Pergamon PII: S0038–092X(02)00007–5
Solar Energy Vol. 73, No. 3, pp. 209–216, 2002

0038-092X/02/$ - see front matter
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A FIELD STUDY OF THE WIND EFFECTS ON THE PERFORMANCE OF AN UNGLAZED TRANSPIRED SOLAR COLLECTOR

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Received 28 May 2001; revised version accepted 3 December 2001

Communicated by BRIAN NORTON

Abstract—An experimental study was carried out on a working unglazed transpired solar collector (UTSC) to determine what effects ambient wind has on its performance. The monitoring system included instruments to measure temperatures, collector outlet flow rates, solar radiation, wind speed, and wind direction; as well as an ultrasonic anemometer placed near the centre of the collector. Efficiency was defined as the fraction of incident solar heat flux that went to preheating the transpired air. Our observations indicate a high degree of turbulence near the wall which feeds the near wall region. This is supported by observations of efficiency which decrease monotonically with increasing turbulence intensities. It was also observed that peak efficiencies did not occur at the lowest wind speeds. Both these findings seem to contradict existing laminar boundary layer models for UTSC performance.

1. INTRODUCTION

Unglazed transpired solar collectors are a simple and inexpensive technology that result in reduced energy consumption and operating costs that are associated with fresh air ventilation requirements (Seidermann, 1997). These devices preheat fresh outside air by drawing it through small holes on a dark coloured thermally conductive surface that is heated by the sun's radiation. They are usually mounted on the side of a building that receives the most sunlight (e.g. the south wall). Such a system is usually subjected to the natural buffeting and turbulence of the wind. Compared to other types of solar heat collectors, the unglazed perforated cladding is a cost effective, virtually maintenance free solution.

A well known and commercially available UTSC systems is the *Solarwall*, which has been the subject of several studies by Hollick (1994, 1996, 1998), Kokko and McClenahan (1994), Gunnewiek *et al.* (1996), and van Decker *et al.* (2001). The system is ideal for industrial and commercial size buildings that require large amounts of fresh air for ventilation requirements.

The basic physical system of the UTSC is one where suction is applied to a heated perforated plate that is placed in a fluid flow. Boundary layer flow parallel to a porous surface with suction has received a great deal of attention in aerodynamic applications, such as the use of suction on airplane wings to reduce drag. This flow model was the basis for the theoretical work of Kutscher *et al*. (1993), later in wind tunnel experiments by Kutscher (1994) and in a computer design model by Dymond and Kutscher (1995). In the cited works, the authors assume a parallel laminar boundary layer flows along a smooth wall. These studies were used to develop methods for estimating performance characteristics of UTSC systems. The aforementioned assumptions led to the conclusion that losses due to wind effects and natural convection would be minimal. Their basis for assuming laminar parallel flow must have been largely due to the attractive simplicity of the differential equations describing such a system, and not for its realism. Admittedly, in the face of dauntingly complex systems, one must first simplify a system to understand its behaviour. However, in spite of the apparent accuracy of the efficiency estimates generated using the laminar parallel flow model, it is quite clear from our observations that such a model is a poor descriptor of the physical phenomena driving UTSC performance.

Aerodynamic applications generally assume an inviscid incompressible irrotational free-stream (potential flow) surrounding a boundary layer

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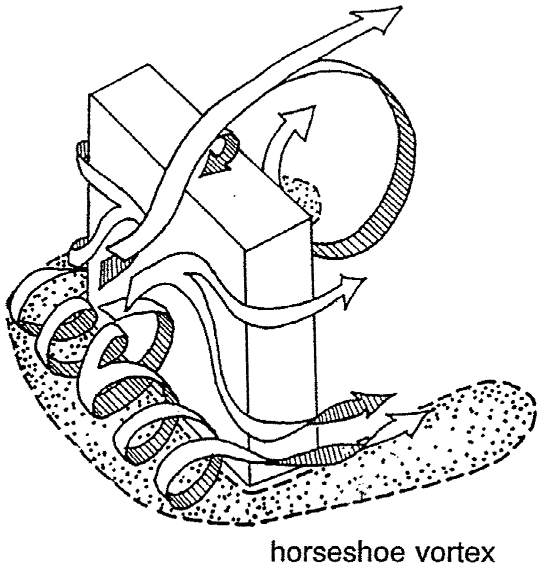

Fig. 1. Schematic representation of typical large scale flow patterns around a building with wind incident normal to one wall.

