Wind effects on the performance of solar collectors on roofs

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Abstract

Convective heat losses depending greatly on the cooling effect of wind, affect the energy performance of solar collectors. The present study demonstrates the importance of using actual velocity distributions corresponding to different locations on the roof, as opposed to a single wind velocity value measured at a reference location. A series of velocity measurements have been conducted to assess the optimum location of a collector on the roof of a commercial-size building model tested at the boundary layer Wind Tunnel laboratory of Concordia University. Wind velocity measurements were performed at nine different locations above the roof and for three different wind directions (0°, 45°, and 90°). The study found that local velocities on different roof locations can vary up to 62% and also assessed the wind impact on a flat-plate solar collector's performance characteristics when placed on different locations of the roof of a building model. It was estimated that for a typical sunny day, thermal energy gains can be 17% higher on windward than leeward locations.

1 Introduction

The main objective of this paper is to address the thermal performance-related effects of wind on solar collectors placed on the roofs of buildings. It is typical in the analysis of flat-plate solar collectors to assume a wind velocity measured at a representative (reference) location on the roof. However, wind does not affect uniformly all points on large areas. The velocity distribution on different parts of the roof depends on the shape of the building, wind direction and surroundings of the concerned region. Such factors would be expected to have an effect on the convective heat losses from flat-plate solar collectors and, therefore, on their thermal performance.

Flat-plate solar collectors are composed of a dark absorber plate that absorbs most of the incoming solar radiation (a small portion is reflected), converts it into heat, and conducts this heat to a fluid (usually air, water, or different types of oils like anti-freezing glycol) flowing through the collector in tubes – Figure 1 depicts a single glazed solar collector mounted on the roof of a building. This is the most commonly used type of solar collector worldwide (Kalogirou, 2004). The solar energy collected is carried from the circulating fluid either straight to the domestic hot water, or to a storage tank, from which it can be drawn for use at a later time. The back side of the absorber plate and casing are well insulated to diminish conduction losses. The liquid tubes are either welded to the absorbing plate, or they are part of the absorber itself. The absorber and insulation of the collector are fitted in a box and sheltered on the top with one or several tempered glass covers (single or double glazed solar collectors) or even occasionally plastic material for protection. The transparent cover must have low reflection and protect the system from the wind and moisture.

The present study examines the importance of using actual velocity distributions corresponding to different locations on the roof, as opposed to a single velocity value measured

at a reference location. The latter is achieved through an experimental investigation of the wind velocity distribution for different wind directions and on different locations of a building roof. The study also attempts the assessment of the wind impact on a flat-plate solar collector's performance characteristics when placed on different locations of the roof of a building model.

Figure 1: Single glazed solar thermal collector on top of a flat roof (Jetson Green, 2011)

2 Background

Wind around Buildings

A typical wind vortex formation on the roof of a rectangular building is shown in Figure 2. For the case of perpendicular wind approaching a basic isolated "bluff" body such as a rectangular building. As the wind hits against the upwind side of the building, it immediately comes to a rest at the "stagnation point" and the flow direction is completely altered from its standard path. The air flows along the building façade until it reaches the edges. Areas of high pressure and increased wind speed are created along the upper edge and sides of the building before it rushes over the top and sides. Eddy currents or small vortices are produced immediately after these windward edges.

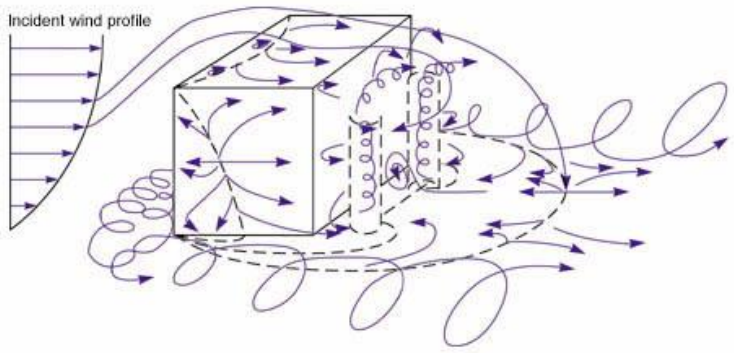

Figure 2: Three dimensional wind flow around a rectangular body (Woo, et al., 1977); modified

A minor increase of pressure and, consequently, wind speed along the downwind portion of the roof and sides are typically monitored. The wind then moves past the back of the building and forms a turbulent wake region and also downward the leeward façade where a large low pressure area is created that causes the wind to curl in to fill the void. For urban terrains, like densely constructed cities, these phenomena are a lot more complicated and challenging to assess analytically. In those terrains, where buildings are so close to each other, the flow patterns of the wind are extremely hard to predict. Generally, wind tunnel experimentation and simulations are the safest and most widely used procedures to examine the effects of such convoluted flows.

Wind-Induced Convective Heat-Transfer Coefficients

It is common that the upper surface of a flat-plate solar collector is exposed to the natural environment so that solar energy can be absorbed. The front surface can be the absorber itself, in the case of unglazed collectors, or one or more sheets of glass in the case of single or double glazed collectors. Regarding glazed collectors, heat losses occur as the glass temperature is commonly higher than the ambient temperature. Usually, during low wind velocities, heat-transfer takes place by free convection whereas forced convection takes over at medium and high wind velocities.

Usually free of obstructions, with good exposure to the sun, rooftop solar installations represent an efficient use of space. However, many factors must be considered before deciding whether a roof is a suitable candidate. The most critical effect that wind may cause on solar thermal devices is convectional cooling. The distribution of wind velocity impinging on a vertical surface is, in most cases, non-uniform depending on the direction of the approach wind and position of surrounding structures. Knowing the actual wind velocity distribution on a building surface enables accurate calculation of possible convection losses that the collector would be subjected to and this in turn aids in improving the performance of not just these devices but of the building envelope as a whole.

