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

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ABSTRACT

Performing accurate hourly building energy modeling requires 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 to have accurate solar radiation intensity on angled building envelope assemblies 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 on inclined surface models, and five sky temperature estimation models are studied for Vancouver climate. For solar radiation validation perspective, 2013 one-year measured total solar radiation on a south-east oriented wall located at BCIT Burnaby Campus is compared with the results from selected solar models. For both solar radiation and sky temperature models, impact of using different models on transient heat transfer results of light-weight and mass-type walls (two walls) are reviewed. Results reveal high impact of both solar and sky temperature models on hourly heat transfer simulation results.

KEYWORDS

Sky temperature, diffuse radiation on tilted surface, decomposition of global radiation, transient thermal simulation.

INTRODUCTION

From the total energy spent in 2013 within Canada, 17% was found in residential sector, and 10% in commercial and institutional sectors (Canada, 2016). Therefore, it is important to thoroughly understand the interaction between energy consuming elements within a building, which requires hourly energy simulation. Performing an accurate hourly 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.

Solar radiation

Most available climatic weather data only contains global value for solar radiation, while direct and diffuse components of solar radiation as well as diffuse radiation on inclined surfaces are not always available (Burlon, et al., 1991). These three components are ultimately required to calculate the total solar radiation on a tilted surface. Many decomposition models for calculation of diffuse solar radiation are developed based on the terminology first studied by Liu & Jordan (1960). Performance of several previous solar radiation models are reviewed in this study, and results are compared with the measured data for validation purposes.

Sky radiation

Measured sky radiation is not always available. 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 clear sky condition (Algarni & Nutter, 2015), while climates with high cloud coverage (i.e. Vancouver) require a certain correlation to account for sky condition. In this study, different models for cloudy sky temperature estimation are reviewed. Since no measured sky temperature values is available, only the impact of using different sky temperature models is reviewed on transient thermal modeling.

METHODS

In this study, total of three hourly horizontal global solar radiation decomposition models, four hourly diffuse radiation on inclined surface models, and five sky temperature estimation models are reviewed.

Solar radiation

The selected hourly horizontal global solar radiation decomposition models are Erbs, et al. (1982), Reindl, et al. (1990), and Orgill & Hollands (1977). Studied hourly diffuse radiation models on an inclined surface are Reindl, et al. (1990), Skartveit & 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 twelve models.

The above-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.). The model results (total of twelve combined models) are compared with 2013 one-year measured total solar radiation on a south-east oriented wall located at BCIT Burnaby Campus. Global solar radiation (Government of Canada, n.d.) is decomposited 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 south-east orientation wall (twelve 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 are used to simulate the transient heat transfer in one-dimensional light-weight 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 Melchor (1982b), Clark & C. Allen (1978), Daguenet (1985) (both England and Sweden), and Aubinet (1994). All these models are developed according to climates with relatively high chance of rain; therefore, they would be potential candidates for climates such as Vancouver.

The above-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 was not available for sky temperature, only impact of using different sky temperature on hourly thermal modeling is reviewed. Sky temperature results from different models are used to simulate the transient heat transfer in one-dimensional light-weight and mass-type walls (total of two walls). 2005 hourly Vancouver International Airport weather data is 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, light weight wall consists of ½" drywall, 5 ½" of batt insulation, ½" plywood sheathing, ½" air cavity and ½" hardie-siding, and mass-type wall consists of ½" drywall, 3" of XPS insulation and 8" concrete structural wall. Material properties are selected from 2013 ASHRAE Handbook – Fundamentals. Interior air film coefficient is assumed 8.33 W/m²K and exterior air film coefficient is assumed 33 W/m²K. 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 Modelling Software has been used. The software results are validated using the four benchmark cases from ISO 10211 (10211, 2007).

RESULTS

Solar radiation

Six days of hourly results for different solar radiation models on the south-east wall are provided in Figure 1. Discrepancy of results are calculated using seasonal and total Mean Absolute Error (MAE) for each model in Table 1. Figure 2 shows percentage of hourly solar radiation results corresponding to specified range of relative error, which reveals the reliability of each model.

Table 2 is provided to review the impact of different solar models on transient heat transfer simulation for light-weight and mass-type wall assemblies. This table contains seasonal and total heat transfer Normalized Mean Absolute Error (NMAE) compare with simulation 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.