(Schlichting, 1979). The outer potential flow is generally assumed to be steady. Wind tunnel studies which simulate such systems generally are made with great efforts to reduce or eliminate free stream turbulence, or to add simulated homogeneous turbulence (using screens or grids) of intensities on the order of 1–10%. The wind tunnel experiments by Kutscher (1994) were conducted intentionally inside the inviscid core region of the wind tunnel.

Both meteorologists and lay observers will attest to the fact that the wind bears little resemblance to a steady unidirectional potential flow parallel to the ground. With the added complexity of building/wind interaction (Dyrbye and Hansen, 1997; Simiu and Scanlan, 1986) undoubtedly present around any UTSC installation, the inviscid parallel flow model seems dubious indeed. A more realistic image of the kind of flow field one might expect around a bluff building is shown in Figs. 1 and 2. It is typical in building design to take into account the recirculation patterns, particularly when air intakes and stacks are involved (ASHRAE, 1997). Furthermore, the air velocity near the ground is often characterized by a high degree of fluctuation relative to the mean value; it is not uncommon for turbulence intensities to be 30% or higher.

It is also important to note that the aforementioned idealized models assume both a smooth flat surface and uniform suction. Typical UTSC systems use corrugated sheet metal with ridges 100 times higher than the boundary layer thickness of 0.6 mm predicted by Kutscher *et al.* (1993), with hole spacing on the order of 1 cm.

The purpose of this work is to provide the first documented attempt at studying the interaction of local meteorology with a fully functioning UTSC. To the best of our knowledge, there have been previously no detailed field studies on the wind effects on UTSC performance.

2. EXPECTED WIND EFFECTS

The atmospheric boundary layer is turbulent, even at low wind speeds. Wind induced air flows close to buildings will have a high degree of turbulence with most of the turbulence kinetic energy carried in the largest eddies of size ℓ,

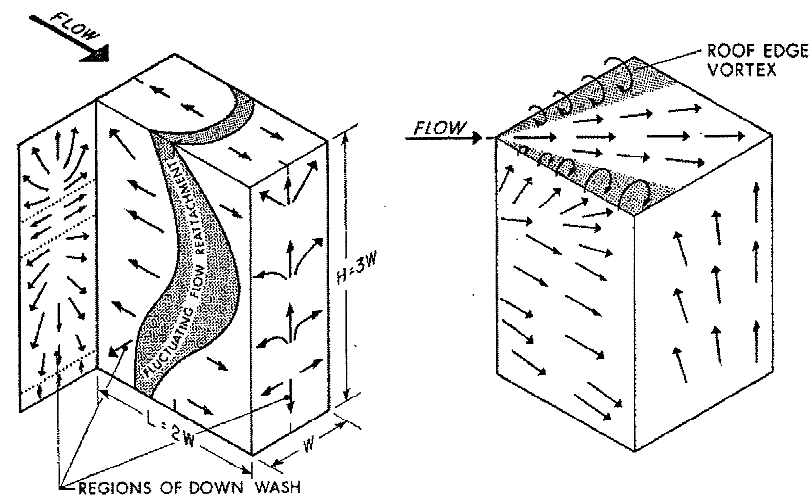

Fig. 2. Detailed schematic showing zones of fluctuating, reverse and parallel flow on a tall building for incident wind normal and diagonal to one wall.

similar in scale to the building itself $\mathcal{O}(10\text{ m})$. Boundary layer theory indicates that turbulent diffusion (that transports heat away from the UTSC, thus reducing the efficiency) will mostly be done by eddies of the size of the diffusive 'boundary' layer δ. Given the macroscopic rectangular corrugations in the UTSC studied here, it seems logical to assume a diffusive layer of similar scale to these corrugations, $\mathcal{O}(10^{-2}\text{ m})$. Turbulent diffusion of the energy carrying eddies in the large scale flow can be estimated by

$$\epsilon \sim \frac{\tilde{U}^3}{\ell}, \tag{1}$$

where $\tilde{U}$ is the magnitude of the large scale velocity fluctuations. Based on the concept of the turbulence cascade (Tennekes and Lumley, 1972), this dissipation rate must be translated down to the scale of the diffusive layer, so we may say

$$\frac{\tilde{U}^3}{\ell} \geq \frac{\tilde{u}^3}{\delta}, \tag{2}$$

where $\tilde{u}$ is the scale of the velocity fluctuations of size δ.

