Hygrothermal Simulations of Cool Reflective and Conventional Roofs

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Abstract

When solar radiation hits a roof surface, a part of solar energy is reflected and part is absorbed. The absorbed part of solar energy results in an increase in the **roof's** surface temperature. Cool reflective (white) roofs use bright surfaces to reflect the incident short-wave solar radiation, which lowers the surface temperature compared with conventional (black) roofs with bituminous membrane**s**. As such, white roofs help reduce the urban heat island effect during the summer. The question is: "Do white roofs lead to moisture-related problems in northern and southern climates?" To answer this question, numerical simulations are conducted to compare the hygrothermal performance of white and black roofs under different outdoor and indoor conditions. The outdoor conditions are obtained from the weather database of the National Research Council of Canada, Institute for Research in Construction (NRC-IRC). The indoor conditions are taken based on European standard (EN 15026) and American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommendations for conditioned space. The roof types considered in this study are polymer-modified

bitumen roof systems. The numerical simulations were conducted using the NRC-IRC's hygrothermal model called "hygIRC-C."

Authors

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Introduction

Climate change is one of the problems we currently face. Roof systems with potential energy savings with no moisture accumulation can help reduce the energy requirements for buildings, thereby reducing operating costs and contributing to the fight against global warming. Ray and Glicksman [1] developed a thermal model used to assess the energy savings of cool and green roofs. Their results showed the potential energy savings are highly sensitive to many parameters: roof type, climate and amount of insulation. It is important to design roof systems that simultaneously can lead to energy savings and low risk of moisture-related problems. Over time, moisture accumulation in roofing materials can damage the materials and reduce the roof's system's effective thermal resistance, resulting in higher energy costs. Typically, short-wave solar radiation can dry out the roof system during the daytime and summer. The amount of short-wave energy absorbed by the roof system depends on the reflectivity of its surface. Because cool (white) roofs have low short-wave solar absorption co-efficient, they maintain lower temperatures than dark (black) roofs and may provide less heat to dry out moisture. This could cause cool roofs to be more susceptible to moisture accumulation when used in cold climates [2]. This phenomenon has been observed in cool and dark roofs in cold climates [3].

Self-drying roof systems are designed to avoid moisture accumulation. Under typical operating conditions, condensation shall not occur under a membrane during winter uptake. The construction in these roof systems typically is sealed to the outside by a membrane that acts as a water and vapor barrier. To the inside, no vapor barrier is used to allow moisture to dry out to the building's interior. Desjarlais [4, 5] conducted extensive studies to investigate the hygrothermal performance of white and black self-drying roof systems in various U.S. locations.

Bludau et al. [6] conducted hygrothermal simulations to investigate moisture buildup in white and black roofs under different climatic conditions (Phoenix; Chicago; Anchorage, Alaska; and Holzkirchen, Germany). The simulations were conducted for five years with short-wave solar absorption coefficients of 0.88 for black roofs and 0.2 for white roofs. That study showed black roofs always run with lower moisture compared to white roofs. In hot climates, such as Phoenix, there is no risk for this kind of moisture buildup for white and black roofs. In colder climates, such as Chicago, Anchorage or Holzkirchen, they found there is less heat available to dry out the cool roofs and more opportunities for moisture buildup with time. Bludau et al. [7] investigated the hygrothermal performance of dark, bright and shaded low-slope roofs with construction moisture where 2 L/m^2 of water was added before the roof was sealed from above. In that study, a short-wave solar absorption co-efficient of 0.9 was considered for the dark roof. For the white roof, a measured short-wave solar absorption co-efficient of 0.2 was considered; this co-efficient can increase to 0.3 with time by aging and the effect of dust [7]. The dark roofs showed the largest surface temperature and humidity fluctuations, including comparatively high heat fluxes during summer. The surface temperature and drying potential were low in roofs with bright and shaded surfaces.

The objective of this paper is to conduct hygrothermal simulations to investigate the moisture accumulation over time, as well as energy use of reflective (cool) and nonreflective (black) polymer-modified bitumen roof systems. These roofs are subjected to different outdoor climates of North America with different heating degree days (HDD), namely: Toronto; St John's, Newfoundland; Saskatoon,Saskatchewan; Seattle; and Wilmington, N.C. The HDD based on degree Celsius (<18 C) for Seattle and Wilmington are 2564 and 1349, respectively [8]. According to the National Building Code of Canada (NBC), the HDD based on degree Celsius for Toronto, St John's and Saskatoon are 3650, 4800 and 5950, respectively [9].

Model Descriptions

In this study, the NRC-IRC's hygrothermal model, hygIRC-C, originally developed for wall systems, was adapted in this project to perform a comparative parametric investigation of the hygrothermal (i.e., heat, air and moisture) performance of reflective and nonreflective roof systems. This model solves simultaneously the 2-D and 3-D moisture transport equation, energy equation, and air transport equation in the various material layers. The air transport equation is the Navier-Stokes equation for the airspace (for example, airspace above the steel deck; see Figure 1), and Darcy equation (Darcy number is less than 10^{-6}) and Brinkman equation (Darcy number is greater than 10^{-6}) for the porous material layers. According to the roof configuration shown in Figure 1, the 2-D version of the hygIRC-C model is adequate for conducting the numerical simulations. This model was benchmarked against the hygIRC 2-D model previously developed at NRC-IRC [10, 11] and test results of different wall systems in a number of projects [12-19].

Roof Descriptions and Assumptions

The numerical simulations are conducted for a low-slope polymer-modified bitumen roof system (289 mil) shown in Figure 1. The cap sheet and base sheet (7.34 mm total thickness) were made of torch-applied asphalt-based membrane. The thermal insulation in this roof system consisted of a fiberboard (25.4 mm thick) and a cover board over a rigid polyisocyanurate board (50.8 mm thick). Unlike self-drying roof systems (see Desjarlais [4, 5]), a vapor barrier made of bituminous paper, Type II felt (0.65 mm thick) was placed between the polyisocyanurate board and steel deck (P-3615). It was assumed all material layers shown in Figure 1 are in good contact (i.e., the interfacial resistances because of heat and moisture transport are neglected).