Wind induced convective heat transfer coefficients for building surfaces, are normally determined experimentally because of their dependence on a variety of parameters like the building geometry, wind speed and direction, local topography, turbulence intensity etc. (Karava, et al., 2011). It is essential that solar thermal devices be positioned such that convection cooling due to wind is minimal. Numerous studies have been performed in the past to establish a relationship between the convective heat transfer coefficient and the reference air velocity for flat-plate solar collectors.

The wind-induced convective heat transfer coefficient h_w was calculated numerically. The local velocities measured above the roof of the building model were applied into analytical models that calculate h_w. Numerous studies have attempted to produce equations for the numerical calculation of h_w [(Jürges, 1924) (Sturrock, 1971) (Watmuff, et al., 1977) (Sparrow, et al., 1979) (Test, et al., 1981) (Kind, et al., 1983) (Shakerin, 1987) (Kumar, et al., 1997) (Emmel, et al., 2007) (Kumar & Mullick, 2010)]. All these studies present a common trend in the variation of h_w with V_{loc}. Nevertheless, the results of most of the studies are clearly separated from each other. This creates dilemmas for design professionals prior to selecting the most appropriate model. In the present study, the model developed with experimental parameters similar to those used in the present study, was selected. Equations (1)-(8) in Table 1 by (Sharples & Charlesworth, 1998), were developed for a solar collector tilted at 45° on top of a building with similar height dimensions with the building of this study exposed in open terrain. V_{loc} measurements were performed at 6 m height. Moreover, the study takes into consideration the natural convection phenomena that are dominant during very low wind velocities. These regression equations are considered the most practical to adopt for the current

study. Since they are functions of wind incidence, it is expected to provide the most accurate results.

Table 1: Regression equations of h_w on V_{loc} by wind incidence angle (Sharples & Charlesworth, 1998)

Wind Incidence Angle (deg)	Regression Equations for h_w $(\frac{W}{m^2K})$	Correlation Coefficient r	
0	$2.2V_{loc} + 8.3$	0.767	**(1)**
45	$2.6V_{loc} + 7.9$	0.675	**(2)**
90	$3.3V_{loc} + 6.5$	0.878	**(3)**
135	$2.2V_{loc} + 7.9$	0.716	**(4)**
180	$1.3V_{loc} + 8.3$	0.439	**(5)**
-135	$2.3V_{loc} + 7.8$	0.618	**(6)**
-90	$2.2V_{loc} + 11.9$	0.651	**(7)**
-45	$3.9V_{loc} + 6.0$	0.834	**(8)**

3 Methodology

The wind tunnel of Concordia University is an open circuit wind tunnel, 12.2 m in length and 1.8 m in width, with a suspended roof that allows the height to be adjusted between 1.4 m and 1.8 m. Models are customarily placed into the downstream section on a turntable of 1.21 m diameter which can revolve manually or electrically and allows them to be rotated in order to be tested for different wind directions. Models can also be tested for different heights as they can move up and down, thus changing their corresponding building height. The wind tunnel's centrifugal blower can produce wind speeds that range from 3 m/s to 14 m/s. The measurements were performed with a Cobra probe, i.e. a flow measurement device with the capability to measure and resolve local static-pressure and all three components of wind velocity. The Cobra probe moves inside the wind tunnel with the help of a three-dimensional traversing system.

A geometric scale of 1:400 was selected for this study by considering the similarity parameters that must be satisfied when performing wind tunnel tests. A wooden model [25 cm (length) × 15 cm (width) × 1.5 cm (height)] was constructed in this scale – see Figure 3. A second roof height of 7.5 cm was also tested as a separate case.

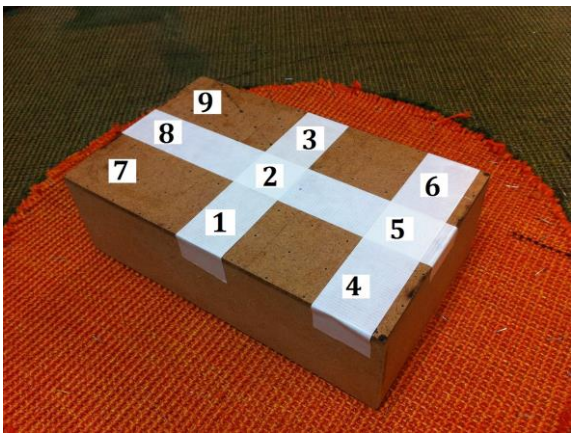

Figure 3: Building model at 1:400 scale

The roof of the model was divided into 9 hypothetical "rectangles" of the same size, the centers of which are the 9 locations where the solar collector is considered to be. More specifically, locations 1-3 are located at the middle of the model from front to back and locations 4-6 and 7-9 are on the right and left of the middle locations respectively. Figure 4 shows the detailed measurement locations.

In both cases, the building model was placed on the turntable of the test section and oriented in a fashion that served the purpose of the experiment. The Cobra probe was moved via the traversing system, above location 1, at a height where a typical commercial solar collector would be located (0.5 cm above the model roof, i.e. 2 m in full-scale). The wind tunnel operated at a speed of 14 m/s.

The experiments, included measurements of local wind velocity V_{loc} above locations 1-9. The velocity readings were done for 30 seconds each, at a sampling frequency of 1000 Hz. The experiments were iterated and measurements were performed for three different angles of incident wind (0°, 45°, 90°) and two building heights (*Case 1*: 6 m and *Case 2*: 30 m).