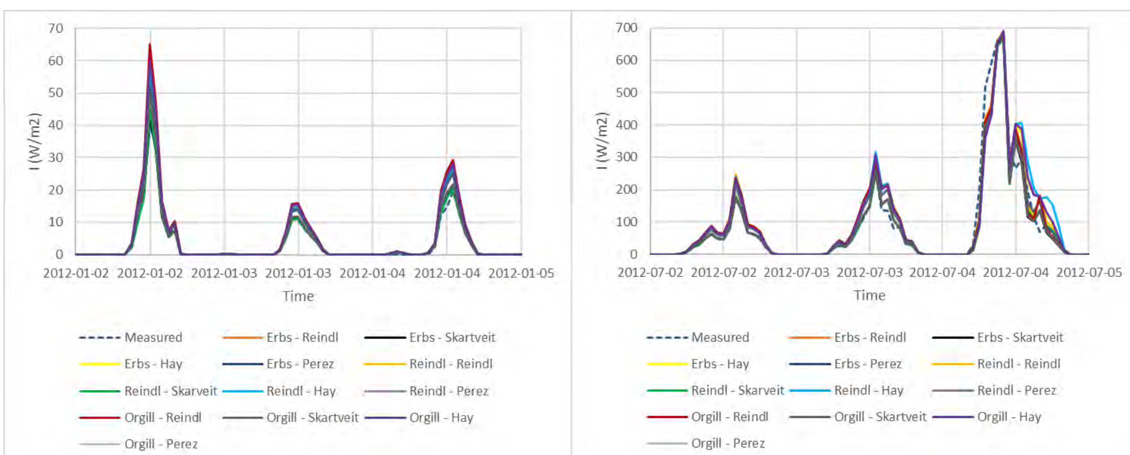

Figure 1. Solar radiation comparison for Jan 2nd-4th and July 2nd-4th.

Table 1. 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

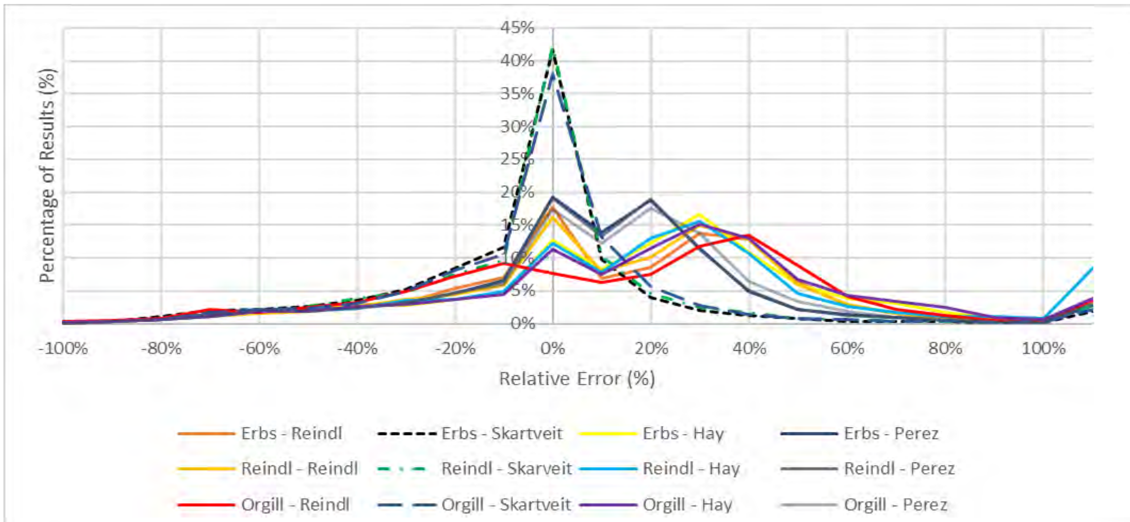

Figure 2. Percentage of results corresponding to selected range of relative error – solar model comparison

Table 2. Transient heat load comparison – Solar radiation – Light-weight and mass-type walls

Model	Light-Weight Wall					Mass-Type Wall				
	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%

Sky temperature

Fourteen days of hourly results for sky temperature are provided for each model in Figure 3. For both light-weight and mass-type walls, NMAE between calculated results from the selected sky temperature models and reference model (no sky temperature) are shown in Table 3 in order to review the heat transfer deviation caused by different models.