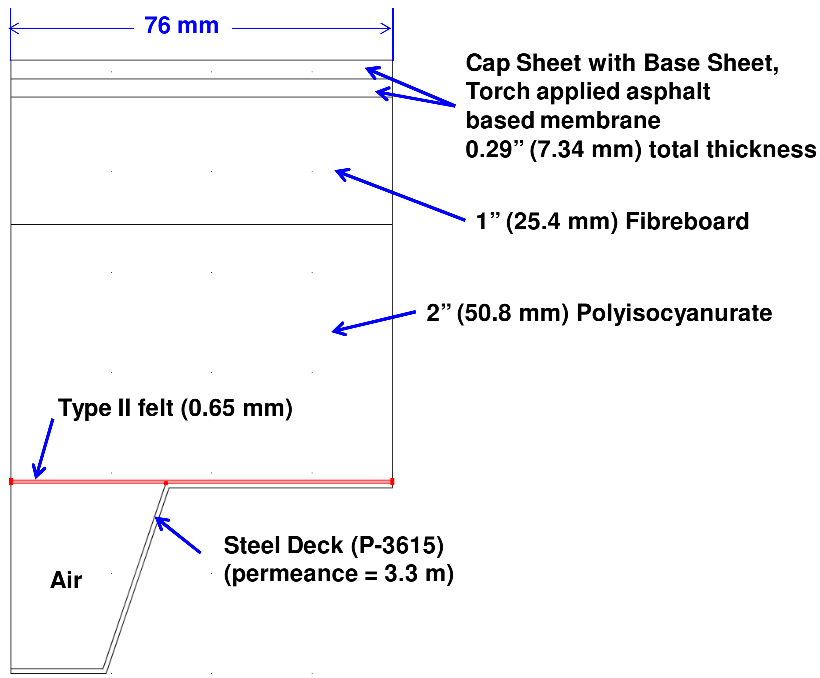

Figure 1. A schematic of a polymer-modified bitumen roof system

The hygrothermal properties of torch-applied asphalt-based membrane, fiberboard, polyisocyanurate and Type II felt were obtained from NRC-IRC's material database [20, 21]. Currently, this database provides the hygrothermal properties of different construction materials as a function of moisture content only (i.e., independent on temperature). However, these properties may change with temperature. For example, Schwartz et al. [22] showed that the measured water vapor permeability of polyurethane and polyisocyanurate foams is constant for temperatures lower than 20 C but increases linearly for temperatures higher than 20 C. Also, laboratory testing has shown that the vapor permeance of EPDM membranes increases nonlinearly with temperature for temperature**s** above 32 C [23].

To account for perforations and joints of the steel deck, its vapor permeability was taken to be 3.3 m (5 U.S. perms) [4, 6]. According to Bludau et al. [6], the long-wave emissivity of the external roof surface was taken to be 0.9, and the short-wave solar absorption co-efficient of 0.2 and 0.88 were used for a white surface and black surface, respectively. Bludau et al. [7] indicated the short-wave solar absorption co-efficient of a white surface can increase from 0.2 to 0.3 with time as a result of aging and accumulation of dust. In cold climates, there is a possibility for snow accumulation on top of a roof system. Snow can affect the long-wave emissivity and short-wave solar absorption co-efficient for white and black roof systems. Shading and insulating effects because of snow are not accounted for in the present study.

Initial and Boundary Conditions

In all material layers, the initial moisture content was set to correspond to 50 percent relative humidity and the temperature was set to 10 C. As a result of symmetry, the boundary conditions on the left and right boundaries of the roof system (see Figure 1) were adiabatic (no energy transport) and sealed (no moisture and air transport). The top boundary was subjected to outdoor conditions while the bottom boundary was subjected to indoor conditions. The outdoor conditions were based on hourly weather data and obtained from the NRC-IRC's weather database for a number of North American cities, namely: Toronto (HDD = 3650), St. John's (HDD = 4800), Saskatoon (HDD = 5950), Seattle (HDD = 2564) and Wilmington (HDD = 1349). To identify the worst-case scenario in terms of hygrothermal performance, numerical simulations were conducted using the weather data of Toronto with two different types of indoor conditions. The first indoor conditions were based on ASHRAE recommendations for conditioned space [24]. The second indoor conditions were based on European standard, EN 15026 [25].

Results and Discussions

In this section, the hygrothermal performances of white and black polymer-modified bitumen roof systems (see Figure 1) are discussed. These roof systems are subjected to different outdoor climates. Because the objective of this study is to investigate the moisture accumulation over time within the roof system, the numerical simulations for different roof systems were conducted for a period of five years. When we observed the moisture accumulation continues to increase over time after five years, the simulation period was extended. In all numerical simulations, the weather data of only one year for each location was used. This weather data was repeated for subsequent years. Also, in all simulations, time = 0 corresponds to Jan. 1.

Effect of Indoor Conditions and Roof Color on Hygrothermal Performance in Toronto

The effect of using different indoor conditions on the hygrothermal performance of black and white roofs was investigated at only one location. For the outdoor climate of

Toronto, Figure 2 shows the average moisture content (MC_{avg}) in the fiberboard, using the indoor conditions of ASHRAE [24] and EN 15026 [25]. As shown in this figure, the black roof runs with lower moisture compared with the white roof. For the black roof, no moisture accumulation occurs from year to year. In the case of the white roof, moisture accumulation occurs during the first four years; however, the highest MC_{avg} in the fiberboard was well below the acceptable limit of 19 percent, according to the National Building Code of Canada [26]. Therefore, the simulation results suggest there is little risk of moisture damage for a white roof for the outdoor climate of Toronto used in this simulation, providing there is no water leakage through the roof system's membrane.