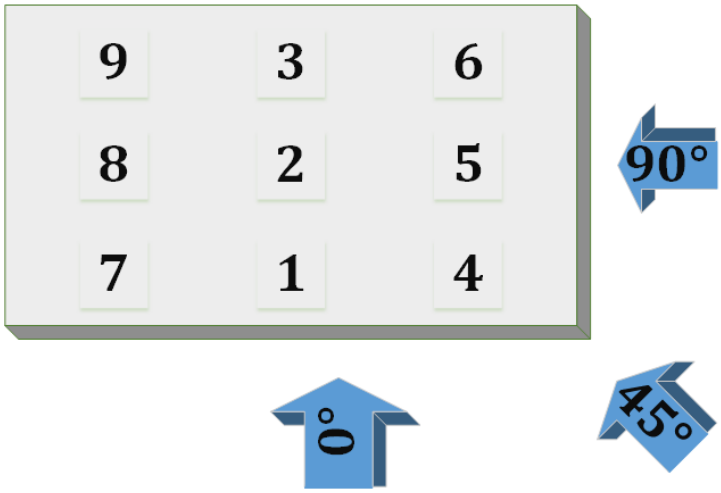

Figure 4: Building model tested at equivalent 6 m and 30 m full-scale height

Thermal modelling

Energy balance equations can be employed to estimate the thermal performance of an *N*-glazed solar collector. The process used in this study is based on the detailed computation of Duffie and Beckman (2006). In this section, a heat transfer model of a solar-thermal, single glazed ($N = 1$), water-based collector is presented. Similar equations can be used for any additional number of glass covers.

A number of simplified assumptions were made for the numerical solution of the model: The amount of solar energy absorbed by the glass cover of the collector is very small, so it does not influence thermal losses. Additionally, the glass cover is opaque to infrared radiation and the heat flow through it is one-dimensional. Finally, it is assumed that the ambient temperature is the same at the front and the back of the collector.

Duffie and Beckman (2006) modeled the thermal performance of the solar collector as the useful energy gain q_u per collector area A_c expressed as:

$$q_u = F_R[S - U_L(T_i - T_a)] \quad \textbf{(9)}$$

where T_i and T_a are the inlet fluid and ambient temperatures respectively (K); F_R is the collector heat removal factor; S is the solar radiation absorbed by the collector plate and finally U_L is the overall collector loss coefficient. The overall loss coefficient for a solar collector U_L consists of all the losses that take place during the solar collector's use; namely the top-loss coefficient U_t, the bottom-loss coefficient U_b and the edge-loss coefficient U_e.

$$U_L = U_t + U_b + U_e \quad \textbf{(10)}$$

The top-loss coefficient expresses the energy lost through the top cover of the solar collector due to convection and radiation between the glazing and the absorber plate. In this model, an empirical equation developed by Klein (1979) is used:

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm} - T_a)}{(N+f)}\right]^e} + \frac{1}{h_w}\right)^{-1} + \frac{\sigma(T_{pm} + T_\alpha)({T_{pm}}^2 + {T_\alpha}^2)}{\frac{1}{\varepsilon_p + 0.00591 N h_w} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N} \quad \textbf{(11)}$$

where:

- N is number of glass covers;
- ε_g is the glass emittance;
- ε_p the plate emittance;
- T_{pm} is the mean-plate temperature (K);
- h_w the wind-induced convective heat transfer coefficient (W/m^{2}K);
- $f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$ the wind factor (W/m^{2}K);
- $C = 520(1 - 0.000051\beta_w^2)$ the collector tilt factor (deg);
- β_w the collector tilt (deg);
- $e = 0.430\left(1 - \frac{100}{T_{pm}}\right)$ the mean-plate temperature factor (K)
- $\sigma = 5.67 * 10^{-8}\, {}^{W}/_{m^2K^4}$ the Stefan-Boltzmann constant.

The bottom loss coefficient expresses the energy lost from the back of the collector and it is a function of the collector's back insulation thermal conductivity k_i (W/m*K) and the back insulation thickness L_t (m):

$$U_b = \frac{k_i}{L_t} \quad \textbf{(12)}$$

The edge-loss coefficient is the energy escaped from the edges of the collector. It is safe to assume that edge insulation has the same thickness as bottom insulation and therefore the losses from the edges can be measured by using one-dimensional heat flow around the perimeter of the whole system. The coefficient is then a function of the edge insulation thickness e_t (m) and the collector thickness C_t (m):

$$U_e = \frac{C_t \left(\frac{k_i}{e_t}\right) P}{A_c} \quad \textbf{(13)}$$

where:

- P is the collector perimeter (m);
- A_c the collector area (m^2)

Furthermore, the efficiency of the collector η was defined as the ratio of the thermal energy gains over the total incident solar radiation:

$$\eta = \frac{q_u}{I_T} \quad \textbf{(14)}$$

4 Results and discussion

The experiments were repeated three times to identify the error in the measurements. By normalizing the standard deviation of each measurement with the mean value above each location, the average error was calculated to be around 5.8%.

Local velocities are presented in the form of contours of local velocity coefficients, defined as the ratio of the local velocity V_{loc} to the gradient wind velocity V_g. The height where the terrain exposure stops affecting the wind velocity, is called gradient height Z_g; and the wind velocity at that height is defined as the gradient velocity V_g. Figure 5 shows the contour plots for the three different wind directions tested for Case 1 (*building height: 6 m*). The plots where created using linear interpolation between each set of measurements above the roof.

In general, wind velocities on the roof of the building are higher in the windward than the leeward area. This is due to flow separation and acceleration at the front edges. However, it is clear that the velocity differences between the front and back area are higher in the case of 45° wind direction. In particular, the ratio between the maximum and minimum velocities measured above the roof, for 45° angle of incidence, was 1.75. Figure 6 shows this ratio of maximum over minimum local velocity above the roof of the building for the three wind incidence angles tested. More specifically, the 90° incidence angle causes a ratio of about 1.6, whereas this ratio drops to 1.5 for the 0° angle of incidence.