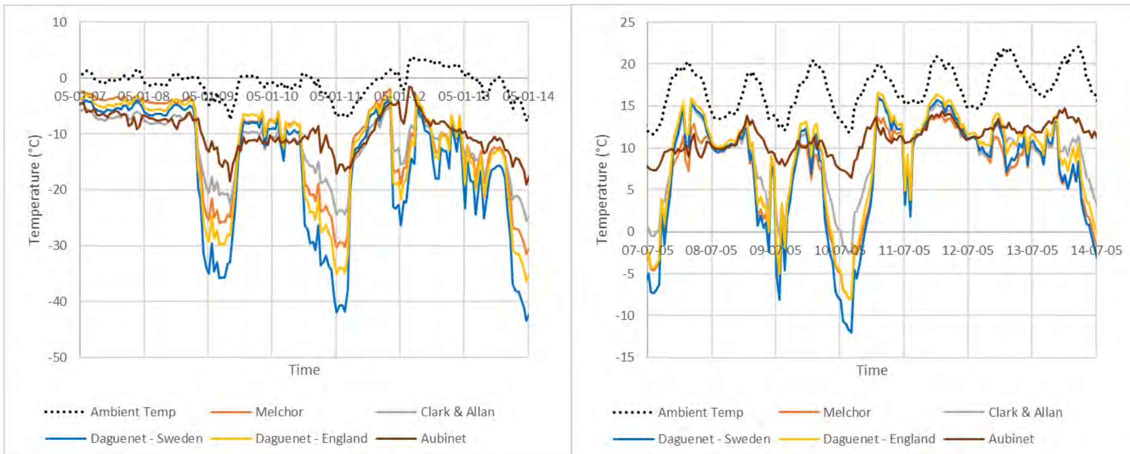

Figure 3. Night sky temperature comparison for Jan 7th-14th and July 7th-14th

Table 3. Transient heat load comparison – Sky temperature – Light-weight and mass-type walls

Model	Light-Weight Wall					Mass-Type Wall				
	Winter	Spring	Summer	Fall	Total	Winter	Spring	Summer	Fall	Total
Melchor	3.6%	7.0%	19.1%	3.4%	6.5%	7.4%	11.2%	25.0%	6.8%	10.6%
Clarke	2.7%	5.5%	14.5%	2.6%	5.0%	7.0%	10.0%	19.9%	6.9%	9.5%
England	5.3%	10.2%	15.2%	8.4%	8.8%	8.9%	14.9%	20.0%	12.8%	13.0%
Sweden	6.5%	12.6%	17.9%	10.4%	10.7%	10.5%	17.5%	23.0%	15.1%	15.3%
Aubinet	1.4%	3.1%	7.3%	1.5%	2.7%	4.4%	7.0%	11.9%	4.3%	6.0%

DISCUSSIONS

Solar radiation

Table 1 and Figure 2 reveal that Erbs - Skartveit, Reindl - Skartveit and Orgill - Skartveit models result in the closest solar radiation values to measured data. Among these three models, 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 2 confirms the fact that Reindl - Skartveit model also results in the lowest seasonal and total NMAE (5.09% for light-weight and 4.31% for mass-type) hourly heat transfer for both light-weight and mass-type walls. Different solar models could result up to 2.26% additional discrepancy in total NMAE for the light-weight 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 days with clear sky. Using different night sky models could result in total deviation (Table 3) in the range of 2.71% to 10.77% for light-weight wall and 6.09% to 15.33% for mass-type wall from the reference case (no sky radiation). Significant seasonal deviation is also shown in Table 3 for both light-weight and mass-type walls. This shows the great impact of utilizing different sky temperature models on transient heat transfer simulations.

CONCLUSIONS

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. Solar radiation models' results are compared with one-year measured data from BCIT campus. With respect to solar radiation, combination of Reindl, et al. (1990) and Skartveit & Olseth (1986) models revealed the best result compare with measured values. Impact of using different solar radiation model on transient heat transfer modelling was reviewed, and 2.26% additional discrepancy on the light-weight wall and 0.47% on the mass-type wall were found. Using different sky radiation models could result in additional deviation of 8% in light-weight wall and 9.3% in mass-type wall compare with reference results.

Transient thermal simulation results reveal the fact that sky temperature models' estimation have more impact on total transient heat transfer compare 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.

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