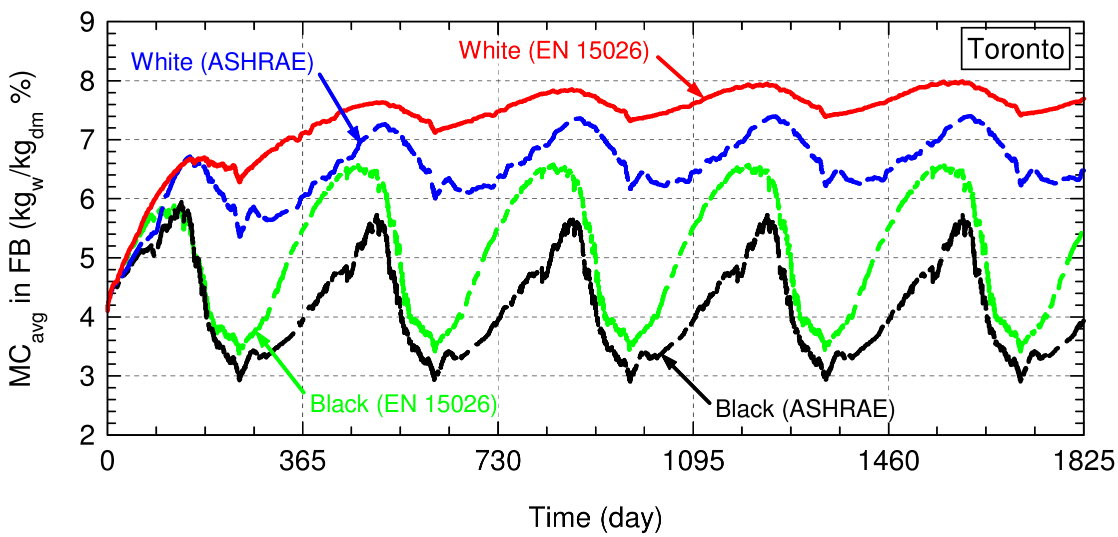

Figure 2. Average moisture content (MC_{avg}) in the fiberboard for white and black polymer-modified bitumen roofs

Figure 2 shows that white and black roofs run with higher moisture in the case of EN 15026 indoor conditions than in the case of ASHRAE indoor conditions. The MC_{avg} for the white roof with EN 15026 indoor conditions was 8 percent, which was higher than that with ASHRAE indoor conditions (7.4 percent). Similarly, the highest MC_{avg} for the black roof with EN 15026 indoor conditions was 6.6 percent, which also was higher than that with ASHRAE conditions (5.7 percent). Therefore, the EN 15026 indoor conditions represent the worst-case scenario in terms of roof systems' hygrothermal performance. As such, all numerical simulations for black and white roof systems for other outdoor climates were conducted using the EN 15026 indoor conditions.

Figure 3a and Figure 4a show comparisons of the hourly and monthly average external surface temperature of white and black roof systems for Toronto's outdoor climate. As a result of the high short-wave solar absorption co-efficient of the black roof (0.88), its surface temperature was found through numerical simulations to be significantly higher than that of the white roof with a short-wave absorption co-efficient of 0.2. The highest surface temperature of the black roof was found to be 67.2 C compared with 38.9 C for the white roof (see Table 1). During nighttime, the surface temperatures of black and white roofs were approximately the same. Figure 4a shows that the highest difference between the monthly average surface temperatures of the black and white roofs occurred in July (6 kelvins [K]) while the lowest difference between these temperatures occurred in November (1.1 K).

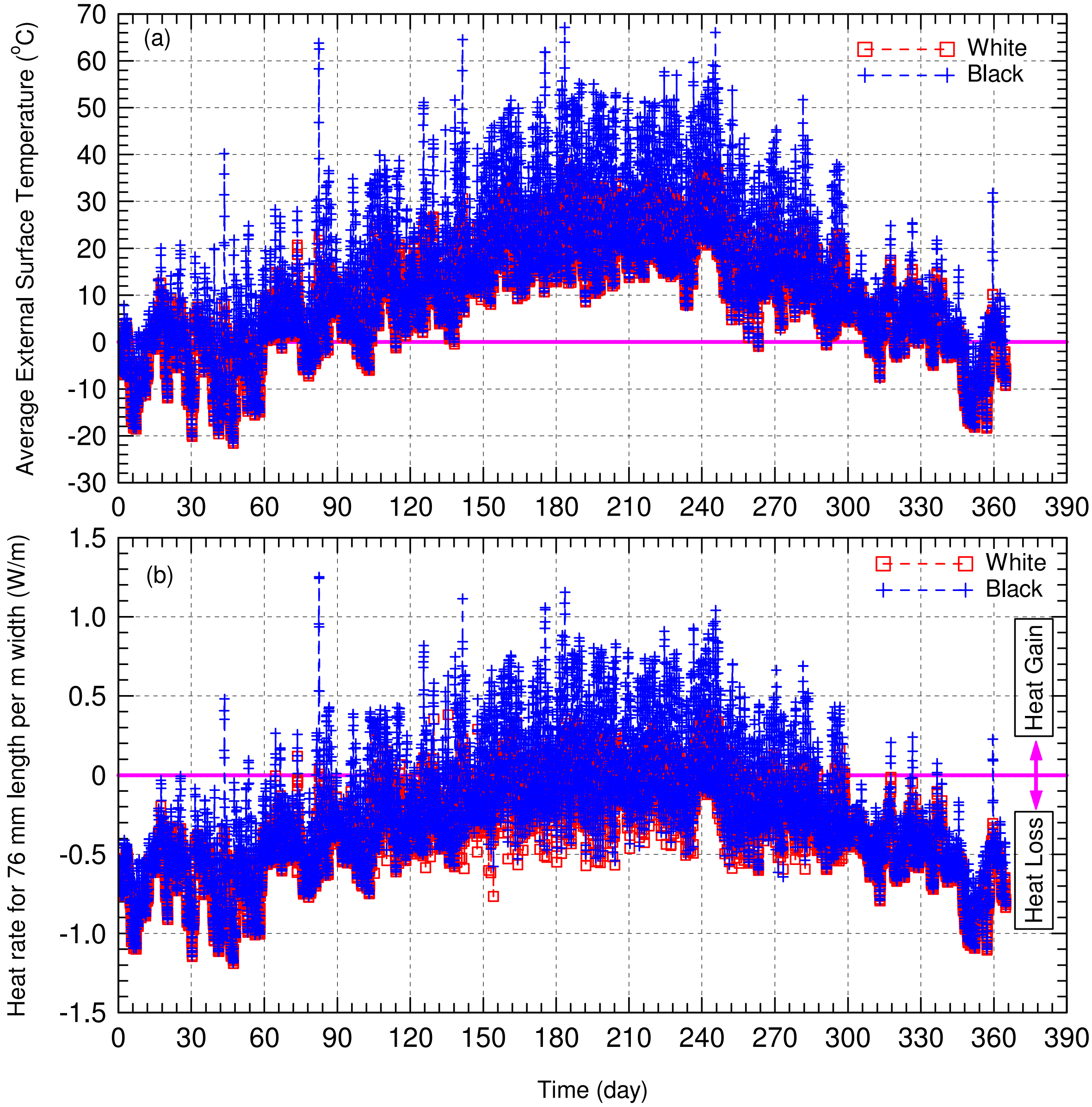

Figure 3. Comparison of hourly external surface temperature and heat gain/loss at the indoor surface of white and black roof systems for Toronto's outdoor climate

