Wind Tunnel Assessment of the Wind Velocity Distribution on Vertical Façades

N. Vasan[1], T. Stathopoulos[2]
[1]Research Assistant, Concordia University, Montreal, Canada
[2]Professor, Concordia University, Montreal, Canada

Abstract

Building integrated photovoltaic/thermal (BIPV/T) systems serve two purposes – generate electricity and heat ambient air using absorbed solar energy. High wind velocity reduces the efficiency of unglazed transpired solar collectors (UTC). Indeed, wind flow on the collector's surface reduces the useful heat transferred to the plenum air by effectuating convection losses and suction in the pores; thereby outflow from the plenum behind the collector. The present study measured the detailed wind speed distribution in front of a building wall by means of wind tunnel experiments. It was observed that indeed heat losses from the solar wall and hence, its thermal efficiency was influenced by wind direction. Assuming that the reference velocity acts uniformly throughout the surface, results in an overestimation of convective losses and underestimation of UTC thermal efficiency. The importance of using actual velocity distribution in building simulation has been discussed.

1 Introduction

Wind flow around bluff bodies has been an area of research for decades. Wind related studies may broadly be classified as those pertaining to a) environmental effects, b) structural effects and c) building performance efficiency. One of the most important aspects of building performance that is very closely related to wind flow is ventilation which further links to ventilation equipment. Wind has a very dynamic, unsteady flow pattern in the environment. Due to this reason, not every point on a plane in the path of flow has the same velocity. This characteristic unsteadiness is reflected in the velocity distributions on a surface in the path of the flow and is taken advantage of in cladding design to optimize cladding element thickness at various parts of the façade. Unglazed transpired collectors consist of a perforated plate heated by solar energy. Air, drawn in through the perforations, is heated by the plate and moves into the ventilation network of the building. Wind flowing parallel to the collector's surface causes suction in the pores, and thereby outflow from the plenum behind the collector. This results in the loss of useful heat being carried by the plenum air (Fleck, Meier & Matovic 2002) in addition to convective heat losses (Kutscher, Christensen & Barker 1993). This paper describes a pilot study that analyzes the wind velocity distribution on a vertical façade and its effect on the heat transfer efficiency of a UTC. Depending on the criticality of the results, further studies may be conducted for detailed analysis.

A number of studies have previously analyzed the effect of wind velocity on UTC efficiency (Kutscher, Christensen & Barker 1991, 1993; Kutscher 1994; Van Decker, Hollands &

Brunger 2001; Fleck, Meier & Matovic 2002; Gawlik & Kutscher 2002; Gunnewiek, Hollands & Brundrett 2002; Augustus Leon & Kumar 2007; Cordeau & Barrington 2011).

Theoretical work by Kutscher, Christensen & Barker (1991, 1993) examined the different modes of heat loss from UTC and derived relations (cited in Delisle 2008) for convective heat loss Q_{conv} and collector efficiency η:

$$Q_{conv} = 0.82\left(\frac{U_\infty \nu}{V_s^2}\right) W\left[\rho c_p V_s (T_{coll} - T_{amb})\right] \quad (1)$$

$$\eta = \alpha_s \left[1 + \left(\frac{h_r}{\epsilon} + h_c\right)\left(\rho c_p V_s\right)^{-1}\right]^{-1} \quad (2)$$

The research was continued and extended to experimental analysis in a wind tunnel to assess the effect of cross-wind (Kutscher 1994) and later on a numerical model, validated by wind tunnel tests and hotwire anemometry, whereby relations were derived for heat loss on corrugated collector plates due to crosswind (Gawlik & Kutscher 2002).

Van Decker, Hollands & Brunger (2001) carried out experimental studies to understand the effect of different plate thicknesses and pore sizes, shapes and orientation on the heat exchange effectiveness of the UTC. The heat exchange effectiveness ϵ, i.e. the air heating effect of the plate is defined by the following expression:

$$\epsilon = \frac{T_{back} - T_{amb}}{T_{coll} - T_{amb}} \quad (3)$$

Predictive models were developed, by considering wind speeds ranging from 0 m/s to 5 m/s, for heat exchange effectiveness at the front, back and holes of the collector plate and ϵ was expressed as a combination of the three values:

$$\epsilon = 1 - (1 - \epsilon_f)(1 - \epsilon_h)(1 - \epsilon_b) \quad (4)$$

$$\epsilon_f = \frac{1}{1 + Re_s \min\left[aRe_w^{-\frac{1}{2}}, f\right]} \quad (5)$$

$$\epsilon_h = 1 - \exp\left[-4\left(c\frac{P}{D} + \frac{3.66}{PrRe_h}\frac{t}{D}\right)\right] \quad (6)$$

$$\epsilon_b = \left(1 + eRe_b^{\frac{1}{3}}\right)^{-1} \quad (7)$$

where, ϵ_f, ϵ_f and ϵ_b are the effectiveness values at the front, holes and back of the plate respectively. Through experiments and global regression fitting process, the values of the constants in equations 5, 6 and 7 were found to be a=1.733, c=0.004738, e=0.2273, f=0.02136 and Pr=0.71 (for air) (Van Decker, Hollands & Brunger 2001). The authors arrived at the following model for heat exchange effectiveness of a UTC with square-hole geometry:

$$\epsilon = \left[1 - \left(1 + Re_s\, max\left[1.733 Re_w^{-\frac{1}{2}}, 0.02136\right]\right)^{-1}\right] \times \left[1 - \left(1 + 0.2273 Re_b^{\frac{1}{2}}\right)^{-1}\right] \times exp\left(-0.01895\frac{P}{D} - \frac{20.62}{Re_h}\frac{\mathrm{t}}{\mathrm{D}}\right) \quad (8)$$