Figure 7 shows contour plots of local velocity coefficients for the three different wind directions tested for Case 2 (*building height: 30 m*). Similar differences are observed in this case, where the building is 5 times higher. There is a general trend of the velocity coefficients in Case 2 being, on average, about 20% to 30% higher than in Case 1. This can be explained by the fact that the measurement was performed at 32 m (whereas in Case 1 it was at 8 m) where the magnitude of the velocities is increased. Nonetheless, the variation between locations remain relatively similar to Case 1. Figure 8 shows the ratio of maximum over minimum local velocity above the roof of the building for the three angles of incidence tested, similar to Figure 6. For wind directions 0°, 45° and 90°, the local velocity ratios of maximum over minimum were 1.48, 1.60 and 1.52 respectively.

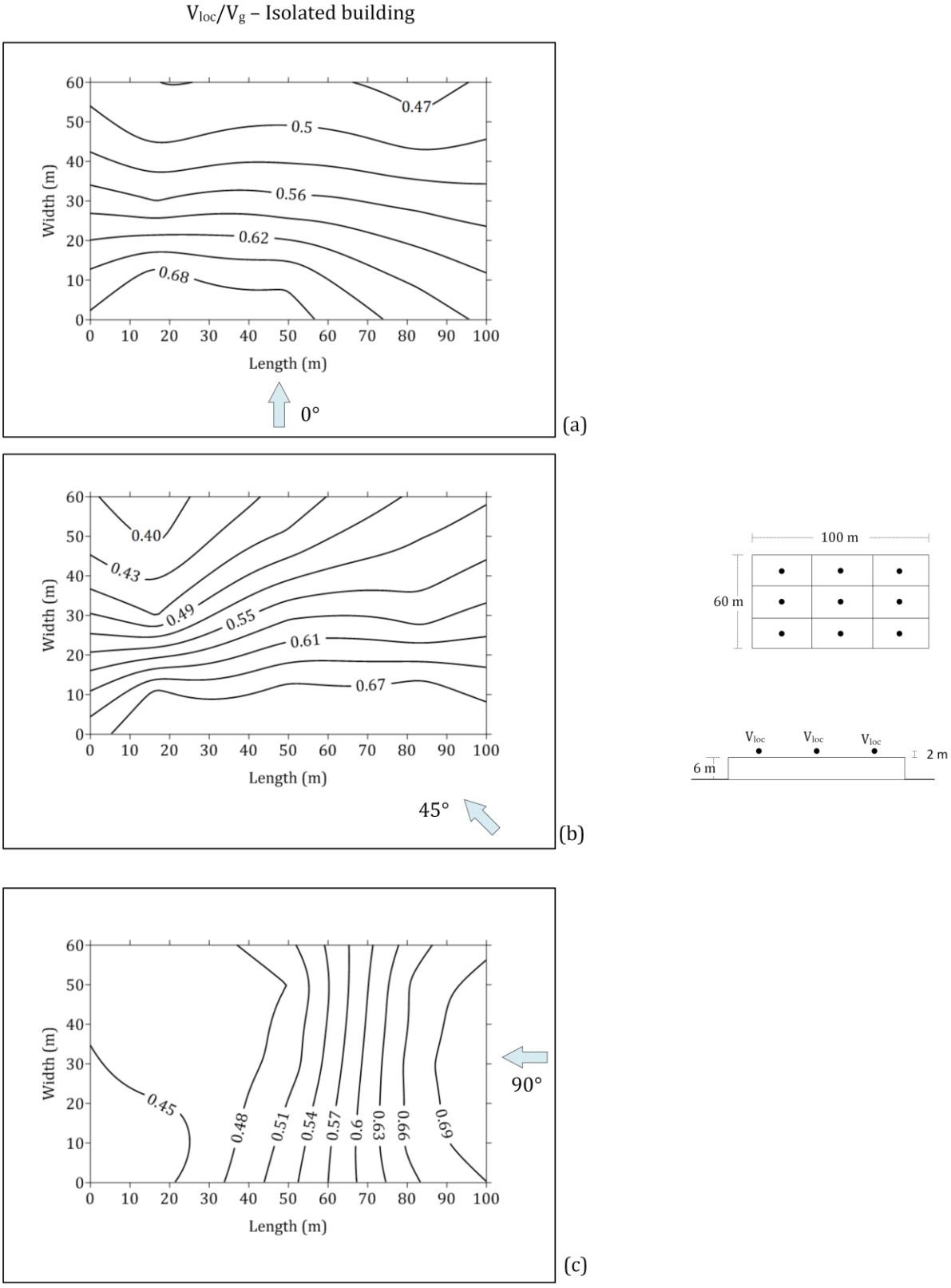

Figure 5: V_{loc}/V_g contours for: (a) 0°, (b) 45° and (c) 90° angle of attack (Case 1)