Table 1 Maximum and minimum hourly and monthly average external surface temperature for white and black roofs at different locations

City	Maximum surface temperature (°C)				Minimum surface temperature (°C)			
	Hourly		Monthly average		Hourly		Monthly average	
	Black roof	White roof	Black roof	White roof	Black roof	White roof	Black roof	White roof
Toronto	67.2	38.9	29.0	23.4	-21.6	-21.7	-2.5	-5.3
St John's	51.0	32.4	19.1	15.1	-14.5	-14.5	-2.4	-3.3
Saskatoon	65.4	38.5	25.7	20.4	-41.9	-41.9	-22.4	-23.8
Seattle	68.0	39.0	30.4	22.5	-10.3	-10.3	3.9	2.4
Wilmington	78.1	41.5	35.2	28.2	-7.6	-7.7	13.3	8.8

Table 2 Maximum hourly and monthly average heat gain/loss at the indoor surface of white and black roofs at different locations

City	Maximum heat gain (W/m)				Maximum heat loss (W/m)			
	Hourly		Monthly average		Hourly		Monthly average	
	Black roof	White roof	Black roof	White roof	Black roof	White roof	Black roof	White roof
Toronto	1.252	0.391	0.135	NA*	-1.185	-1.189	-0.647	-0.727
St John's	0.765	0.411	NA*	NA*	-0.988	-0.988	-0.644	-0.670
Saskatoon	1.187	0.402	0.061	NA*	-1.772	-1.772	-1.221	-1.262
Seattle	1.020	0.416	0.187	NA*	-0.871	-0.875	-0.462	-0.508
Wilmington	1.509	0.462	0.295	0.092	-0.791	-0.793	-0.217	-0.343

* NA means that the maximum monthly average heat gain showed heat loss instead (see Figure 6).

Table 3 Yearly accumulation of energy gain/loss (in W-day/m) at the indoor surface for each 76-mm length per meter width of black and white roofs at different locations

City	Yearly accumulation of energy gain (W-day/m)		Yearly accumulation of energy loss (W-day/m)	
	Black roof	White roof	Black roof	White roof
Toronto	26.23	4.94	-116.10	-131.87
St John's	6.77	0.52	-146.25	-162.78
Saskatoon	15.42	2.09	-168.12	-188.13
Seattle	30.68	4.48	-82.19	-98.53
Wilmington	61.82	14.89	-44.41	-55.93

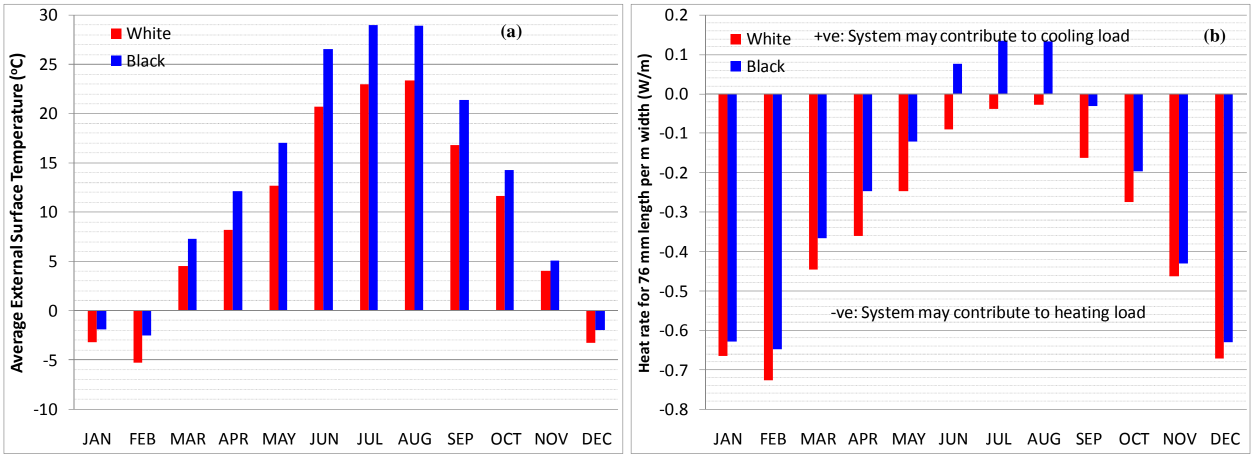

Figure 4 Comparison of monthly average external surface temperature and heat gain/loss of white and black roof systems for Toronto’s outdoor climate

Figure 3b and Figure 4b compare the hourly and monthly average heat rate (in W/m) for 76-mm length per meter width at the indoor surface of white and black roof systems. In these figures, a zero heat rate represents the case of no heat entering or leaving the building through the roof. Note that when the monthly average heat rate is positive, it is called “heat gain” (i.e., heat into the building where the system may contribute to an increased cooling load). Also, when the monthly average heat rate is negative, it is called “heat loss” (i.e., heat out of the building where the system may contribute to an increased heating load). Because of the higher surface temperature of black roofs, its heat gain is significantly higher than that for white roofs. During one year, the hourly highest heat gain for the black roof was 1.252 W/m (see Table 2), which was about 3.2 times that for the white roof (0.391 W/m, see Table 2). Furthermore, the highest hourly heat loss of black and white roofs was approximately the same and occurred during the night (1.185 W/m and 1.189 W/m for black and white roofs, respectively, see Table 2).

During the winter and for a roof with no snow accumulation, lower energy gain resulting from short-wave solar radiation for the white roof resulted in higher heat loss from the building than that of the black roof (see Figure 4b). Consequently, buildings with white roofs would require more heating load during the winter days than buildings with black roofs provided there is no snow accumulation on the roof system. For example, in February, the monthly average heat loss for the white roof is 0.73 W/m, which is 12 percent higher than that of the black roof (0.65 W/m). Conversely, during the summer, low short-wave solar radiation for the white roof resulted in less heat gain into the building compared to that of the black roof. Therefore, buildings with white roofs in our simulation would require less cooling load in the summer than buildings with our simulated black roofs (Figure 3b). Table 3 shows the yearly accumulation of energy loss for white roofs is 131.87 W-day/m for 76-mm length per meter width, which is 14 percent higher than that of the black roof. However, the yearly accumulation of energy gain for the black roof is 26.23 W-day/m, which is 5.3 times that of the white roof (4.94 W-day/m). Moreover, as explained previously, the average moisture content in the fiberboard for the white roof was well below the acceptable limit of 19 percent [26]. As a result, the simulations suggest buildings with white roofs would experience a net yearly energy savings and run with slightly higher moisture contents that nevertheless are predicted to be well below 19 percent for the roof system’s wood-based elements.

