THE EFFECT OF WIND VELOCITY DISTRIBUTION ON UNGLAZED TRANSPIRED COLLECTORS

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ABSTRACT

High wind velocity affects the efficiency of unglazed transpired collectors (UTC) by effecting convection losses and suction in the pores. Local wind velocities impinging on a surface differ from the approach wind velocity due to obstructions and redirection caused by surrounding structures. This paper describes an experimental study in a wind tunnel and analytical parametric study to assess the significance of using actual non-uniform, rather than an assumed uniform, wind speed distribution in UTC performance calculations. The assumption of uniform wind velocity distribution throughout the UTC area resulted in the underestimation of convective heat transfer coefficients by up to 20%. The significance of using proximity models in wind simulation for UTC analysis is discussed.

INTRODUCTION

UTCs are one of the most efficient solar heating technologies available today. It consists of adark absorber cladding, of 0.5% - 2% porosity (Dymond, et al., 1997), installed about 10 to 20 cm off the equator-facing wall of a building, forming a plenum behind the cladding – see schematic in Figure 1. Heat absorbed by the metal cladding forms a layer of warm air on either of its sides that is drawn in through the perforated cladding using a fan and supplied for building heating. The U. S. Department of Energy claims this technology to be the most efficient air heating system available today – 75% efficiency as claimed by Solarwall® (Heinrich, 2007).

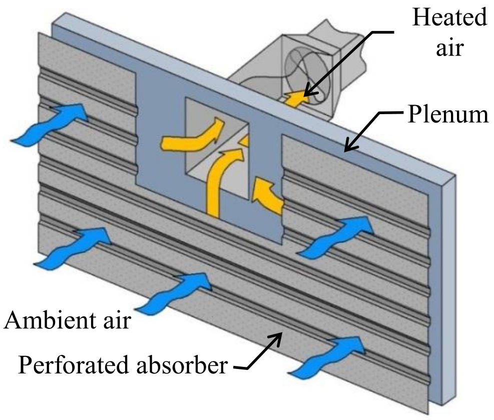


Figure 1 Schematic of a UTC

High performance of solar thermal devices is attained by reducing heat losses to a minimum. In this regard, wind-induced convection heat loss is a major concern and extensive studies with improved wind simulations are necessary to arrive at generalized guidelines for efficient system design. In computer simulations of such systems, it is common practice to have wind velocity to be represented by one or a few numerical constants over the entire collector area due to programming, time or data size constraints. In reality, the local wind velocity distribution at or near the surface of buildings is different from the approach wind velocity, mainly due to wind direction and the influence of immediate surroundings. The present study aims to assess the significance of using a realistic non-uniform wind velocity distribution, as opposed to a uniform velocity distribution for UTC analysis.

BACKGROUND KNOWLEDGE

Convective heat transfer coefficients (CHTC) on vertical façades

The general methodology for full scale studies of CHTC on building surfaces involves thermal measurements on heated metal strips positioned high on the walls of tall buildings and wind velocity measurements at at atleast two locations – V_{ref} above the building roof and V_{loc} at a small distance, 0.3 to 2 m, from the test wall. Although a number of CHTC-wind velocity relations are available in literature (Ito et al., 1972; Sharples, 1984; CIBSE, 2006; Liu & Harris, 2007; Blocken et al., 2009), the studies differed in test parameters such as plate dimensions, velocity measurement locations, surroundings, etc. Therefore, one has to be mindful of the test conditions when selecting one or more of these relations.

Wind effects on UTC

One of the first studies of wind effects on UTCs was by Kutscher (1992) followed by Kutscher, et al. (1993) who theoretically examined different modes of heat loss from UTCs and derived relations for UTC thermal efficiency η:

$$\eta = \alpha_s \left[1 + \left(\frac{h_r}{\epsilon} + h_c \right) \left(\rho c_p V_s \right)^{-1} \right]^{-1} \qquad (1)$$

where, ϵ is the plate heat exchage effectiveness. Air exiting at the back of the plate, i.e. the outlet air, is at a lower temperature than the plate surface. Plate heat exchange effectiveness, the air heating effect of the plate, relates the outlet air temperature T_{back} with the plate surface temperature T_{coll} and ambient air temperature T_{amb}:

$$\epsilon = \frac{T_{back} - T_{amb}}{T_{coll} - T_{amb}} \tag{2}$$

Van Decker et al. (2001) developed a more detailed expression for ϵ (Equation 7) based on experimental studies and theoretical models from literature.