Using CFD simulations, Gunnewiek, Hollands & Brundrett (2002) studied wind effects on the flow distribution in UTC plenum and recommended minimum suction velocities required in the plenum in order to avoid outflow through the collector pores corresponding to a wind speed of 5 m/s at building height. The wind conditions were simulated on the basis of established pressure coefficients for normal and 45° wind.

Fleck, Meier & Matovic (2002) conducted field tests on transpired solar collectors and showed that there exist turbulent fluctuations outside the boundary layer that affect the heat transfer efficiency on the surface of the collectors by enhancing convective losses. It was also seen that peak collector efficiencies occurred at wind speeds between 1 – 2 m/s. Results on the relation between collector efficiency and wind direction were stated to be inconclusive due to lack of sufficient data. The paper also 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. Cordeau & Barrington (2011) also conducted field measurements on UTC for broiler barns and found that maximum efficiency of 65% was seen for wind velocities below 2 m/s and that the efficiency dropped below 25% for wind velocities higher than 7 m/s. Athienitis et al. (2010) described the design of a BIPV/T system combining UTC and PV panels. The prototype consisted of a UTC with PV panels covering 70% of the area; whereby wasted heat from the PV would also heat the air drawn into the UTC. The prototype was later developed into a fully operational BIPV/T system and incorporated in the John Molson School of Business (JMSB) building of Concordia University, Montreal. The design and analysis of the system assumed constant wind speeds less than 2 m/s (Athienitis et al. 2010). Predominant winds, in reality, for the JMSB building are normal to the BIPV/T wall as opposed to parallel flows mainly considered in many previous published studies that dealt with heat loss from UTC.

Convective heat transfer coefficients (CHTC) on vertical facade

Numerous researchers in the past have studied heat transfer coefficients on horizontal and vertical flat plates; they subsequently conducted studies for applications on building surfaces. The most recent works, primarily computational analyses, focused on improving the accuracy of CHTC – wind velocity relations (Blocken et al. 2009; Defraeye & Carmeliet 2010; Defraeye, Blocken & Carmeliet 2010).

Sharples (1984) conducted full-scale measurements of forced CHTC h_c and local wind speeds V_{loc}, at 1 m from the façade surface, on a 78 m tall building. The study classified winds as windward and leeward only, windward being those directions less than +/-90° with respect to the monitored façade. Measurements taken at 4 different façade positions were reported and their relationships with reference wind speed V_R at 6 m above roof level and U_{10} at a nearby airport were expressed as follows (cited in Blocken et al. 2009):

$$h_c = 1.7V_{loc} + 5.1 \quad (9)$$

$$V_{loc,ww} = 1.8U_{10} + 0.2 \quad (10)$$

$$V_{loc,lw} = 0.2U_{10} + 1.7 \quad (11)$$

Blocken et al. (2009) performed CFD simulations of forced convective heat transfer on a 10 m tall cubic building for four reference wind speeds at building height, which in this case is U_{10} (1, 2, 3 and 4 m/s). Nine wind directions were considered, namely 0°, 11.25°, 22.5°, 33.75°, 45°, 56.25°, 67.5°, 78.75° and 90°, with prime focus on the windward facade. The study found that wind direction indeed influenced the heat loss on the windward façade; however, relatively low variations of CHTC distribution on this façade was found for wind directions in the range 0° to 67.5°. It is to be noted here that only four positions on the windward façade were considered in the analysis. Correlations between CHTC and V_{loc} (at 0.3 m and 1 m from the façade) were developed for the four test positions and wind directions. CFD studies performed by Defraeye, Blocken & Carmeliet (2010) also used a similar configuration as Blocken et al. (2009) and reported the distribution of CHTC-U_{10} correlation over the windward face of a 10 m tall cubic building. Based on their study, a methodology for estimating the statistical-mean CHTC for building surfaces was proposed subsequently (Defraeye & Carmeliet 2010). The authors stated that the method and results they presented were '*... only valid for the windward and leeward surfaces of an isolated cubic body in a neutral ABL for an incidence angle of 0°...*'