Effect of Roof Color and Climate on Roof Surface Temperatures

Figure 5 shows the monthly average external surface temperature for white and black roofs at different locations (St. John’s, Saskatoon, Seattle and Wilmington). Similar to

Toronto's outdoor climate (see Figure 4a), the highest monthly average surface temperature occurred in July at these locations. The lowest monthly average surface temperature occurred in January at St John's, Saskatoon and Wilmington and in December and February at Seattle and Toronto. The lowest monthly average surface temperature was above 0 C at Seattle and Wilmington but below 0 C at the other locations.

Table 1 lists the maximum and minimum hourly and monthly average external surface temperature for white and black roofs at different locations. As shown in the table, for a given location, the hourly minimum surface temperatures for black and white roofs were approximately the same and occurred at night. The outdoor climate of Wilmington showed the highest surface temperature for black and white roofs, followed by Seattle and Toronto. The maximum hourly and monthly average surface temperatures at Wilmington for the black roof were 78.1 C and 41.5 C, respectively, and 41.5 C and 35.2 C for the white roof (see Table 1). For black and white roofs, St John's outdoor climate showed the lowest surface temperature during the summer and Saskatoon's outdoor climate showed the lowest surface temperature during the winter. Consequently, it would be expected that black and white roofs would function with higher moisture at St. John's and Saskatoon compared with the other locations, and this was confirmed with hygrothermal results as discussed later.

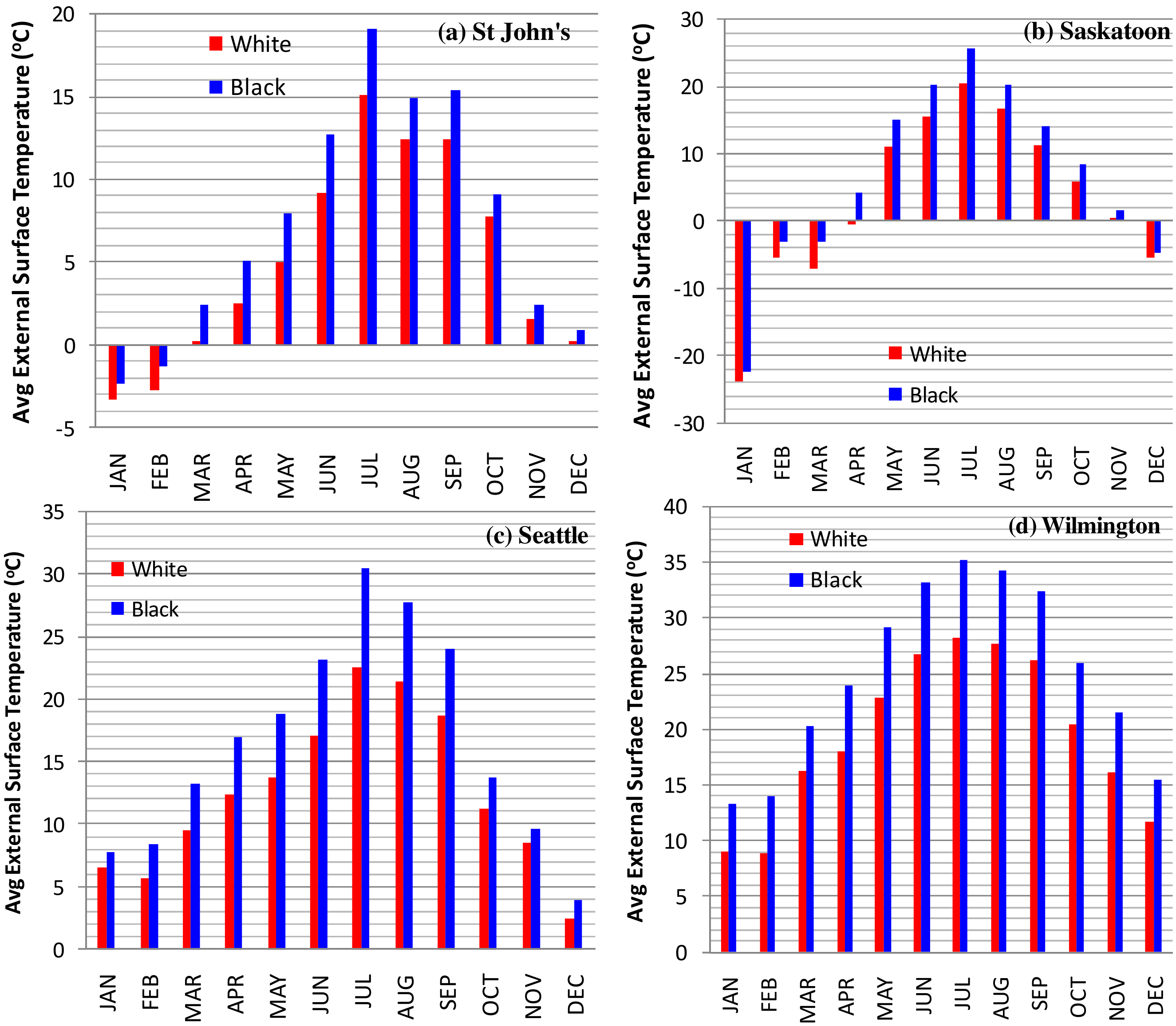

Figure 5. Comparison of monthly average external surface temperature of white and black roofing systems at different locations

Effect of Roof Color and Climate on Heat Gain/Loss

Figure 6 compares the monthly average heat gain and heat loss at the indoor surface of white and black roof systems at different locations. Also, Table 2 lists the maximum hourly and monthly average heat gain and heat loss at the indoor surface for white and black roofs at different locations. For black roofs, Wilmington's climate resulted in the highest maximum hourly heat gain (1.509 W/m), followed by Toronto (1.252 W/m); St. John's climate resulted in the lowest value (0.765 W/m). For white roofs, Wilmington's climate showed the highest maximum hourly heat gain (0.462 W/m), followed by Seattle (0.416 W/m). In terms of the maximum monthly average heat gain for black roofs, the highest value occurred at Wilmington, followed by Seattle. For white roofs, the only outdoor climate that showed a monthly average heat gain was Wilmington (Table 2). In general, all outdoor climates investigated in this paper showed black roofs experience lower heating loads than white roofs.