Using the length scales estimated above, one can estimate that the magnitude of the velocity fluctuations responsible for turbulent diffusion at the collector surface will be about one tenth the scale of the large scale atmospheric fluctuations. At the boundary layer scale, other large scale fluctuations will 'appear' simply as an increased free stream velocity. In other words, a 30% atmospheric turbulence intensity could be modelled as a unidirectional turbulent boundary layer of roughly 3% turbulence intensity with a slightly increased free stream velocity compared to the ambient wind speed.

3. EXPERIMENTAL PROCEDURE

Two separate UTSC's (the brand used was Solarwall) were installed in early 1999 at the Canadian Coast Guard Prescott Base (located on the St. Lawrence River between Kingston and Montréal), one on either side of a large welding shop door. The west collector was selected for experimental purposes, as its surface area did not become significantly shaded during the course of the day. Its area is 63 m^2 with two ducts and fans which vent heated air into the attached building. The collector is oriented facing a bearing of 145° (where 180° is due south).

The collector performance was monitored by measuring duct flow rate and temperature, solar irradiance (both diffuse and direct over the entire solid angle visible by the collector) and wall temperature. Ambient conditions were measured at 10 m elevation with a cup and vane anemometer and a shaded thermocouple. A model 81000 Young sonic anemometer was installed on a bracket in the centre of the collector, 61 cm from the collector surface. The sonic anemometer logged 5 min averages of three velocity components and the air temperature, as well as averaged covariances of each of these four variables (10 in all). The three components of velocity were labeled U along the wall (positive being on a bearing of ~55°), V normal to the wall with positive values indicating flow toward the collector and W in the vertical direction with positive up; this gives a right handed system where U, V and W are the mean velocity components in the x, y and z directions respectively.

After some testing, it was found that one of the fans had to be deactivated and one duct closed off to allow for proper operation of the collector (details are described by Meier, 2000). This resulted in a transpired flow rate of ~0.01 m^3/s per m^2 of collector, which was below the design value of roughly 0.02 m^3/s per m^2. Continuous monitoring of the system was undertaken through the months of February and March of 2000, and only the results obtained when all instruments were functioning were retained.

A summary of experimental uncertainties is given in Appendix A for measurements of velocity, temperature and radiation. The effective uncertainty in the (15 min average) efficiency, η, based on component uncertainties is estimated at 8% for solar radiation $>600\ W/m^2$.

4. RESULTS AND DISCUSSION

After data filtering and quality control, the usable data set was culled down to approximately 30 days. This represented times when all instruments were functioning normally and the incident solar radiation was high enough to merit the use of the collector. During this time period, 95% of the 5 min average wind speeds were less than 5.4 m/s ('gentle breeze' or weaker on the Beaufort scale). Also of note was that based on a 16 category wind rose, over 30% of the 5 min average wind directions were out of the southwest (225°), roughly in line with the St. Lawrence River at Prescott. All other categories of the wind rose were below 10%.

The efficiency of the UTSC system was evaluated by comparing the total radiant heat energy flux to the wall with the change in energy of the transpired air after passage through the collector. This is given in the equation,

$$\eta = \frac{\dot{m} c_P T_{\mathrm{rise}}}{IA}, \tag{3}$$

where $\dot{m}$ is the mass flow rate of the transpired air, c_P is the air heat capacity, T_{rise} is the temperature rise of the air, I is the integrated hemispherical intensity of the direct and diffuse irradiance on the wall and A is the wall area. Note that as I approaches zero around dawn and dusk, the uncertainty in the estimated efficiency becomes excessively high. For this reason, estimates of efficiency are only presented for when I was above 200 $\mathrm{W/m^2}$. This left 1300 five minute averages in the data set.