$$\epsilon = \left[1 - \left(1 + Re_s \max\left[1.733 Re_w^{-\frac{1}{2}}, 0.02136\right]\right)^{-1}\right] \times \left[1 - \left(1 + 0.2273 Re_b^{\frac{1}{2}}\right)^{-1}\right] \times \exp\left(-0.01895\frac{P}{D} - \frac{20.62}{Re_h}\frac{t}{D}\right) \tag{3}$$

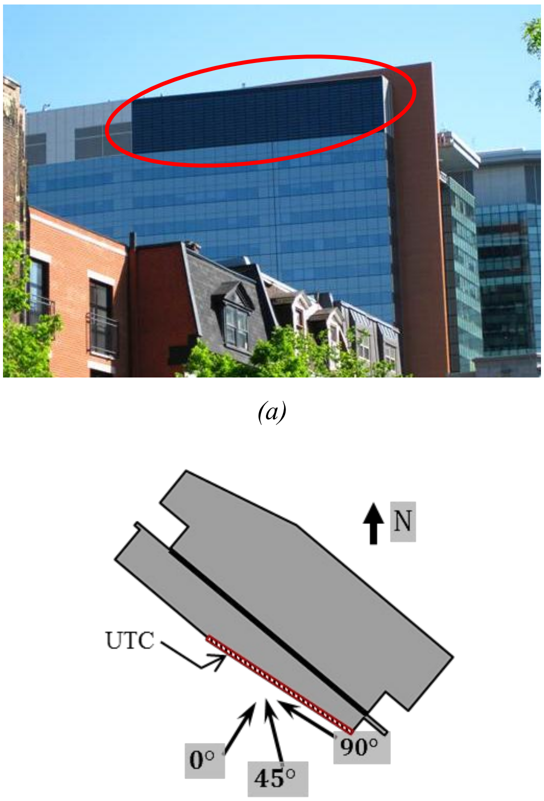
Fleck, et al. (2002), through field tests on transpired solar collectors, showed that turbulent fluctuations outside the boundary layer enhance convective losses on the UTC surface. The study addressed certain drawbacks in Kutscher's studies viz. the use of laminar uniform flow parallel to the ground, which in reality is not the case of flow around bluff bodies. Fleck, et al. (2002) also concluded that above certain velocities, depending on the air intake rate of the collector, wind parallel to the collector's surface causes suction in the pores, and hence outflow, resulting in loss of useful heat being carried by the plenum air. Using CFD simulations, Gunnewiek, et al. (2002) recommended minimum suction velocities to avoid such reverse flow.

Athienitis, et al. (2010) developed a prototype PV/thermal (PV/T) system consisting of a UTC with 70% of its area covered by PV panels (O'Neill et al., 2011). Ventilation air is preheated by heat from the PV and UTC. This system was integrated into the façade of the John Molson School of Business (JMSB) building in Montreal, Canada. Predominant winds in Montreal are actually perpendicular to the façade integrated PV/T system. However, the design and initial analysis of the PV/T system assumed that wind flow was parallel to the PV/T surface, which has also been a common assumption in many previously published studies that dealt UTC heat loss. Wind effect on the performance of this UTC was studied by Vasan and Stathopoulos (2012) using wind tunnel experiments; preliminary results showed that wind direction did indeed have an impact on its efficiency.

The objective of the study described in this paper was to investigate the significance of including proximity models in wind simulation for UTC analysis by assessing the error in assuming a uniform local velocity distribution over the UTC surface for calculations relating to its performance parameters. Detailed wind speed distribution in front of the JMSB building, was measured by means of wind tunnel experiments on a reduced-scale model and the information obtained was applied to existing analytical models of UTC performance evaluation.

EXPERIMENTS

The Building Aerodynamics Laboratory at Concordia University, Montreal, was used for this study. It houses an open circuit wind tunnel that has a working cross-section of 1.8m × 1.8 m, length of 12 m and an adjustable roof that renders any pressure gradient of the flow reaching the test section negligible. The JMSB building is 54 m tall and houses a 300 m^2 building integrated PV/T system on the southwest wall (also referred to as solar-wall) – see Figure 2. For simplicity of the case study, it has been assumed that the UTC is a flat plate type and is not covered by PV panels. A 1:400 scale wooden model of the JMSB building was constructed (Figure 3) along with all surroundings within a full-scale radius of 450 m for a more realisting wind flow simulation. Terrain roughness beyond the modelled area was configured using roughness elements whereby wind velocity profile developed at the test section had a power law exponent of 0.3, which represented the exposure in Montreal to sufficient accuracy.