For the outdoor climate of St. John's, Figure 6a shows there is no monthly average heat gain (i.e., net heat into the building) during the whole year, not only for the white roof but also for the black roof. Also, as will be explained in the next subsection (see Figure 7 and Figure 8), the black roof functions with much lower moisture compared with the white roof in St. John's. As a result, for energy savings with low risk of moisture damage, buildings with black roofs are recommended for St. John's outdoor climate. For the same reasons, buildings with black roofs also are recommended in the outdoor climate of Saskatoon because there is only one month during the year (July) when a relatively small amount of monthly average heat gain occurs (0.061 W/m) (see Figure 6b and Table 2).

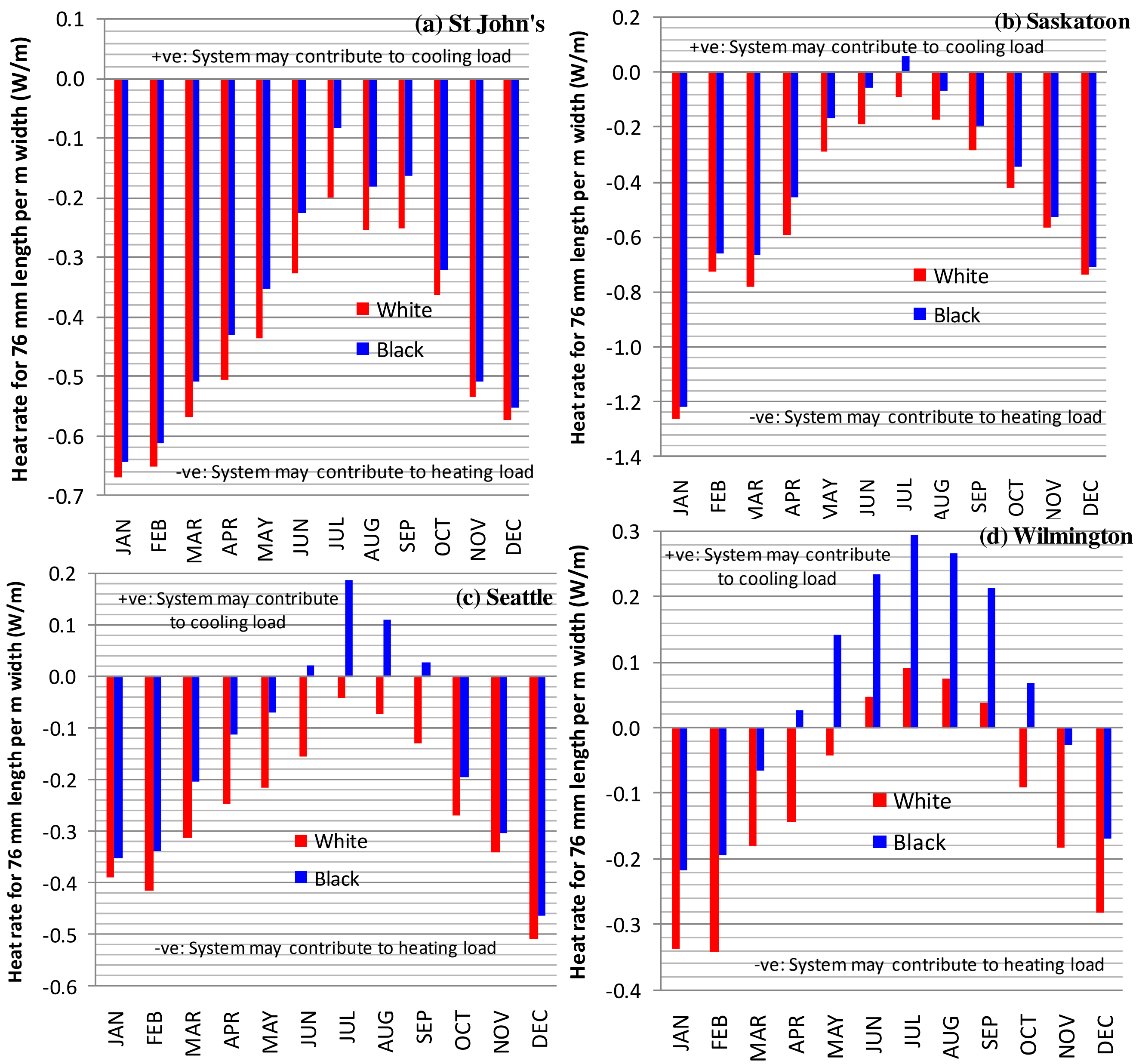

Figure 6. Comparison of monthly average heat gain/loss at the indoor surface of white and black roof systems at different locations

Similar to Toronto, Figure 6c shows there is no monthly average heat gain for the white roof during the whole year for Seattle's outdoor climate. For the black roof, however, there is monthly average heat gain during four months (June, July, August and September), resulting in an increased cooling load during these months. During the winter, the highest monthly average heat loss for the white roof occurred in December (0.508 W/m, Table 2). However, the heat loss is approximately 10 percent higher than that of the black roof (0.462 W/m, Table 2). Table 3 shows the yearly accumulation of energy gain for the black roof was 30.68 W-day/m for 76-mm length per meter width, which is about 6.8 times that of the white roof (4.48 W-day/m). Furthermore, the yearly accumulation of energy loss for the white roof was 98.53 W-day/m, which is 20 percent higher than that of the black roof (82.19 W-day/m). Figure 7 and Figure 8 show that white and black roofs function with low moisture (moisture content in fiberboard was well below the acceptable limit of 19 percent [26]). Therefore, buildings with white roofs would be expected to experience a net yearly energy savings and function with a low risk of moisture damage.