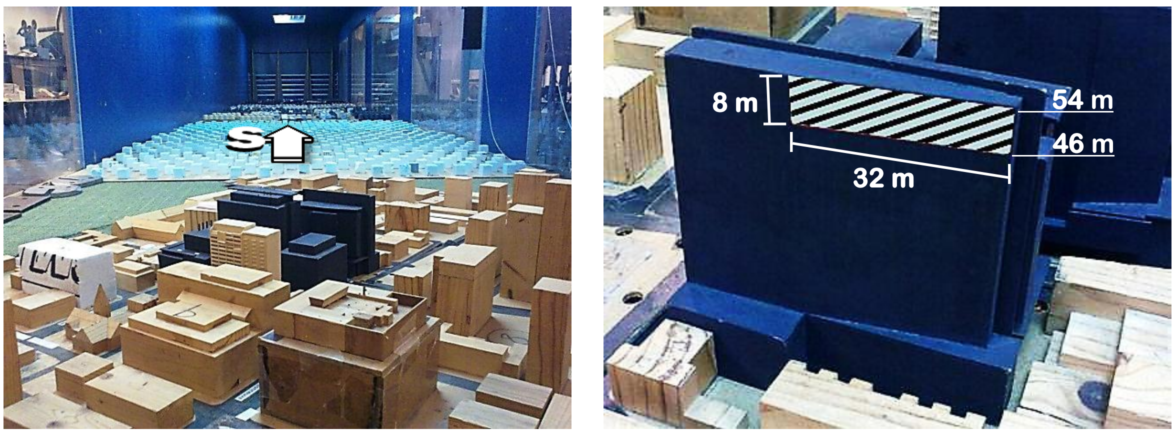
These previous studies have shown that wind direction is an important factor that determines heat losses from a vertical surface subjected to a flow. When the surface considered is a UTC, these losses are translated into thermal efficiency of the collector. It is worth mentioning that most of the previous studies were based on measurements taken in open terrain conditions, i.e. with little or no obstruction to the approach wind flow. To the best of our knowledge, there have been no previous studies assessing the effect of the wind speed distribution on a UTC plate and UTC orientation with respect to wind on the heat exchange effectiveness of the UTC plate. The present study measured the detailed wind speed distribution in front of a building wall by means of wind tunnel experiments and used the information thus obtained to analyze its effect on the heat exchange effectiveness of a UTC. The significance of using an accurate wind velocity distribution for design purposes is discussed in this paper.

2 Experimental setup and test procedure

The Building Aerodynamics Laboratory at Concordia University, Montreal, was used for this study. The Laboratory houses an open circuit wind tunnel that has a working cross-section of 1.8m X 1.8 m, length of 12 m and an adjustable roof that renders any pressure gradient of the flow reaching the test section negligible. In order to assess the wind distribution on a vertical façade in a realistic condition, an existing building, in this case the JMSB building was chosen for the study – see Figure 1a. The building is 54 m tall and the BIPV/T system, consisting of a UTC with 70% of its area covered by PV panels (O'Neill, Chen & Koziol 2011), is 32 m long and 8 m wide. The BIPV/T forms part of the south-west wall of the building, extending from an elevation of 46 m to 54 m (Figure 1b and 2). The analysis in this paper is focused on the velocity distribution on vertical facades; therefore, 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 along with all surroundings within a full-scale radius of 450 m and placed at the test section in the wind tunnel. In order to simulate the approach wind profile that the actual building encounters in downtown Montreal, terrain roughness beyond the modeled area was configured using roughness blocks and egg boxes such that the wind velocity profile developed had a power law exponent of 0.31 which replicates the downtown terrain in Montreal to sufficient accuracy.

The wind tunnel was operated at a speed of 12 m/s and local wind velocity at various locations on the area covered by the BIPV/T system was measured using a Cobra Probe, which is a very accurate 4-hole pressure probe that measures three velocity vector components, mean velocity vector and static pressure. Readings were taken at 40 measurement points on an 8×5 grid located 5 mm directly in front of the BIPV/T wall on the model (Figure 3). Measurements were taken for three cases, i.e. for wind flow coming from the following directions, as these are the predominant wind directions in Montreal that are relevant to the BIPV/T system:

- South – 32° east of the normal to the wall
- South-West – Normal to the wall
- North-West – Parallel to the wall



(a) **(b)**

Figure 1: (a) Test building, surroundings and roughness models placed in the wind tunnel; test wind direction - South (b) Model of the JMSB building with BIPV/T location hatched

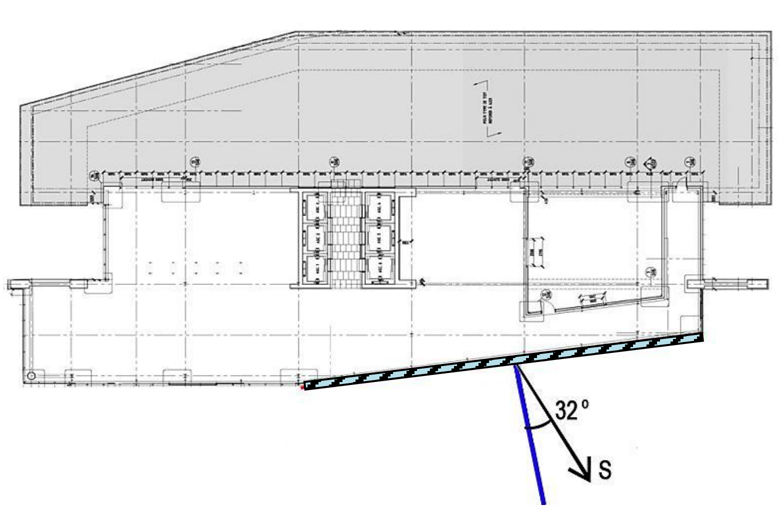


Figure 2: Schematic plan of the JMSB building showing the orientation of the BIPV/T wall