(a)

(b)

Figure 2 (a) The JMSB building showing the location of the Building Integrated PV/T wall
(b) Schematic plan of the JMSB building showing the building's orientation and test wind directions

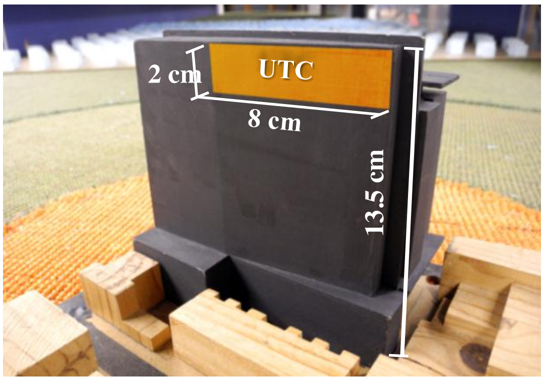


Figure 3 JMSB building model at 1:400 scale

Two proximity model cases

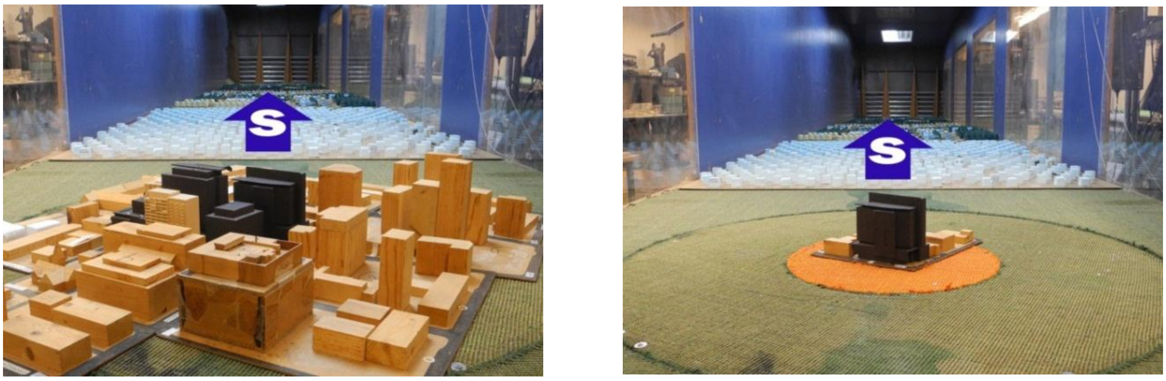
- Case 1: Test building with proximity model
- Case 2: Test building without proximity model

shown in Figure 4a and 4b, respectiveley, and three wind directions were chosen based on their predominance in Montreal and relevance to the building orientation (see Table 1 and Figure 2b).

Velocity measurements were made with a Cobra Probe (Figure 5) – a 4-hole pressure probe that measures velocity vector components, mean velocity vector and static pressure. Readings were taken at 40 measurement points on an 8×5 grid located 5 mm off the UTC area (Figure 6). In addition, reference velocity at 6.25 mm above the roof of the model, hereafter referred to as the reference height, was also measured for each configuration. This height, corresponding to 2.5 m above the roof in full-scale, is the location of the anemometer that provided the full-scale reference wind velocities.

Table 1
Wind directions used for experiments

DESCRIPTOR	DIRECTION RELATIVE TO THE UTC	CARDINAL DIRECTION
0°	Perpendicular	S32°W
45°	Oblique at 45°	S13°E
90°	Parallel	N52°W



(a) *(b)*

Figure 4 Test wind direction - 45° (a) Case 1: Test building with proximity model (b) Case 2: Test building in the absence of proximity model