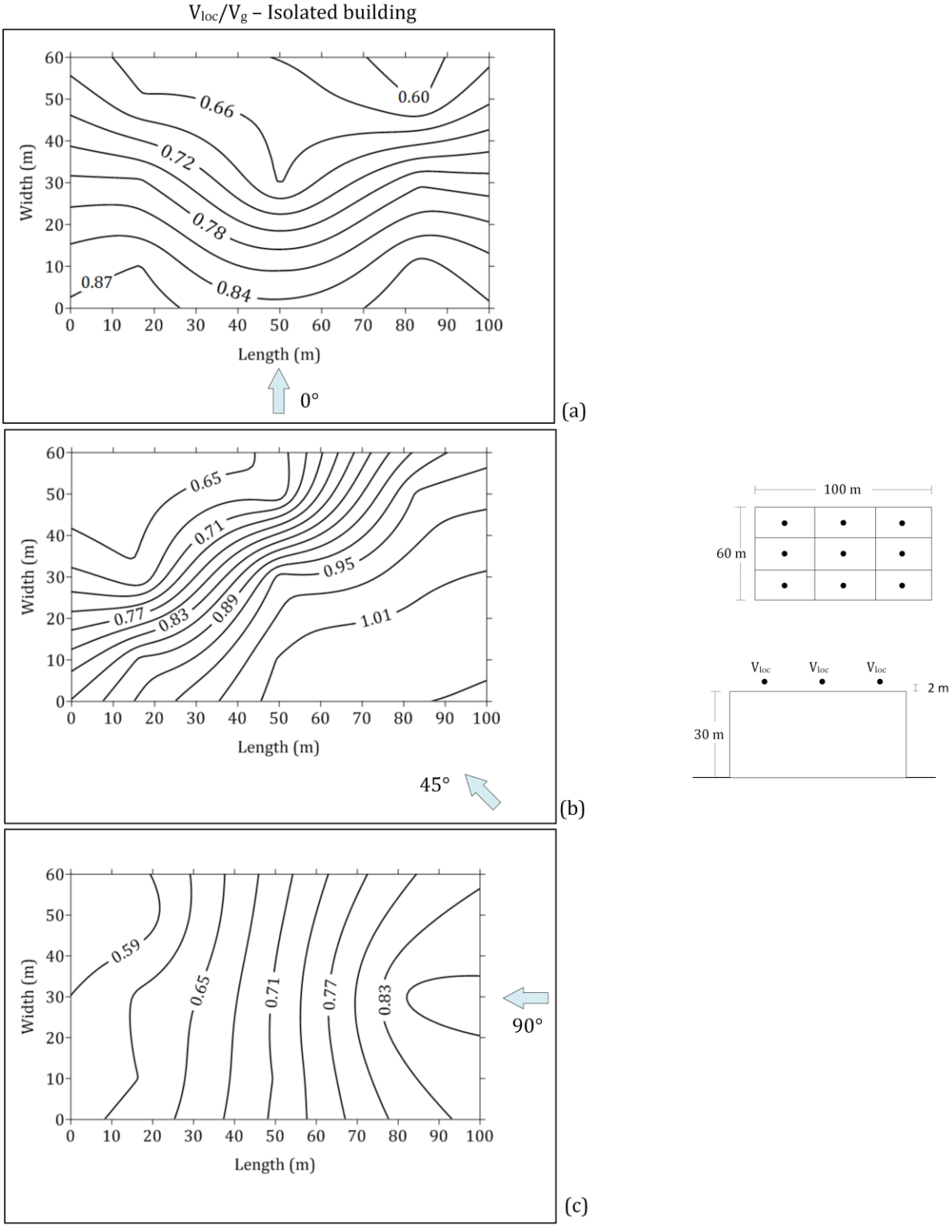

Figure 7: V_{loc}/V_g contours for: (a) 0°, (b) 45° and (c) 90° angle of attack (Case 2)

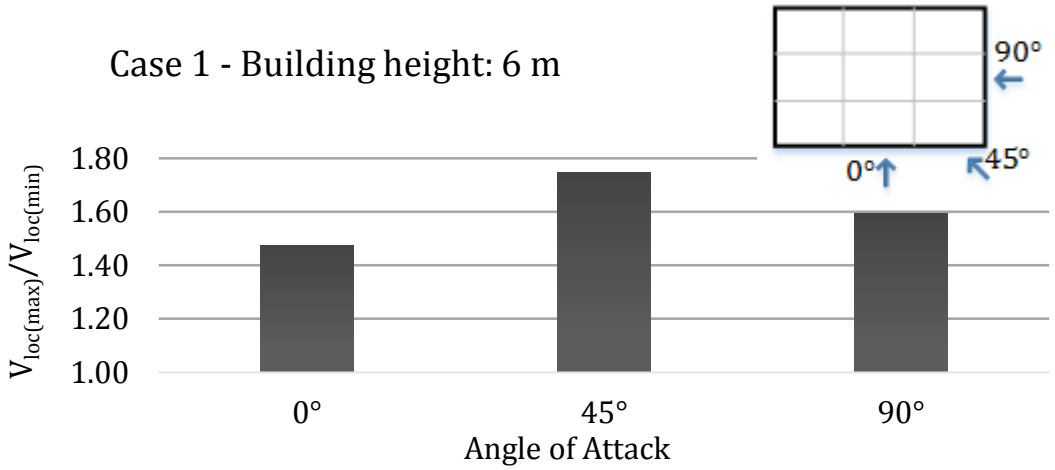

Figure 6: Ratio of maximum over minimum local velocity above roof for 0°, 45° and 90° angle of attack (Case 1)

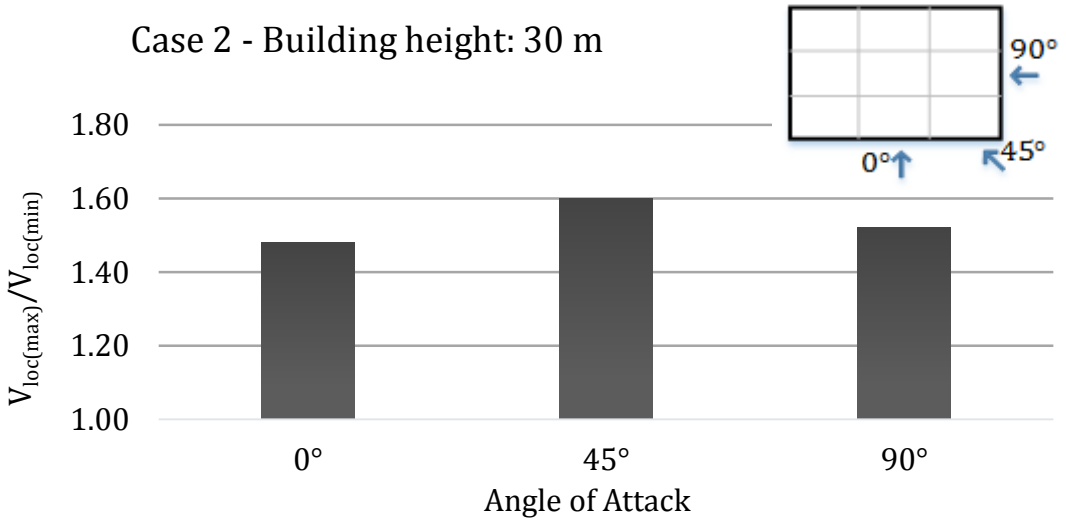

Figure 8: Ratio of maximum over minimum local velocity above roof for 0°, 45° and 90° angle of attack (Case 2)