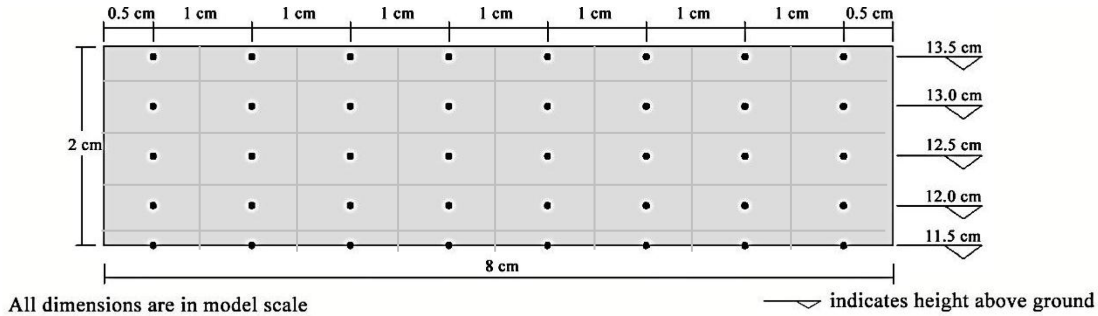


Figure 3: Schematic of the BIPV/T wall showing the positions of velocity measurement points

In addition, reference velocity at a height of 6.2 mm above the roof of the model, hereafter referred to as the reference height, was also measured for each configuration. This height, corresponding to 2.48 m above the roof in full scale, is the location of the anemometer that provided the full-scale reference wind-speeds.

3 Results

The aim of this paper is to evaluate the importance of using actual velocity distribution in place of a uniform or constant velocity value over a vertical surface exposed to wind. Four sets of calculations were done for h_c, ϵ and η – one using the reference velocity and the others using velocity values from the distributions for the three wind directions. A comparative analysis was done to assess the criticality of each case. Figure 4 shows the distribution of the magnitude of local velocity vector V_{loc} obtained, expressed as a fraction of the reference velocity vector, for the three cases tested.

Convective heat transfer coefficient h_c

The velocity distributions obtained by wind tunnel experiments were applied to the correlations between V_{loc} and CHTC derived by Blocken et al. (2009) for V_{loc} at 1 m from the building surface. The following correlations were adopted for the different wind directions:

South-west $$h_c = 10.2V_{loc}^{0.90} \quad \text{(edge zones 2 m to 8 m and 24 m to 30 m)} \qquad (12)$$

$$h_c = 10.2V_{loc}^{0.93} \quad \text{(central zone 10 m to 22 m)} \qquad (13)$$

South $$h_c = 11.7V_{loc}^{0.79} \qquad (14)$$

North-west $$h_c = 7.7V_{loc}^{0.77} \qquad (15)$$

The CHTC distribution thus calculated is shown in Figure 5. Blocken et al. (2009) used a 10 m tall model in an unobstructed terrain. For roughness length z_o=0.03 m, and reference speed of 3 m/s (Blocken et al. 2009), it can be shown that the approach velocity profile with respect to the 10 m building in that study is similar to the velocity profile with respect to the 54 m building in urban terrain (α=0.31) considered in the present study; thereby justifying the use of Blocken et al.'s V_{loc}-CHTC correlations. It can be seen from Figures 4 and 5 that CHTC distribution closely follows the local velocity distribution. Disregarding the wind direction and distribution, i.e.

assuming that the reference speed acts normal to the surface at all points on the vertical facade, led to an overestimation of the surface averaged CHTC by up to 48% for the north-west, 34% for the south and 28% for the south-west wind speed distributions.