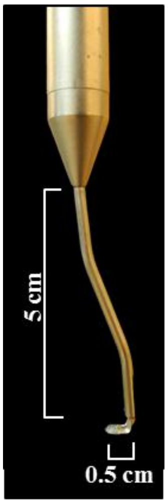


Figure 5 Cobra Probe used for velocity measurements in the wind tunnel

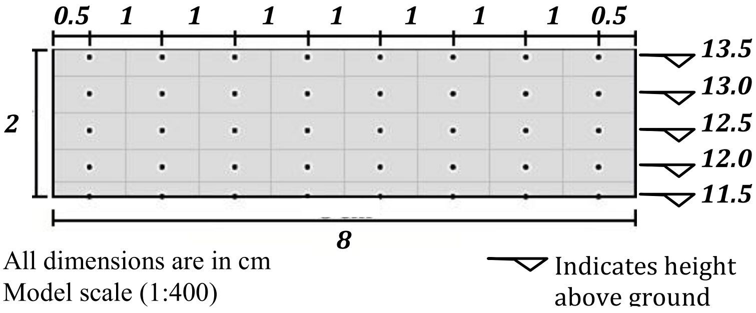


Figure 6 Schematic of the test area showing velocity measurement points

RESULTS AND DISCUSISON

The results presented pertain to four velocity distributions for each proximity model case – assumed uniform distribution (roof level velocity, V_{ref}, acts normal to the surface and uniformly at all points) and the actual distributions for the three wind directions tested.

Local velocity distribution near the UTC area

Figure 7 shows the distribution of local velocity coefficients – defined as the ratio of the magnitude of V_{loc} to V_{ref} – for all test configurations. In general, blockage in the form of buildings, landscaping, vegetation etc., causes mean wind speed reaching a target building to be lower than what would be expected in an open area without as much blockage. This can be seen in the V_{loc} distribution for 90°, where the terrain is very lightly built-up. Other directions, however, are more built-up and surrounding structures redirect wind flow, create turbulence and thereby result in higher local velocities. It can be seen from Figure 7 that V_{loc} in Case 1 are, on average, about 20% to 30% higher than in Case 2. This quantifies the impact of surrounding structures on the wind flow near the JMSB building. V_{loc} near building edges are up to 50% higher than V_{ref} due to flow acceleration, highest values being for the 45° winds.

Typical wind speeds at the JMSB building were of the order of 1 m/s as recorded by the roof-mounted anemometer. Results in the following sections have been classified as pertaining to reference wind speeds of 1 m/s (low wind condition) and 3 m/s (high wind condition). These two values were chosen so as to be able to compare the results of this study with previous studies that were related to the JMSB solar-wall.

Convective heat transfer coefficient (CHTC) h_c

CHTC h_c for the UTC was estimated by applying the experimental results of V_{loc} in the CHTC-V_{loc} relations developed by Liu & Harris (2007) – Equations (4) though (6). These relations are based on regression fits on full-scale data that was categorized into different wind direction segments. Narrow directional segments reduced scatter in CHTC versus velocity plots and resulted in better regression fits.

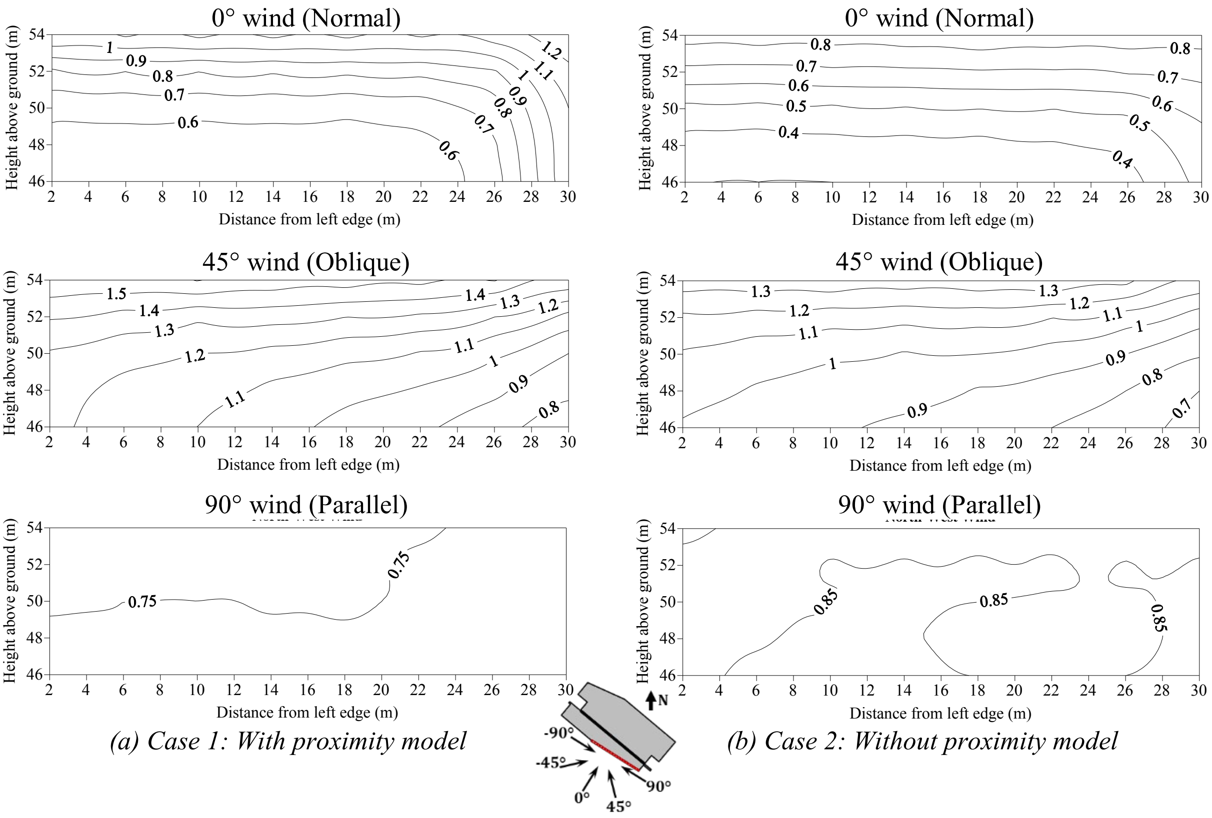
0° $$h_c = 5.90V_{loc} + 3.95 \quad (4)$$