4.1. Observed flow field near the wall

Histograms of the three components of velocity near the wall are given in Figs. 3–5. These data are presented for five minute averages using standard Reynolds averaging with the notation

$$U(\mathbf{x}) \equiv \frac{1}{\tau}\int_0^{\tau} u(\mathbf{x}, t)\,\mathrm{d}t, \tag{4}$$

with τ being 5 min and u as the instantaneous velocity. The velocity fluctuations are thus $u'(\mathbf{x}, t) \equiv u(\mathbf{x}, t) - U(\mathbf{x})$.

Due to the occasional reversals in flow direction around the sonic anemometer over the five minute averaging time, the 5 min averages tend to under-predict average velocity magnitudes. The U velocities (Fig. 3) have a bimodal distribution around 0. It shows that a cross flow component of velocity (in either direction along the wall) slightly greater than zero (~1 m/s) was most common.

The other two components of velocity have closer to normal distributions. The V velocities (Fig. 4) have a mean of 2 cm/s toward the wall, while the mean W velocity (Fig. 5) is 15 cm/s up. More interesting is the standard deviation of the normal velocities (19 cm/s). It indicates that for a substantial fraction of the time there are normal velocities an order of magnitude greater than the suction velocity in the neighbourhood of the plate.

The histogram of the square root of the turbu-

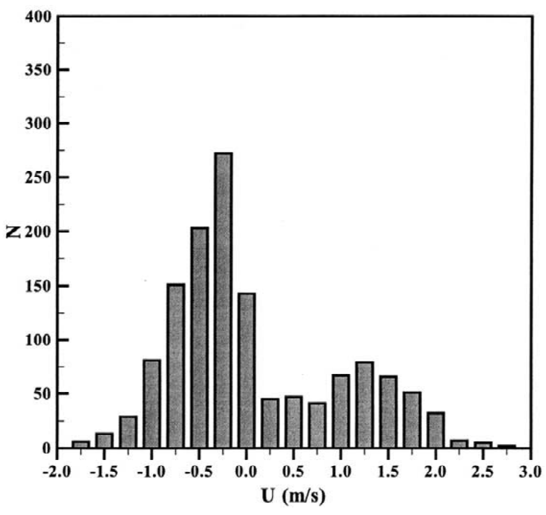

Fig. 3. Five minute mean tangential–horizontal velocity (U) distributions 61 cm away from the wall.

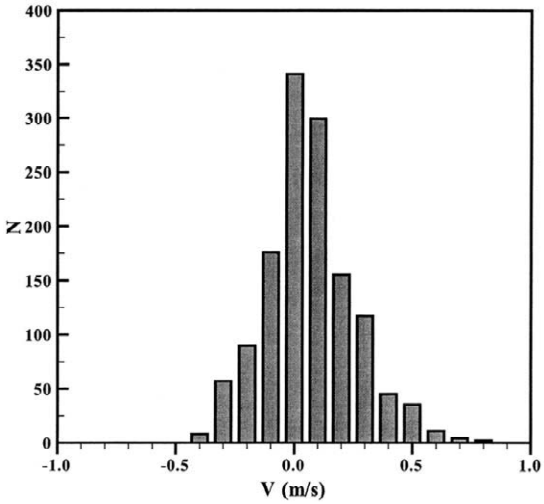

Fig. 4. Five minute mean normal velocity (V) distributions 61 cm away from the wall indicating an average close to the suction velocity but a high degree of variation due to near wall turbulence.