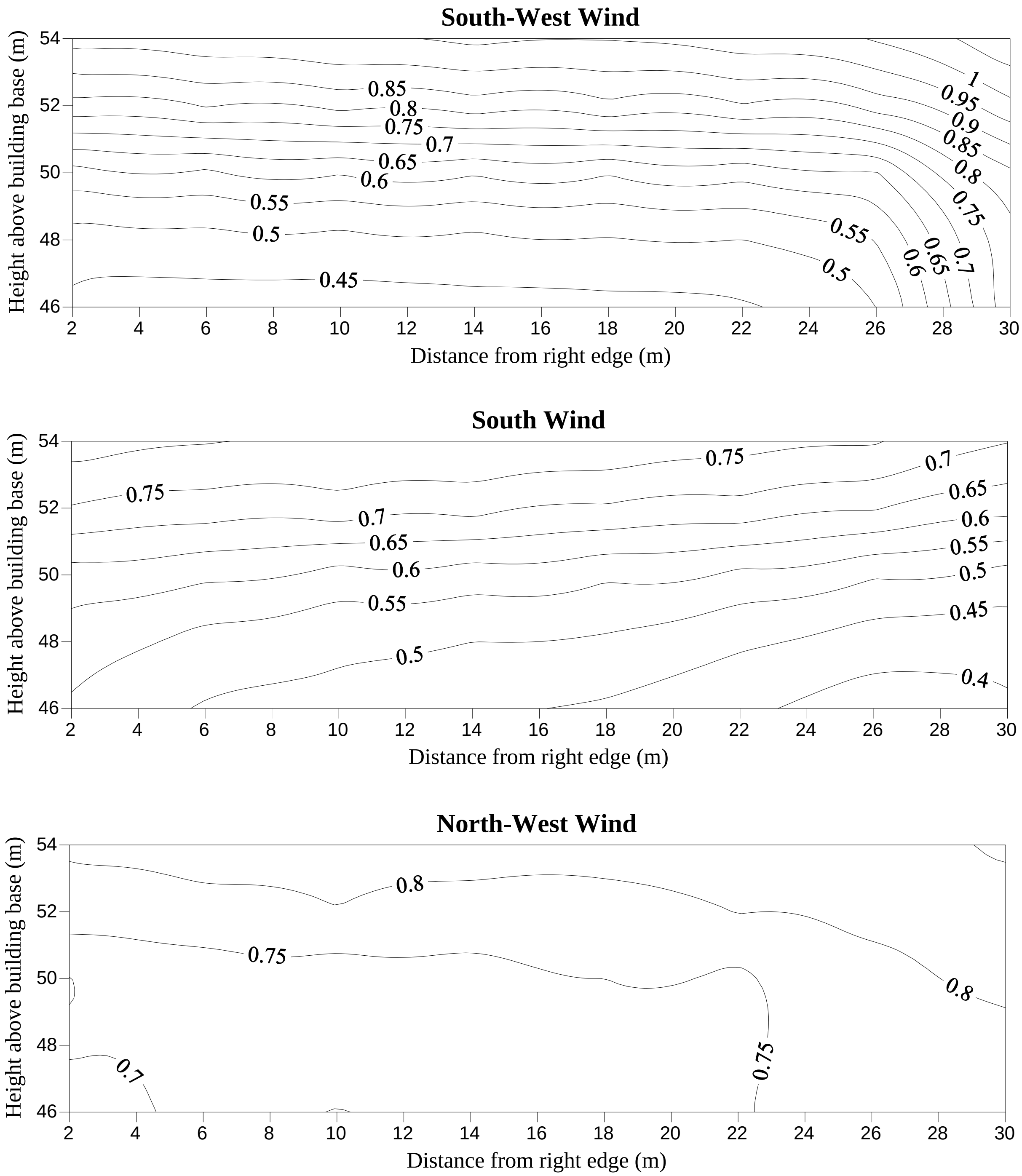


Figure 4: Distribution of V_{loc} (as a fraction of reference speed) over the UTC surface