45° $$h_c = 6.42V_{loc} + 3.17 \quad (5)$$

90° $$h_c = 7.42V_{loc} + 2.98 \quad (6)$$

The test building in that study faced the predominant wind direction (Liu & Harris, 2007) and wind speeds were similar to those at the JMSB building. CHTC for the assumed uniform normal distribution case was obtained by replacing V_{loc} in the equations with V_{ref}.

Errors in surface-averaged CHTC as a result of using the assumed uniform velocity distribution in place of actual distributions are presented in Table 2. These



(a) Case 1: With proximity model

(b) Case 2: Without proximity model

Figure 7 Distribution of local velocity coefficients [V_{loc}/V_{ref}] over the test area

Values were calculated as follows:

$$\%Error = \frac{(Value\ for\ assumed\ distribution - Value\ for\ actual\ distribution)}{Value\ for\ actual\ distribution} \times 100 \qquad (7)$$

Positive values indicate an overestimation as a result of the assumption.

Table 2
Error in surface-averaged CHTC using uniform wind speed distribution assumption as compared to the results for actual directional distributions

DESCRIPTOR	**CASE 1: WITH PROXIMITY MODEL**		**CASE 2: WITHOUT PROXIMITY MODEL**	
	1 m/s	**3 m/s**	**1 m/s**	**3 m/s**
0° wind	13%	19%	34%	53%
45° wind	-10%	-19%	0%	-7%
90° wind	16%	11%	4%	-3%

The assumed uniform distribution, led to an overestimation of the surface-averaged CHTC by up to 16% for 90° and 19% for 0° in Case 1. For the 45° direction however, results from the actual distribution are higher than the assumed case by 10% for low wind speeds and the error is almost double for high wind speed (19%). This is a direct result of the high local wind speeds corresponding to this angle of approach.