Thermal Performance of Solar Collectors

Daily thermal energy gains q_u (W/m^2) and efficiency η of a solar collector for each of the nine locations that were designated on the building model, were evaluated by using the model described by equations 9 and 10 in order to quantify the effects of wind convection above different parts of the roof. The solar conditions selected were those of a typical sunny day with total solar radiation (I_T) peaking at 1:00 pm at $I_{T(max)}$ = 850 W/m^2. The values of solar radiation were calculated with the use of a typical meteorological weather file for Montreal in EnergyPlus Simulation Software (U.S. Department of Energy, 2014). The ambient temperature was assumed to be T_a = 20 °C, typical Montreal summer conditions. These conditions remain the same throughout this study for all the cases that presented in this section. The wind velocity and as a result the wind-induced convective heat transfer coefficient are the only parameters that change in every calculation. Figure 9 presents the total daily thermal energy gains of

the collector for a very windy day and Figure 10 the equivalent daily efficiency. It is assumed that the incident angle of the wind velocity is 0° and that the gradient velocity is V_g = 40 m/s.

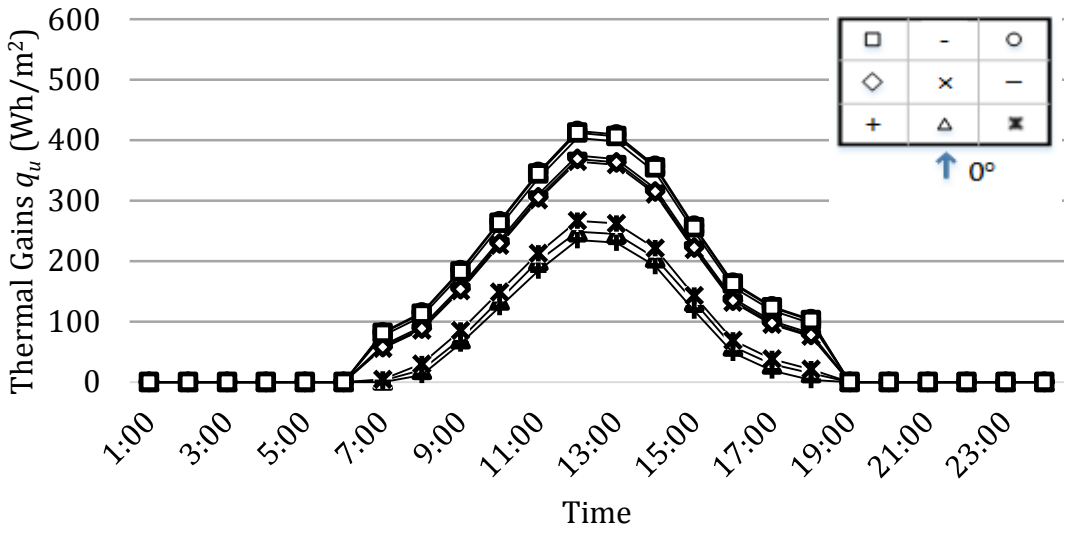

Figure 9: Thermal gains during a very windy day (Case 1 / 0°)

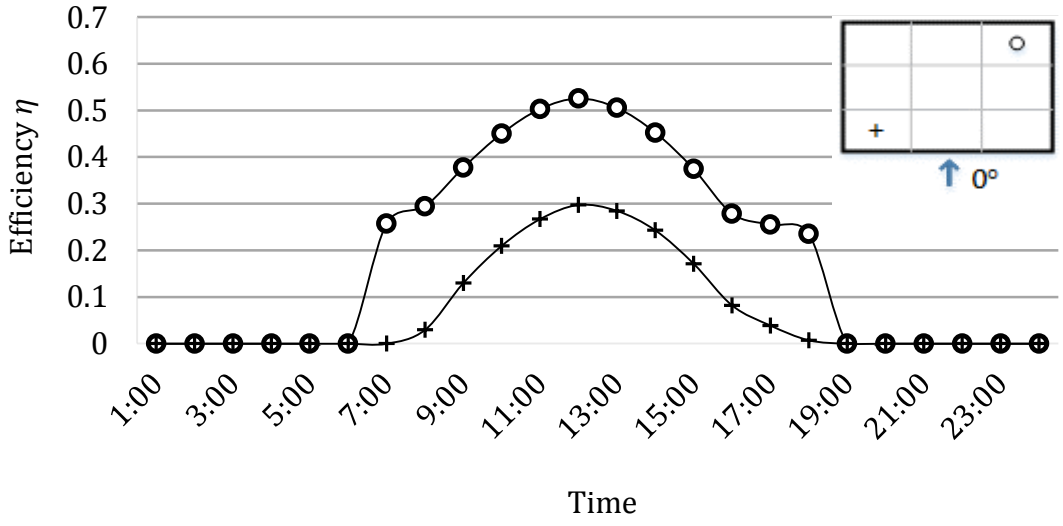

Figure 10: Solar collector efficiency during a very windy day (Case 1 / 0°)

With this gradient velocity, the local wind velocities at full-scale above the building roof are between 7 m/s and 25 m/s, values that very often occur in windy days in Montreal. In Figure 9 the thermal gains above all nine locations are depicted. Figure 10 and subsequent figures show only data for the two critical locations.