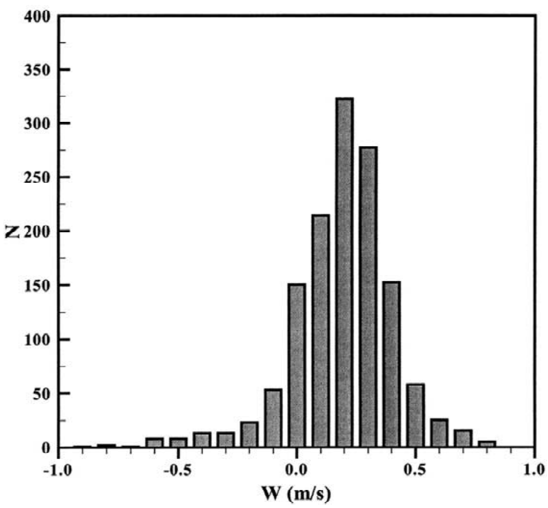

Fig. 5. Five minute mean tangential–vertical velocity (W) distributions 61 cm away from the wall indicating a mean upward velocity expected due to natural convection with frequent downward average velocities due to recirculation.

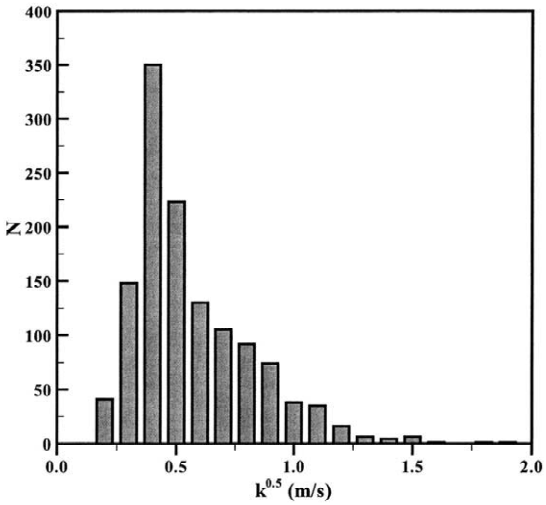

Fig. 6. Five minute mean $k^{0.5}$ 61 cm away from the wall showing mean fluctuations typically on the order of the mean 5 min velocity magnitude.

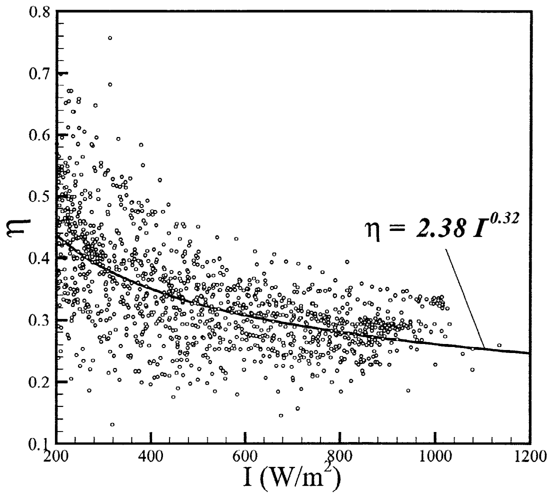

Fig. 7. Evidence of decreasing solar collector efficiency with increasing irradiation.

lence kinetic energy (with energy defined as $k \equiv 1/2(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$ in Fig. 6 is given to give a rough idea of the scale of the turbulent fluctuations near the wall and its variability over the testing period. The sonic anemometer samples velocity at a much higher frequency (160 Hz) than is needed given the low velocities and the spatial averaging through its 10 cm diameter measurement volume. This spatial averaging results in an under-prediction in fluctuation intensity. In spite of this bias to lower k values, the histogram shows fluctuation intensities of similar order of magnitude to the mean velocity. This amounts to typical turbulence intensities of roughly 100% (compared to means in the previous three velocity distributions), most likely attributable to the high degree of recirculation near the wall due to building effects. It should be noted however that this is not an indication of intensity in the boundary layer, since the sonic anemometer is still 61 cm from the collector surface.

4.2. Efficiency as a function of meteorology

The purpose of this work was to evaluate the practical performance of the UTSC as a function of local meteorology. The efficiency as defined in Eq. (3) was used since it measures the conversion rate of solar energy to useful energy in the transpired air stream.

It was observed that the strongest factor in determining efficiency was the measured solar irradiance. Fig. 7 shows a scatter plot of this phenomenon. In spite of the scatter in the data, there is clearly some inverse correlation between η and I. This may seem surprising at first, but this behaviour is similar to the concept of 'diminishing return'. Physically this can be attributed to the fact that higher solar intensities will result in a higher collector surface temperature which in turn leads to more radiative and convective losses to the surroundings. The power-law fit (roughly a one third exponent) is indicated in the figure as a trend rather than the proposed empirical relationship, due to the high variability of the raw data.