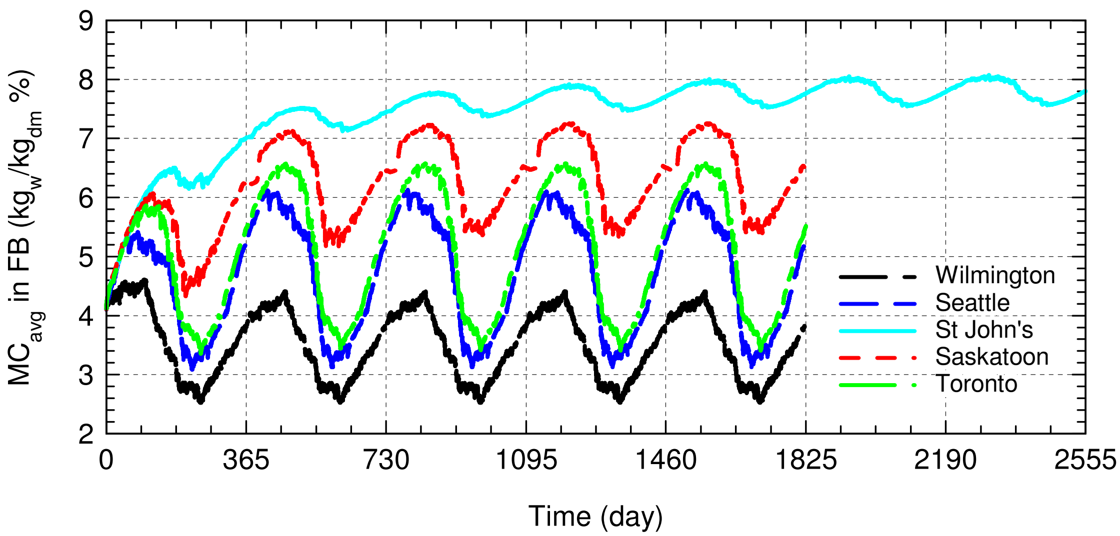

Figure 7. Comparison of average moisture content in the fibreboard (FB) for black MOD-BIT roofing systems at different locations

Unlike other locations, the outdoor climate of Wilmington resulted in a non-zero monthly average heat gain for black and white roofs during the summer (see Figure 6d). Also, Figure 7 and Figure 8 show white and black roofs function with low moisture (moisture content in FB was well below the acceptable limit of 19% [26]). Table 3 shows the yearly accumulated energy gain for the black roof was 61.82 W-day/m, which is about 4.2 times that of the white roof (14.89 W-day/m). However, the yearly accumulation of energy loss for the white roof was 55.93 W-day/m, which is 26 percent higher than that for the black roof (44.41 W-day/m). Consequently, buildings with white roofs would experience a net yearly energy savings compared with black roofs in the outdoor climate of Wilmington.

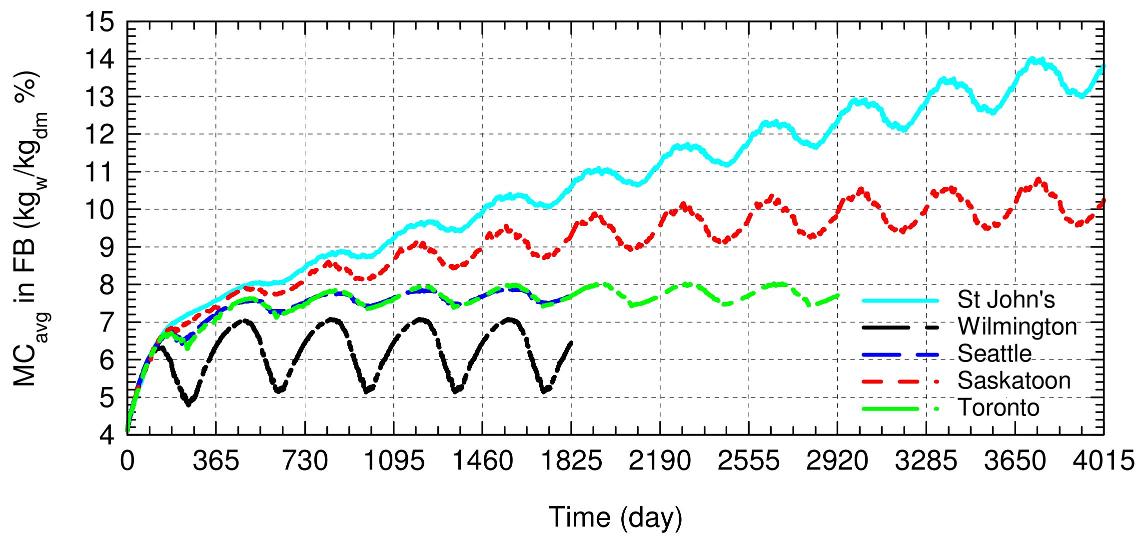

Figure 8. Comparison of average and moisture content in the fiberboard for white polymer-modified bitumen roof systems at different locations

Effect of Outdoor Conditions and Roof Color on Moisture Accumulation

Figure 7 and Figure 8 show the average moisture content (MC_{avg}) in the fiberboard for black and white roofs, respectively, at different locations. Also, Figure 9a and Figure 9b show the moisture content of the upper surface of the fiberboard (MC) beneath the membrane in these roof systems. As shown in these figures, St. John's outdoor climate resulted in the highest moisture content in the fiberboard for black and white roofs, followed by Saskatoon's outdoor climate; Wilmington's outdoor climate resulted in the lowest moisture content. For black roofs, no moisture accumulation occurred after two years in outdoor climates of Wilmington, Seattle and Toronto and after four years and six years for Saskatoon and St. John's. Additionally, the highest MC and MC_{avg} in the fiberboard for different outdoor climates were below the acceptable limit of 19 percent (Figure 7 and Figure 9a). As such, the simulations suggest the modelled black roof would run with a low risk of moisture damage at the different locations investigated in this paper.