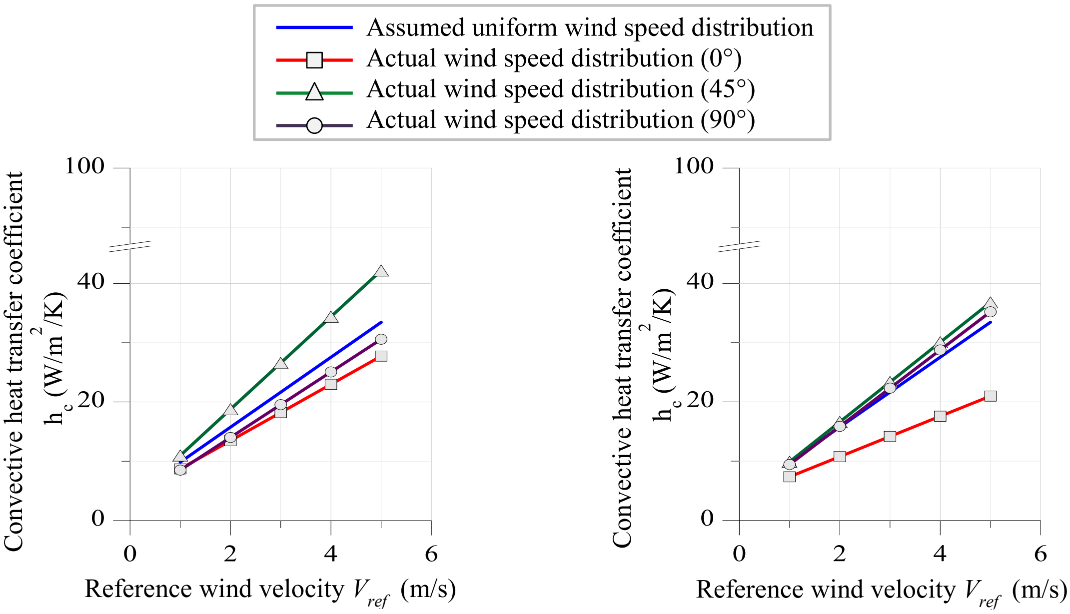
Figure 8 shows a graphical representation of the results. The presence of surroundings seems to effectuate higher convection heat transfers due to flow acceleration. The values for Case 2 were, on average, about 30% lower than in Case 1, i.e. simulation without proximity models, underestimated CHTC by about 30%. It can also be seen that the graphs for the three wind directions do not vary equally between the two Cases; this is because the surrounding structures offer different levels of blockage at different angles depending on the terrain build-up. This varies from building to building and cannot be generalized.

UTC thermal efficiency η

Thermal efficiency η of a UTC defines how much of the available solar thermal energy is converted into useful form by heating air. η was calculated using Kutscher's model (1993) for UTC thermal efficiency – see Equation (1). The errors in using the assumed distribution as opposed to actual distributions are shown in Table 3. The results are shown graphically in Figure 9, where it is clear that, there is a general underestimation of thermal efficiency by the uniform wind velocity distribution assumption.

Table 3
Error in thermal efficiency using uniform wind speed distribution assumption as compared to the results for actual directional distributions

DESCRIPTOR	**CASE 1: WITH PROXIMITY MODEL**		**CASE 2: WITHOUT PROXIMITY MODEL**	
	1 m/s	**3 m/s**	**1 m/s**	**3 m/s**
0° wind	-5%	-11%	-11%	-22%
45° wind	4%	13%	0%	4%
90° wind	-6%	-6%	-2%	2%



(a) With proximity model *(b) Without proximity model*

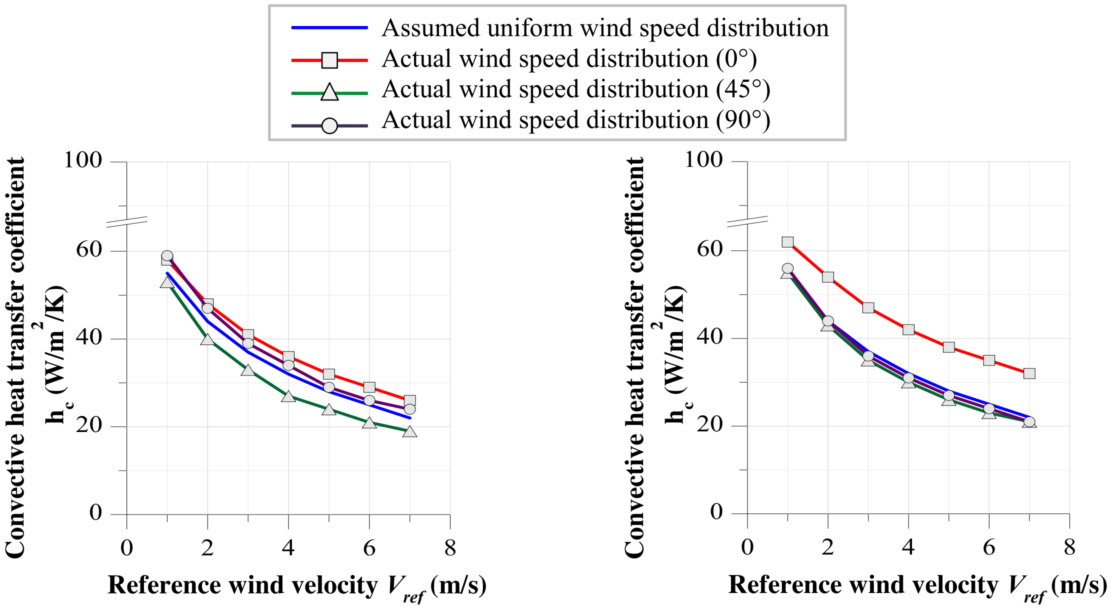
Figure 8 Comparison of convective heat transfer coefficient for different reference wind speeds and directions