Next we compare the system efficiency to the mean wind speed in Fig. 8 measured at a nearby 10 m anemometer (the low resolution of the anemometer output is the cause of the vertical

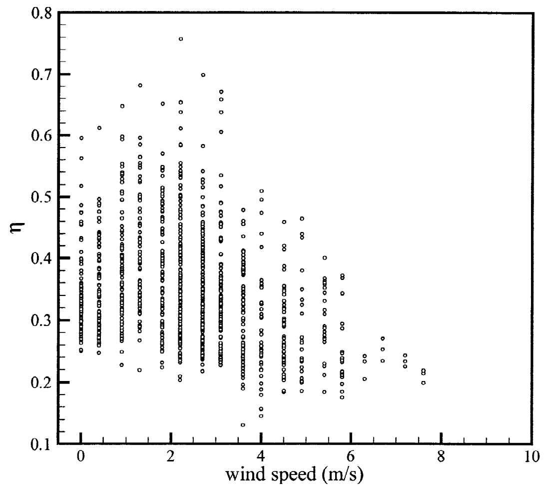

Fig. 8. Comparison of collector efficiency and mean wind speed (5 min averages measured on a 10 m mast) indicating peak efficiency at roughly 1.5 m/s.

'stripes' in these data). It is important to note that the cup and vane anemometer used to measure wind speed and direction was far enough away from the collector and other buildings to be considered practically unaffected by the building recirculation zones.

Fig. 8 surprisingly shows that peak efficiencies do not occur at zero wind speed. The data seem to suggest the collector operates at peak efficiency when the wind speed is at 1–2 m/s. Currently we have no firm explanation for this trend but suspect there is a logical reason for this hiding in the covariance of wind speed with other parameters like direction and solar intensity (this is currently under investigation). The most important observation to make from this figure is that these field measurements to not support the model of Kutscher *et al.* (1993) that predict peak efficiencies at zero wind speed with a monotonic decrease in efficiency with increasing wind speed.

A less surprising result comes from comparing the turbulence kinetic energy with efficiency (Fig. 9). There is an obvious decreasing trend in efficiency with k. This supports the hypothesis that it is the turbulent fluctuations that reduce collector efficiency by increasing macroscopic heat transfer away from the collector surface.

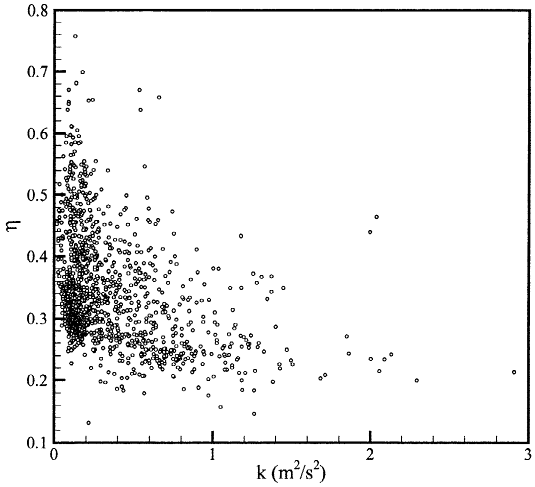

Fig. 9. Comparison of collector efficiency and turbulence kinetic energy showing a monotonic decrease in η with k.

