | 0.12 (0.069)                              | 460 (28.72)              | 1880 (0.45)                      |
| 5      | Concrete                         | 203.2 (8)              | 1.8 (1.04)                                | 2250 (139.5)             | 850 (0.20)                       |
| 6      | Plywood sheathing                | 12.7 (1/2)             | 0.091 (0.053)                             | 460 (28.72)              | 1880 (0.45)                      |
| 7      | Air cavity                       | 12.7 (1/2)             | 0.098 (0.057)                             | 1.225 (0.08)             | 1005 (0.24)                      |
| 8      | Fiber cement board               | 12.7 (1/2)             | 0.25 (0.145)                              | 1400 (87.40)             | 840 (0.20)                       |

**Results**

**Solar radiation**

For illustration purposes, three days in January and three days in July (six days in total) of hourly results for different solar radiation models on the southeast wall are provided in Figure 2. Discrepancies of results are calculated using seasonal and total mean absolute error (MAE) for each model in Table 3. Figure 3 shows percentage of hourly solar radiation results corresponding to specified range of relative error, which reveals the reliability of each model.

**Sky temperature**

For illustration purposes, 14 days (7 days in January and 7 days in July) of hourly results for sky temperature are provided for each model in Figure 4. For both lightweight and mass-type walls, NMAE values between calculated results from measured solar values. The errors are normalized by dividing MAE by the average heat transfer results corresponding to measured values for the specified period of time.

![Fig. 1. Geometries of case 3 from ISO standards.](image)
model (no sky temperature) are shown in Table 5 in order to review the heat transfer deviation caused by different models.

### Discussion

#### Solar radiation

Table 1 and Figure 2 reveal that the Erbs–Skartveit, Reindl–Skartveit, and Orgill–Skartveit models result in the solar radiation values closest to measured data. Among these three models, the Reindl–Skartveit model has the best performance, with 42% of the results within ±10% relative error, and has the lowest seasonal and total MAE (35.78 W/m²). This model also shows the least seasonal fluctuation in MAE values, which proves the stability.

Table 4 confirms the fact that the Reindl–Skartveit model also results in the lowest seasonal and total NMAE (5.09% for lightweight and 4.31% for mass-type) hourly heat transfer for both lightweight and mass-type walls. Different solar models could result in up to 2.26% additional discrepancy in total NMAE for the lightweight wall and 0.47% additional discrepancy in total NMAE for the mass-type wall. Similar pattern could be found for seasonal NMAE results.

#### Sky temperature

Significant variation between sky temperature models’ results is revealed in Figure 3, which mostly occurs during

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**Table 2.** Results comparison between COMSOL and ISO.

| Items            | Nodes | Listed temperatures in ISO 10211-1 (°C) | Modeled temperatures with COMSOL (°C) | Discrepancy |
|------------------|-------|----------------------------------------|-------------------------------------|-------------|
| Temperature (°C) | U     | 12.9                                   | 12.908                              | 0.008       |
|                  | V     | 11.3                                   | 11.341                              | 0.041       |
|                  | W     | 16.4                                   | 16.409                              | 0.009       |
|                  | X     | 12.6                                   | 12.557                              | 0.043       |
|                  | Y     | 11.1                                   | 11.124                              | 0.024       |
|                  | Z     | 15.3                                   | 15.287                              | 0.013       |
| Heat flow (W/m)  | α     | 46.3                                   | 45.88                               | 0.97%       |
|                  | β     | 14                                     | 13.91                               | 0.64%       |
|                  | γ     | 60.3                                   | 59.79                               | 0.85%       |

**Table 3.** Solar radiation model comparison—MAE.

| Models          | Winter | Spring | Summer | Fall | Total |
|-----------------|--------|--------|--------|------|-------|
| Erbs–Reindl     | 32.7   | 37.8   | 49.6   | 33.4 | 39.6  |
| Erbs–Skartveit  | 29.6   | 30.4   | 49.6   | 27.6 | 35.6  |
| Erbs–Hay        | 33.5   | 38.5   | 50.0   | 34.7 | 40.3  |
| Erbs–Perez      | 31.4   | 34.5   | 50.8   | 31.4 | 38.3  |
| Reindl–Reindl   | 32.5   | 37.0   | 50.1   | 32.4 | 39.3  |
| Reindl–Skartveit| 29.6   | 29.8   | 48.4   | 26.2 | 34.7  |
| Reindl–Hay      | 33.7   | 47.3   | 73.3   | 33.2 | 49.9  |
| Reindl–Perez    | 31.4   | 34.4   | 50.8   | 31.5 | 38.3  |
| Orgill–Reindl   | 33.5   | 38.5   | 50.0   | 34.7 | 40.3  |
| Orgill–Skartveit| 29.5   | 30.3   | 49.7   | 28.3 | 35.7  |
| Orgill–Hay      | 34.3   | 44.8   | 66.3   | 35.8 | 47.6  |
| Orgill–Perez    | 32.0   | 35.3   | 51.7   | 32.6 | 39.2  |

**Fig. 2.** Solar radiation comparison for January 2–4 and July 2–4
Fig. 3. Percentage of results corresponding to selected range of relative error—solar model comparison.