It is clear in Figure 9 that the areas above the roof where the largest amount of cooling is caused are the windward areas. However, the best locations to install a solar collector are the leeward areas, i.e. the locations at the back of the roof. More specifically, the ratio of maximum (location 6) over minimum (location 7) daily thermal energy gains (or efficiency) for a

solar collector is 2.30. Similar results are visible in the 45° angle of attack in Figures 11 and 12. The ratio of maximum (location 9) over minimum (location 4) daily thermal energy gains (or efficiency) for a solar collector is 2.36.

Figure 13 shows the ratio of potential maximum over potential minimum daily thermal energy gains for a solar collector mounted above the roof of that specific building. The results are presented based on gradient wind velocity.

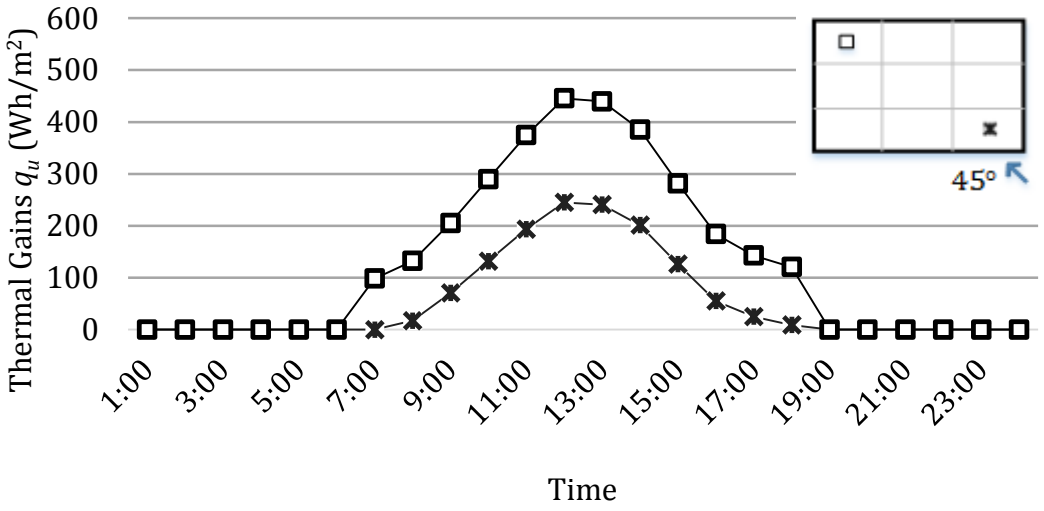

Figure 11: Thermal energy gains during a very windy day (Case 1 / 45°)

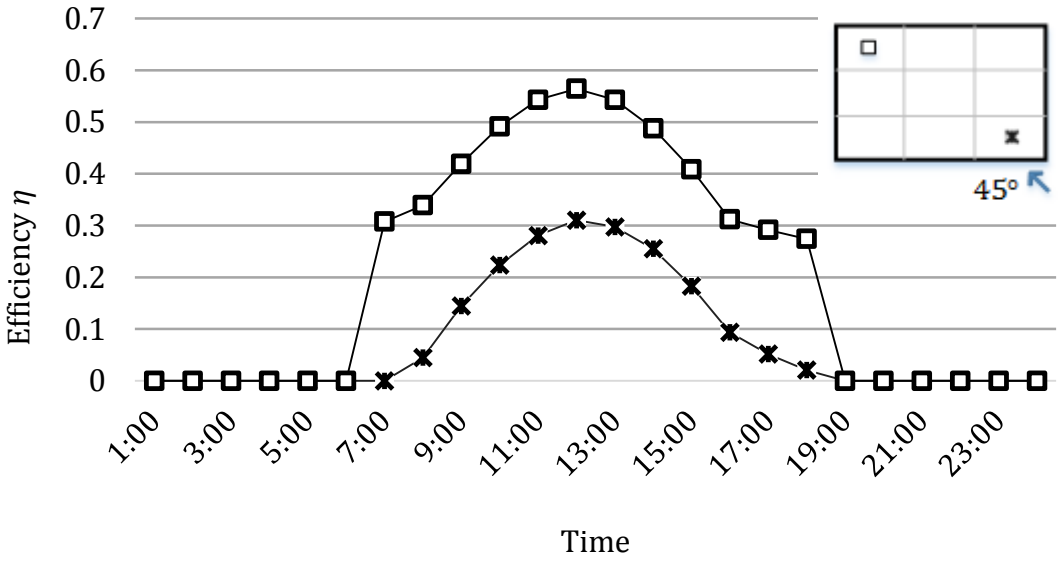

Figure 12: Solar collector efficiency during a very windy day (Case 1 / 45°)

It is apparent that as the wind velocity becomes lower, the differences between locations become smaller. However, in the case of V_g = 30 m/s the difference is still significant. The ratio of maximum over minimum daily thermal energy gains (or efficiency) for a solar collector is 1.24 for 0° (and 1.28 for 45°) angle of attack. Even for V_g = 20 m/s the ratios are around 1.1. When the gradient velocities are of that magnitude, the velocities measured above the roof are those of a typical day in Montreal. Very similar differences were found in Case 2 (building height: 30 m).