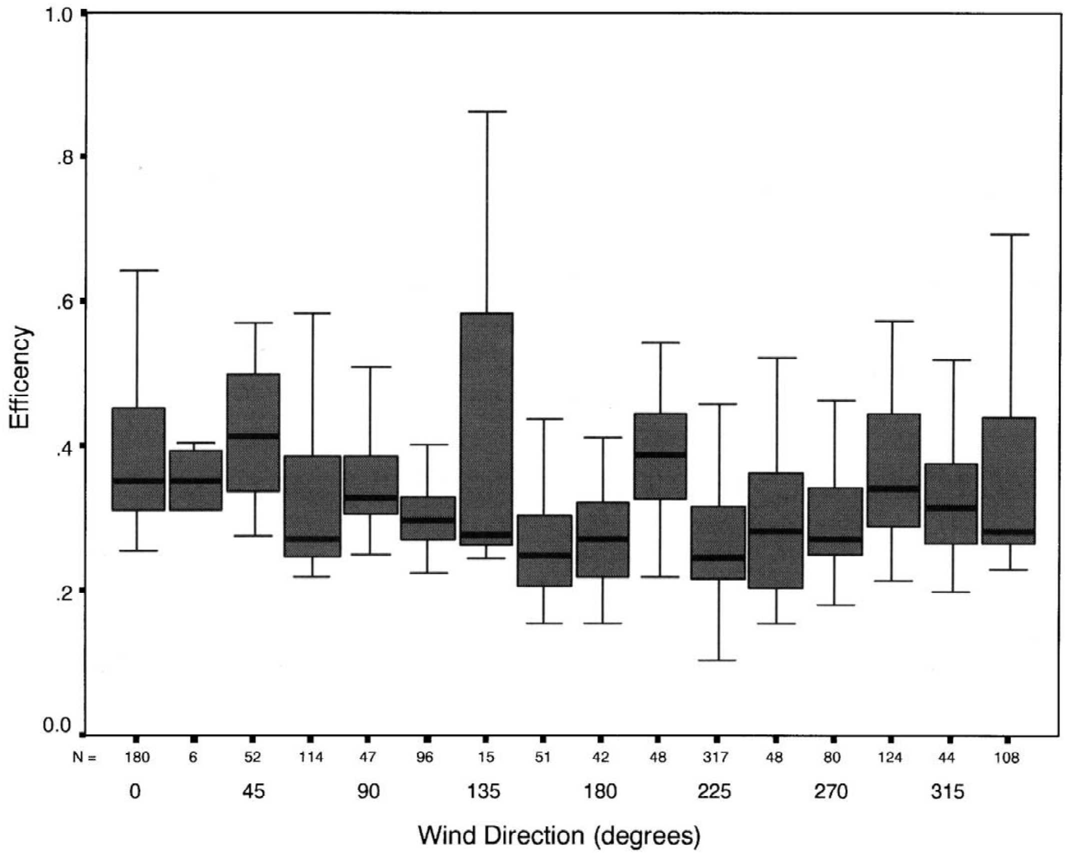

Fig. 10. Collector efficiency shown as a function of 16 wind directions (based on standard compass directions). The bars show the limits of the data while shaded boxes delineate the quartile ranges with the mean shown as a thick black line. The number of 5 min averages in each direction bin is shown in small font below each box.

In an attempt to explain the effects of near building recirculation on the UTSC performance, a box plot of wind direction with efficiency is shown in Fig. 10. At the outset of this study, it was presumed that certain wind directions would affect efficiency by generating large scale recirculation zones while others might be more likely to generate simpler boundary layer flows. In spite of 2 months of continuous monitoring, there is simply not enough data to draw a strong conclusion for the wind direction effects on efficiency. There appears to be a trend of higher efficiency for NW wind (45°) with lower efficiencies for southerly (impinging) winds, but the data in the SSW (202.5°) confound this conclusion.

The main problem with doing field studies is the lack of control over the multiple parameters that affect a system's performance. Apart from the uneven distribution of data through the wind direction range (compare the number of SW (225°) to the number of NNW (20.5°) measurements), there is the added complexity of multi-variable interaction and covariance. Some attempts were made to perform a principal component of variance analysis (based on finding the eigenvectors of the covariance matrix of the variables) but since this requires normally distributed continuous variables (our wind direction data are neither), the results were not conclusive or dependable. The only thing that was observed was a codependence between wind speed and fluctuation, neither a surprising or enlightening finding.

Earlier field studies by Kokko and Marshal (1992) using thermography showed that the presence of persistent recirculation zones on the solar wall leads to hot spots on the collector surface and perhaps results in associated losses in efficiency correlated to the average wind speed. Thermography studies were not conducted in this field study, but are planned as a followup aimed at answering some of the questions which arise from the data at hand.