Table 4. Transient heat load comparison—solar radiation, lightweight and mass-type walls.

| Model       | Winter | Spring | Summer | Fall | Total | Winter | Spring | Summer | Fall | Total |
|-------------|--------|--------|--------|------|-------|--------|--------|--------|------|-------|
| Erbs–Reindl | 5.3%   | 7.2%   | 35.8%  | 2.8% | 5.7%  | 4.3%   | 6.2%   | 30.3%  | 2.0% | 4.6%  |
| Erbs–Skartveit | 4.8%  | 5.9%   | 36.3%  | 2.3% | 5.2%  | 4.3%   | 5.5%   | 35.4%  | 1.5% | 4.6%  |
| Erbs–Hay    | 5.4%   | 7.3%   | 35.8%  | 2.9% | 5.8%  | 4.4%   | 6.4%   | 30.3%  | 2.0% | 4.7%  |
| Erbs–Perez  | 5.2%   | 6.7%   | 37.1%  | 2.6% | 5.6%  | 4.1%   | 5.4%   | 29.9%  | 1.7% | 4.4%  |
| Reindl–Reindl | 5.2%  | 7.1%   | 36.2%  | 2.7% | 5.7%  | 4.0%   | 5.7%   | 26.5%  | 1.9% | 4.3%  |
| Reindl–Skartveit | 4.7%  | 5.7%   | 35.8%  | 2.1% | 5.0%  | 4.0%   | 5.2%   | 31.0%  | 1.4% | 4.3%  |
| Reindl–Hay   | 6.6%   | 9.2%   | 53.7%  | 2.8% | 7.3%  | 4.1%   | 5.8%   | 28.7%  | 1.8% | 4.4%  |
| Reindl–Perez | 5.1%   | 6.7%   | 37.1%  | 2.5% | 5.5%  | 4.0%   | 5.3%   | 29.3%  | 1.7% | 4.3%  |
| Orgill–Reindl | 5.4%  | 7.3%   | 35.8%  | 2.9% | 5.8%  | 4.4%   | 6.4%   | 30.3%  | 2.0% | 4.7%  |
| Orgill–Skartveit | 4.9%  | 5.9%   | 36.5%  | 2.4% | 5.2%  | 4.3%   | 5.5%   | 35.3%  | 1.6% | 4.7%  |
| Orgill–Hay   | 6.3%   | 8.8%   | 48.4%  | 2.9% | 6.9%  | 4.2%   | 6.0%   | 27.9%  | 2.0% | 4.5%  |
| Orgill–Perez | 5.3%   | 6.9%   | 37.9%  | 2.8% | 5.7%  | 4.1%   | 5.5%   | 29.1%  | 1.9% | 4.4%  |

Fig. 4. Night sky temperature comparison for January 7–14 and July 7–14.
Table 5. Transient heat load comparison—sky temperature, lightweight and mass-type walls.

| Model   | Winter | Spring | Summer | Fall | Total  |
|---------|--------|--------|--------|------|--------|
| Melchor | 3.6%   | 7.0%   | 19.1%  | 3.4% | 6.5%   |
| Clarke  | 2.7%   | 5.5%   | 14.5%  | 2.6% | 5.0%   |
| England | 5.3%   | 10.2%  | 15.2%  | 8.4% | 8.8%   |
| Sweden  | 6.5%   | 12.6%  | 17.9%  | 10.4%| 10.7%  |
| Aubinet | 1.4%   | 3.1%   | 7.3%   | 1.5% | 2.7%   |

| Model   | Winter | Spring | Summer | Fall | Total  |
|---------|--------|--------|--------|------|--------|
| Melchor | 7.4%   | 11.2%  | 25.0%  | 6.8% | 10.6%  |
| Clarke  | 7.0%   | 10.0%  | 19.9%  | 6.9% | 9.5%   |
| England | 8.9%   | 14.9%  | 20.0%  | 12.8%| 13.0%  |
| Sweden  | 10.5%  | 17.5%  | 23.0%  | 15.1%| 15.3%  |
| Aubinet | 4.4%   | 7.0%   | 11.9%  | 4.3% | 6.0%   |

Conclusions

The performances of several different horizontal global solar radiation decomposition models, hourly diffuse radiation on inclined surface models, and sky temperature estimation models are reviewed in this study. Moreover, the impact of each model on a 1-year transient thermal simulation of one lightweight and one mass-type wall assembly has been reviewed. The goal was to understand the potential inaccuracies caused by using different sky and solar radiation models. Solar radiation models’ results are compared with 1-year measured data from the British Columbia Institute of Technology campus. With respect to solar radiation, a combination of the Reindl et al. (1990a) and Skartveit and Olseth (1986) models revealed the best result compare with measured values. The impact of using different solar radiation model on transient heat transfer modelling was reviewed, and 2.26% additional discrepancy on the lightweight wall and 0.47% additional discrepancy on the mass-type wall were found. Using different sky radiation models could result in additional deviation of 8% in the lightweight wall and 9.3% in the mass-type wall compared with reference results.

Transient thermal simulation results reveal that sky temperature models’ estimations have more impact on total transient heat transfer compared to solar radiation models. Overall, in order to conduct an accurate building energy simulation, it is critical to diligently select the proper estimation model for both solar radiation and sky temperature if the measured values are not available.

This study is conducted on a 1-year simulation of Vancouver type climatic condition; therefore, the performance and impact of each model could be further analyzed under other climate conditions as well. Moreover, sky and solar radiation models could reveal different impact on more complicated building envelope details such as thermal bridging, which could be studied further from this research.

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