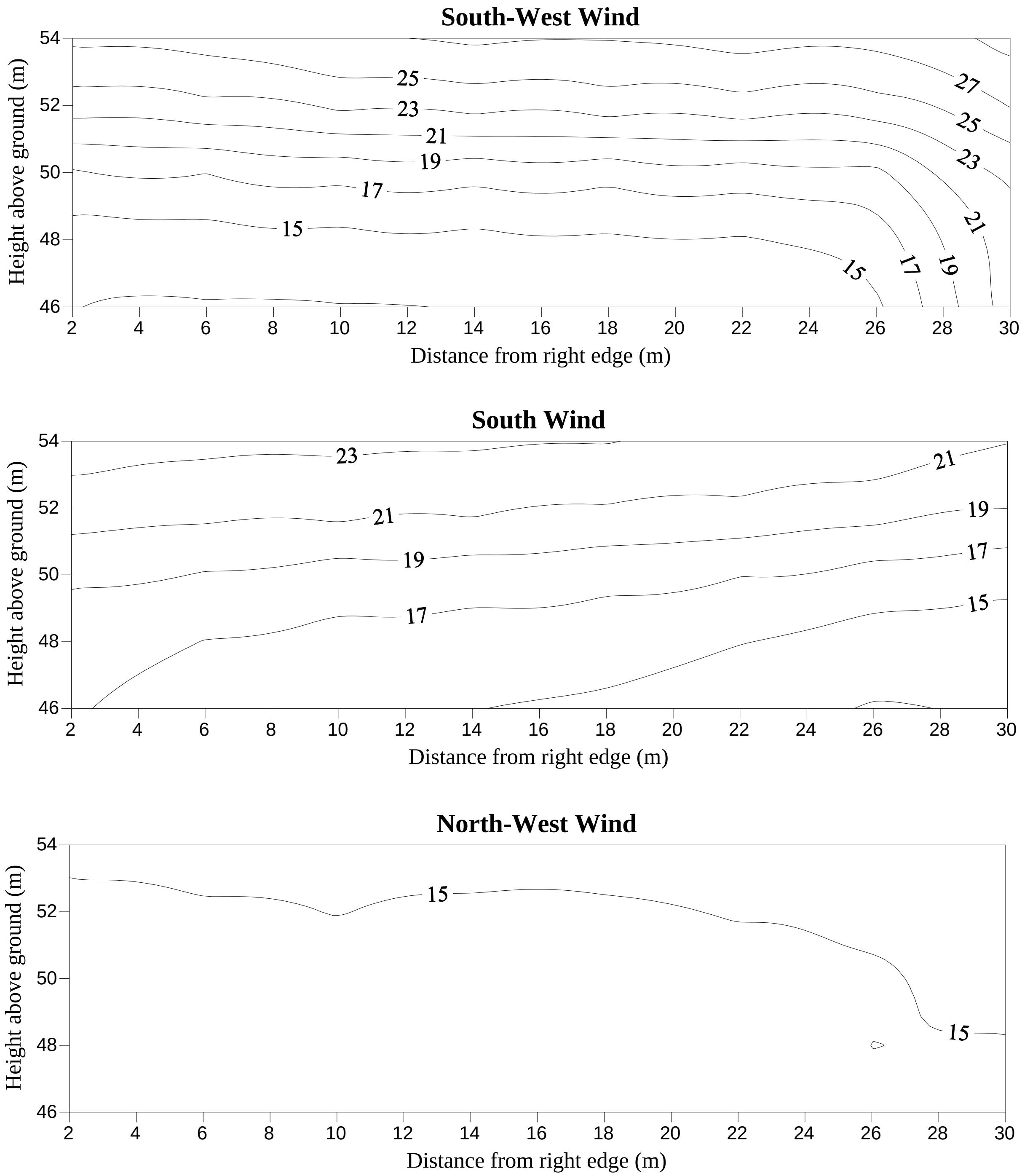


Figure 5: Distribution of CHTC (W/m^{2}K) over the UTC surface for a reference velocity of 3 m/s in full-scale

UTC Plate heat transfer effectiveness ϵ

Existing models for ϵ developed as a function of wind velocity, assume that the wind acts normal to the UTC plate and the pores. For this reason, calculations of ϵ in this paper have used the component of V_{loc} acting normal to the BIPV/T wall, V_{normal}. The distribution of V_{normal} on the BIPV/T wall surface for the three wind directions are shown in Figure 6.