5. CONCLUSION

The purpose of this investigation was to find evidence of effects of wind direction, speed and fluctuation intensity on the performance of an unglazed transpired solar collector operating in the field. Our measurements took place over the late winter operating season of a relatively small UTSC.

The distribution of the wind data measured 61 cm from the collector surface clearly indicate that outside the boundary layer there is a large source of turbulence dominating the near wall heat transfer. It seems unlikely, given the free stream turbulence and the large rectangular corrugations in the collector surface, that a laminar boundary layer thinner than the diameter of the perforations in the collector cladding exists and can be used to model the system performance. Our order of magnitude analysis predicts that there is boundary layer turbulent diffusion with an intensity on the order of 3%.

Our measurements led to the surprising observation that peak collector efficiency occurs at non-zero wind speeds between 1 and 2 in/s. Comparing turbulence kinetic energy and efficiency gave a less surprising result, showing that increasing fluctuation intensity results in a monotonic decrease in efficiency. This is support for our hypothesis that turbulence has a strong influence on collector performance.

We remain conservative in our conclusions about the effects of wind direction on this system. It seems logical that wind direction will be a dominant factor in determining the near building flow patterns, but we have yet to draw a clear picture from our multi-parameter field study. Our current efforts are in finding a multi-variable correlation or model to explain the scatter in the field measurements.

Acknowledgements—Instruments for this work were supplied by the Departments of Mechanical Engineering at the Royal Military College of Canada and Queen's University. We give thanks for the cooperation of Lorne Macmillan and Rick Renick from the Coast Guard base at Prescott, Steve Harrison from the Solar Laboratory at Queen's University, and David Wilson from the University of Alberta.

APPENDIX A. MEASUREMENT UNCERTAINTY

In terms of measured quantities, the solar wall efficiency (3) can be expressed as

$$\eta = \frac{(\rho\beta v_{\mathrm{d}} A_{\mathrm{d}}) c_p T_{\mathrm{rise}}}{IA} \tag{A.1}$$

where ρ is air density, $\beta = 0.86$ is the duct velocity coefficient, v_{d} is the centreline duct velocity, A_{d} is the duct area and other symbols are same as in (3). Assuming ρ, A, A_{d} and c_p are all constant and measured more accurately than other flow parameters, the relative uncertainty for efficiency becomes:

$$\frac{\Delta\eta}{\eta} = \frac{\Delta v_{\mathrm{d}}}{v_{\mathrm{d}}} + \frac{2\Delta T_{\mathrm{rise}}}{T_{\mathrm{rise}}} + \frac{\Delta I}{I} \tag{A.2}$$

Expanding

$$\frac{\Delta v_d}{v_d} = \frac{1}{2}\frac{\Delta P_d}{P_d} + \frac{1}{2}\frac{\Delta T_\infty}{T_\infty} \quad \text{(A.3)}$$

where P_d is the measured duct pressure and T_∞ is the ambient temperature away from the collector surface, the final expression for the uncertainty is given by

$$\frac{\Delta \eta}{\eta} = \frac{1}{2}\frac{\Delta P_d}{P_d} + \frac{1}{2}\frac{\Delta T_\infty}{T_\infty} + \frac{2\Delta T_{rise}}{T_{rise}} + \frac{\Delta I}{I} \quad \text{(A.4)}$$

Component uncertainties are estimated as:

- $\Delta P_d / P_d = 0.01$ FS (Setra pressure transducers, 0–125 Pa range)
- $\Delta T_\infty = 0.2°C$ (Sonic anemometer temperature)
- $\Delta T_{rise} = 0.2°C$ (K type thermocouple)
- $\Delta I / I = 0.02$ (Second class pyranometer limit based on WMO standards)

The worst case scenario of the March data set (solar radiation >600 W/m^2) where $T_\infty = 265$ K, $T_{rise} = 10°C$ and $P_d = 38$ Pa, results in the uncertainty of efficiency of 8%. Under these same conditions but with $I = 200$ W/m^2, the maximum uncertainty increases to 14% and decreases to 6% when $I = 1000$ W/m^2.

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