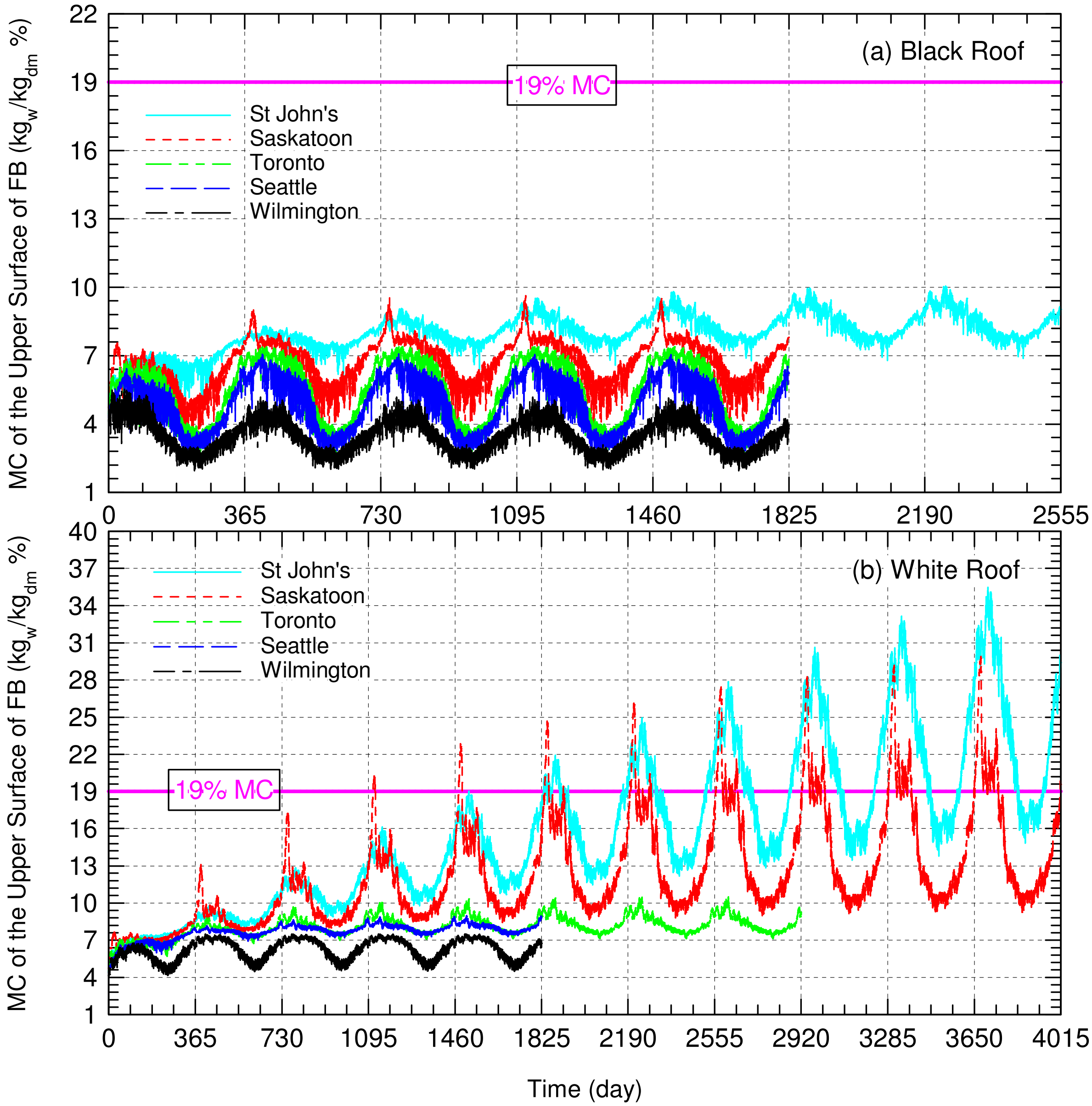

Figure 9. Moisture content (MC) of the upper surface of fiberboard (beneath the membrane) at different locations

In the case of the white roofs, Figure 8 and Figure 9b show that no moisture accumulation with time occurred after three years, four years and five years in the outdoor climates of Wilmington, Seattle and Toronto, respectively. Furthermore, the highest MC and MC_{avg} in the fiberboard for these outdoor climates were below the acceptable limit of 19 percent [26]. Therefore, the model predicts white roofs have a low risk of moisture damage in these locations. However, the outdoor climates of St. John's and Saskatoon resulted in significant moisture accumulation over time (see Figure 8 and Figure 9b). For example, after 11 years, the highest MC_{avg} reached 14.1 percent and 10.8 percent in St. John's and Saskatoon, respectively. Figure 9b shows the moisture content of the upper surface of fiberboard exceeded the acceptable limit of 19 percent (reached 35.4 percent and 29.8 percent in St. John's and Saskatoon, respectively). Therefore, the model predicts white roofs would function with a high risk of moisture damage in the outdoor climates of St. John's and Saskatoon.

Summary and conclusions

Numerical simulations were conducted using the NRC-IRC's hygrothermal model hygIRC-C, to investigate the hygrothermal performance of white and black roof systems. The roofs considered in this study were reflective (white) and nonreflective (black) polymer-modified bitumen roof systems. These roofs were subjected to different climates of North America with different HDD, namely: Toronto (HDD = 3650), St. John's (HDD = 4800), Saskatoon (HDD = 5950), Seattle (HDD = 2564) and Wilmington (HDD = 1349). Numerical simulations were conducted using the two indoor conditions of ASHRAE and European standard (EN 15026) for the outdoor conditions of Toronto. Results showed that the indoor conditions of EN 15026 resulted in higher moisture content in the roof system compared with the indoor conditions of ASHRAE. Therefore, the numerical simulations for the other outdoor climates were conducted using the indoor conditions of EN 15026.

Simulation results showed that black roofs performed with lower moisture content than white roofs. For the outdoor climates of St. John's and Saskatoon, the model suggests that black roofs have a low risk of moisture damage. In these locations, the simulations suggest the white roofs could lead to longer-term moisture-related problems, where the moisture content of the upper surface of the fiberboard beneath the roof membrane exceeds the acceptable limit of 19 percent (35.4 percent and 29.8 percent for St. John's and Saskatoon, respectively). For the outdoor climates of Toronto, Seattle and Wilmington, the simulation results showed the white roofs have a low risk of experiencing moisture damage. The yearly accumulation of energy loss (i.e., heat out of the building, system contributing to heating load) of the white roof was only 14 percent, 10 percent and 26 percent higher than that of the black roof for Toronto, Seattle and Wilmington. Conversely, the yearly accumulation of energy gain (i.e., heat into the building, system contributing to cooling load) of the black roof were much higher than that of the white roof (5.3, 6.8 and 4.2 times that for white roofs in Toronto, Seattle and Wilmington, respectively). Therefore, buildings with white roofs in these locations should result in a net yearly energy savings compared with buildings with black roofs.

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