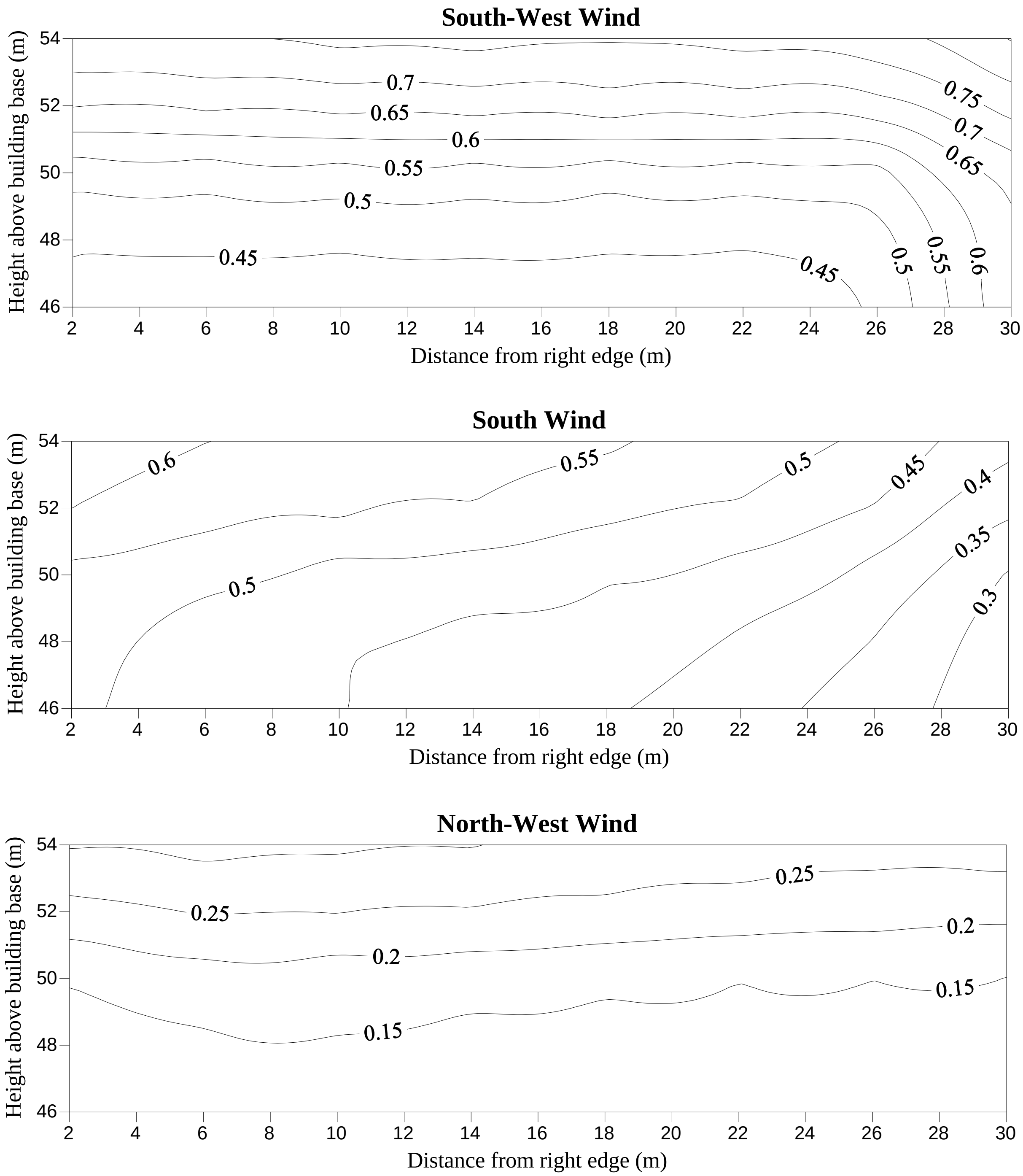


Figure 6: Distribution of V_{normal} (as a fraction of reference speed) over the UTC surface

Plate heat exchange effectiveness relations derived by Van Decker, Hollands & Brunger (2001) have been used here. In order to apply the velocity distribution to this model, it was assumed that the transpired collector wall was composed of 40 individual collectors, each represented by one measurement point – see Figure 3. It was assumed that each collector was subjected to a different velocity and the net effect of all 40 collectors working together in parallel was considered for overall plate heat exchange effectiveness ϵ.

The calculations assuming uniform distribution of reference wind speed over the entire wall area overestimate the effectiveness. Effectiveness values obtained using the actual distribution, as expected, are highest for the orientation that produces the largest normal velocity component. In the case of the JMSB solar wall, local velocities due to winds from south-west have the largest normal component and those due to winds from north-west have the smallest normal component. The effect of the normal velocity component is to carry out the heat exchange more effectively, as can be seen in Figure 7. It can also be seen that with increase in free stream velocity, hence increase in normal velocity component, the effectiveness increases until it reaches a maximum beyond which the curve is asymptotical. This behaviour is typical of perforated plates subjected to wind (Kutscher 1994).

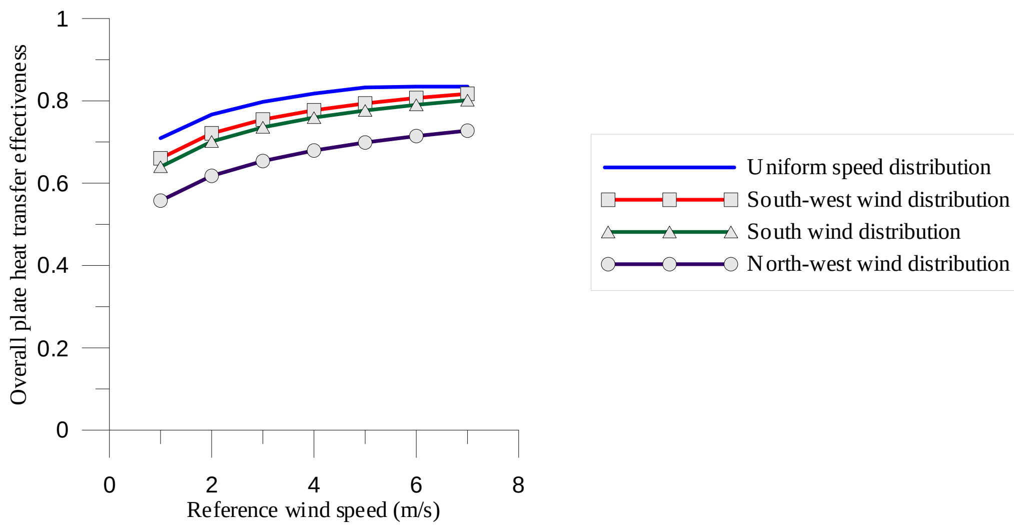


Figure 7: Comparison of ϵ for different wind speeds and directions

UTC thermal efficiency η

Figure 8 shows the comparison between thermal efficiency of the collector, calculated for uniform free stream velocity distribution and the actual velocity distribution for each wind direction, using Kutscher's model (1993). Thermal efficiency of a UTC is largely dependent on the convective heat loss term. It has been shown that assuming the reference speed acts uniformly throughout the UTC area highly overestimates convective heat loss. The corresponding effect is an underestimation of thermal efficiency. With the use of actual distribution, the actual estimates of thermal efficiency for different wind directions are at least 20% higher for typical wind speeds concerning the case-study location.