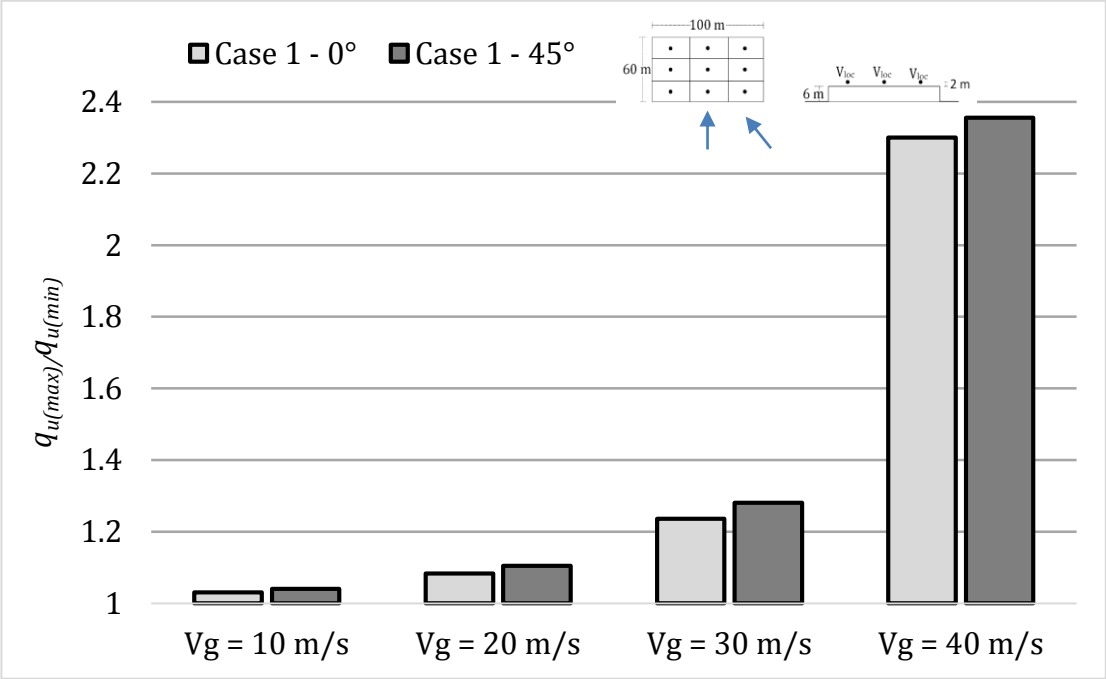

Figure 13: Ratio of maximum over minimum daily thermal energy gains on the building roof for two angles of attack

It is of course understood that the conditions assumed so far for analysis purposes may not be realistic. For instance, the wind would not blow from the same direction throughout an entire day. If a typical day in Montreal is considered with different wind velocities and directions, taken from the hourly weather data found in Government of Canada (2013), the results will be different. Indeed, Figure 14 shows the thermal energy gains of a solar collector mounted at the best and worst locations of the roof during a typical sunny day in Montreal. The wind velocities averaged between 4 m/s – 7 m/s during the day and the predominant wind direction was south and southwest.

The data shows that even for these regular conditions there is a significant difference in mounting a solar collector on different locations on the roof. More specifically, the ratio of maximum (location 6) over minimum (location 1) daily thermal energy gains (or efficiency) for a solar collector is 1.21.

Additional issues, which have not been addressed in this paper include, the effect of building shape, surrounding buildings, as well as the effect of roughness of upstream exposure. It is expected that these issues will introduce additional variability and uncertainty in the results.

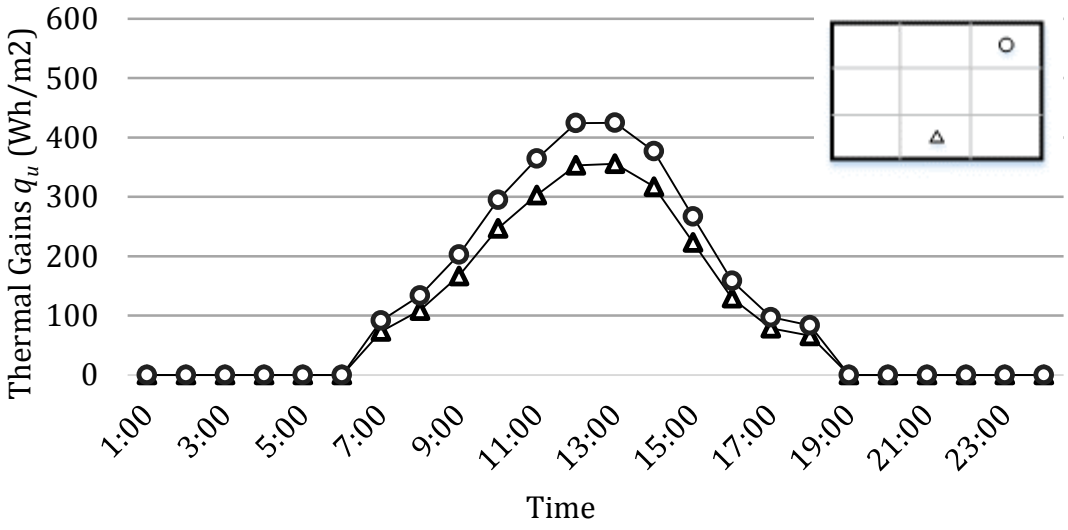

Figure 14: Thermal energy gains during a typical day -all wind directions- (Case 1)

5 Summary and Conclusions

The purpose of this study was to highlight the significance of using actual wind velocity distributions, rather than a single velocity value, to study the performance of solar thermal collectors mounted on building roofs. In previous studies, wind was not regarded as a critical parameter for the performance of solar collectors. However, this experimental study demonstrated that differences in wind velocities on various roof locations may be substantial and have an effect on the thermal performance of solar collectors.

Wind velocity distributions above the roof of a building model were measured experimentally in a wind tunnel. The measurements were performed under various wind angles of incidence, for an isolated building model. The experimental results were used for a parametric analysis utilizing a numerical model of a solar thermal collector. The main conclusions of this study can be summarized as follows:

- Measured wind velocity distributions on building roofs showed that the ratio between the maximum and minimum velocities can be as high as 1.75 due to flow phenomena that are driven by the geometry of the building and the wind direction.
- A numerical model of a roof mounted, water-based solar collector, and utilizing energy balance equations, was developed. It was estimated that the ratio of thermal energy gains in the windward areas compared to the leeward sections of the roof, during a typical sunny day, is 1.21.

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