For Case 2, without proximity models, the underestimation is most prominent for 90° (about 15% on average, estimated from Table 3 and Figure 9). The exception is 45° direction where due to high local velocities, and hence high CHTC, thermal efficiency is lower than for other directions.

Comparing the two proximity model cases (see Figure 9), η in Case 1 is lower due to higher CHTC as a result of higher localized wind acceleration brought about by the surrounding structures. For bothcases, there is a reduction in η by 20 percentage points for the range of wind speeds measured at JMSB (1 to 3 m/s). For a UTC working under typical conditions at say, 50% efficiency in a geographic region receiving an average 800 W/m^2 of solar irradiance at peak hours, reduction of thermal efficiency to 30% would translate to about 160 W.hr/m^2 of heat loss through convection.

Comparison of wind tunnel and solar simulator results (Bambara, 2012)

Bambara (2012) conducted experimental studies on the JMSB solar-wall in a solar simulator at Concordia University whereby the effects of parallel (0°) wind on the solar-wall was investigated. The solar simulator is an indoor research facility that reproduces natural sunlight and allows for testing of solar systems in controlled laboratory environments. The experimental setup included a fan fixed below the UTC test panel, used emulate wind speeds of 1 and 3 m/s. η was presented as a function of air suction rate V_s of the UTC. The study showed that a wind speed increase from 1 to 3 m/s reduced η by about 20 percentage points – this has been confirmed in the present wind tunnel study. The results from the two studies are compared in Figure 10.



(a) With proximity model *(b) Without proximity model*

Figure 9 Comparison of UTC thermal efficiency for different reference wind speeds and directions

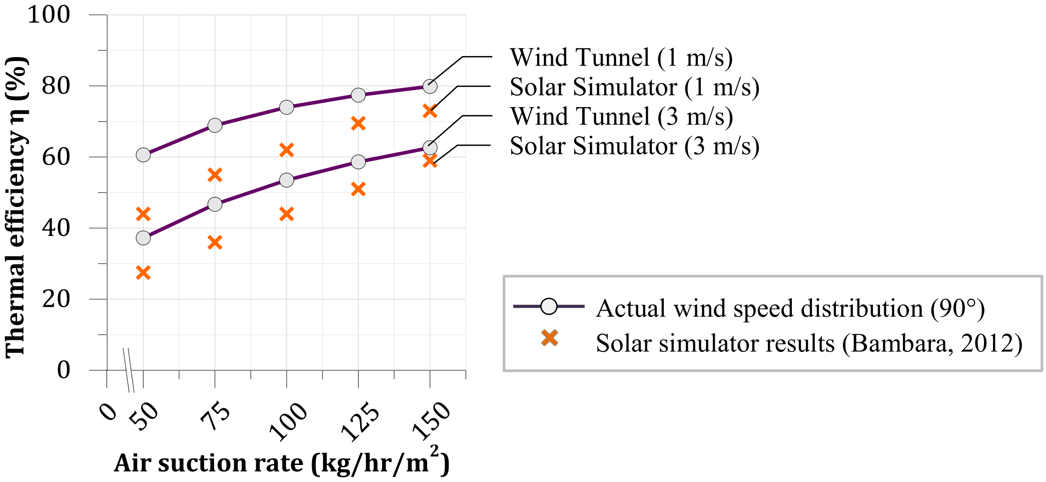


Figure 10 Comparison of UTC thermal efficiency with solar simulator results for parallel wind

On comparing the two studies (see Figure 10), it can be seen that the solar-simulator results, are closer to the values for the assumed uniform wind speed distribution in the present study, especially for the high wind condition. This was expected based on the assumption of uniform distribution in that study. Bambara (2012) assumed a vertical parallel flow over the UTC based on bluff body aerodynamics and the presence of a stagnation point. However, this is only true for winds that approach the building without the influence of any obstructions. For buildings located in an urban setting, surrounded by structures of similar heights, this is seldom the case. The present study addresses this aspect by the inclusion of proximity models for more accurate flow simulation.