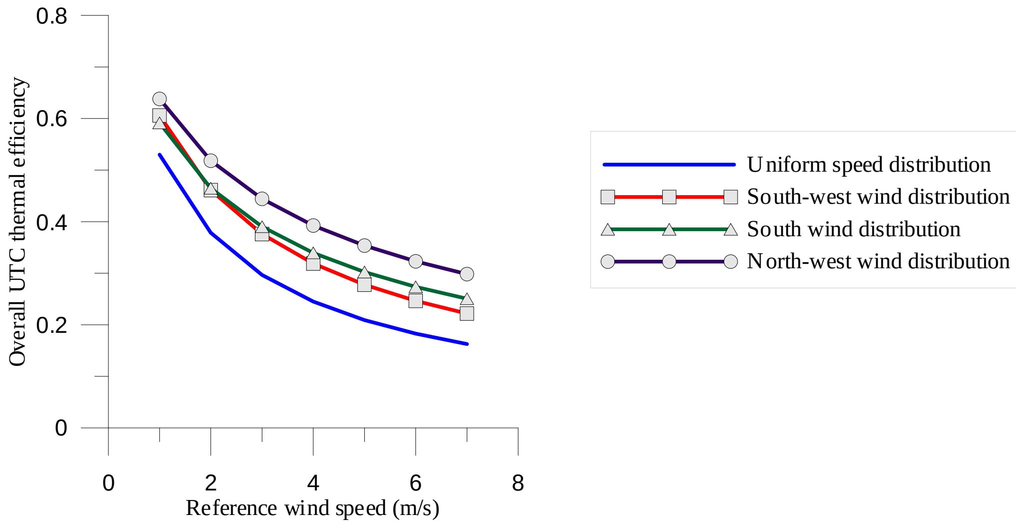


Figure 8: Comparison of η for different wind speeds and directions

4 Conclusion

It can hereby be concluded that solar-wall orientation with respect to wind direction plays a major role in the thermal efficiency of the system. In this study maximum thermal efficiencies were observed for flows parallel to the wall surface, which was primarily due to lower wind heat loss coefficients as compared to the other two directions.

Most research studies in the past dealing with wind distribution on vertical walls, including studies of CHTC on building facades, were limited to terrain conditions with little or no obstruction to the flow. This is seldom the case in reality and local wind velocities and distribution patterns at a surface are effects of the upstream terrain conditions and immediate surroundings of the concerned object. Therefore existing correlations for local wind velocities, although broadly accepted for application to conditions similar to those they were developed in, cannot be generalized. Due to the case-specific nature of these correlations, it is advisable to use a combination of appropriate roughness lengths and scaled models of the immediate surroundings when simulating flow around buildings. This will allow for local wind turbulence to be more accurately simulated as compared to the use of roughness length alone to generate the appropriate wind profile incident on the facade. This measure is simpler in flow simulation programs where the surroundings can be modeled as separate subjects or 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. This may be achieved by external coupling of CFD and thermal simulation packages by which both the thermal and flow domains may be synchronized and coupled (Djunaedy, Hensen & Loomans 2004; Mirsadeghi, Blocken & Hensen 2008).

Future work on this topic will focus on developing more generalized models and correlations that will allow easier prediction and application of wind velocity distribution on vertical building surfaces. Methods to incorporate terrain condition factors into these correlations for more accurate estimation of local winds will also be studied.

5 Nomenclature

a,c,e,f constants in equations 4 through 8
c_p specific heat of air at constant pressure (J/kgK)
D UTC hole diameter (m)
h_c coefficient of radiative heat transfer (W/m^2K)
h_r coefficient of convective heat transfer (W/m^2K)
P UTC hole pitch (m)
Pr Prandtl number
Q_{conv} convective heat loss (W/m^2)
Re Reynolds number; $Re_w = \frac{V_{wind}P}{\nu}$, $Re_s = \frac{V_sP}{\nu}$, $Re_b = \frac{V_sP}{\nu\sigma}$, $Re_h = \frac{V_sD}{\nu\sigma}$
t UTC plate thickness (m)
T_{amb} temperature of ambient air (^0C)
T_{back} temperature of the air coming out at the back of the collector (^0C)
T_{coll} temperature at the collector surface (^0C)
U_{10} reference wind speed at 10 m height in the upstream undisturbed flow (m/s)
U_∞ free stream velocity (m/s)
V_{loc} magnitude of local wind velocity vector (subscripts *ww* = windward, *lw* = leeward)
V_{normal} velocity component perpendicular to the building/UTC surface
V_s suction velocity (m/s)
V_{wind} approach wind velocity (m/s)
W width of the collector (m)

α_s solar absorptance of the collector surface
ϵ UTC plate heat exchange effectiveness
ϵ_f, ϵ_h, ϵ_b heat exchange effectiveness at the front, hole and back of the plate respectively
η UTC thermal efficiency
ν Kinematic viscosity of air
η UTC thermal efficiency
ρ density (kg/m^3)
σ UTC porosity

ABL atmospheric boundary layer
BIPV/T building integrated photovoltaic/thermal
CFD computational fluid dynamics
CHTC convective heat transfer coefficient
JMSB John Molson School of Business
UTC unglazed transpired collector

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