PRACTICAL IMPLICATIONS & BUILDING SIMULATION

The most critical effect wind can have on UTCs is the removal of useful heat leading to reduced thermal efficiency. Most research studies in the past dealing with wind distribution on vertical walls were limited to terrain conditions with little or no obstruction to the flow; this is seldom the case in reality. Therefore existing correlations for local wind velocities, although broadly accepted for application to conditions similar to those they were developed in, cannot be generalized. A method to incorporate terrain condition factors into these correlations is desirable for greater accuracy in estimation of local winds.

Due to the fact that the nature of immediate surroundings cannot be generalized, it is advisable to use a combination of appropriate roughness lengths and scaled proximity models in studies concerning local flow around buildings. This will allow for local wind turbulence and flow accelerations to be better simulated as compared to the use of roughness length alone to generate the velocity profile. This measure is simpler in flow simulation programs where proximity models can be simulated as separate entities. However, in thermal simulation tools like DOE, ESP-R etc. where the external environment is simulated based on representative numerical inputs, the task of using accurate wind distributions may be difficult at this point. External coupling of flow and thermal simulation programs by which both domains may be synchronized and coupled (Djunaedy et al., 2004; Mirsadeghi et al., 2008) could be a way to get around this limitation.

CONCLUSIONS AND FURTHER THOUGHTS

This study is an attempt to demonstrate the significance of using proximity building models in wind flow simulation and actual velocity distributions on large areas for UTC analyses. Surrounding structures were seen to have a notable influence on the flow around the JMSB building; had there been no surrounding structures, the local wind velocities would have been about 20% to 30% lower than the prevailing conditions. The most significant effects were for 0° winds, which is the predominant direction in the JMSB area. Local flow patterns are highly dependent on immediate surroundings and are very difficult to generalize. This emphasizes the importance of including proximity models in wind related studies for more accurate simulation of wind flow around the test building in both experimental and computational studies.

Other conclusions from this study are:

1. Local velocities, especially those near building edges, could be up to 50% higher than those measured above the roof owing to flow acceleration at these areas.
2. Winds approaching from 45° angle were shown to have the greatest effect on CHTC - about 20% higher than those for the assumed uniform wind speed distribution.
3. A narrow range of wind speeds (between 1 and 3 m/s) was found to reduce the UTC thermal efficiency by up to 20 percentage points.

Although this study refers to a particular building – the JMSB – the qualitative results are expected to be applicable to other buildings in similar conditions of exposure. An ideal study set-up would be one where the simulation functions of a wind tunnel and solar simulator could be combined to investigate the wind effects and corresponding thermal changes simultaneously. Further investigation through full-scale studies and CFD modelling could provide detailed insights into the wind effects on UTC performance.

NOMENCLATURE

c_p = specific heat of air at constant pressure (J/kgK)

D = UTC hole diameter (m)

h_c = convective heat transfer coefficient (W/m^{2}K)

h_r = radiative heat transfer coefficient (W/m^{2}K)

P = UTC hole pitch (m)

Re = Reynolds number;

$$Re_w = \frac{V_\infty P}{\nu}$$

$$Re_s = \frac{V_s P}{\nu} \qquad Re_b = \frac{V_s P}{\nu\sigma} \qquad Re_h = \frac{V_s D}{\nu\sigma}$$

t = UTC plate thickness (m)

T_{amb} = temperature of ambient air (^{0}C)

T_{back} = temperature of the air coming out at the back of the collector (^{0}C)

T_{coll} = temperature at the collector surface (^{0}C)

V_∞ = free stream velocity parallel to the UTC (m/s)

V_{loc} = local wind velocity (m/s)

V_{ref} = magnitude of reference wind velocity measured above the roof (m/s)

V_s = suction velocity in the UTC pores (m/s)

α = wind profile power law exponent
α_s = solar absorptance of the collector surface
ϵ = UTC plate heat exchange effectiveness
η = UTC thermal efficiency
ν = kinematic viscosity of air (m^2/s)
ρ = density (kg/m^3)
σ = UTC porosity

CFD = computational fluid dynamics
CHTC = convective heat transfer coefficient
JMSB = John Molson School of Business
PV/T = photovoltaic/thermal
UTC = unglazed transpired collector

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