Journal of Wind Engineering & Industrial Aerodynamics 161 (2017) 27–41

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Wind effects on the performance of solar collectors on rectangular flat roofs: A wind tunnel study

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ARTICLE INFO

Keywords:
Wind effects
Solar collectors
Local flow distributions
Thermal performance

ABSTRACT

Wind induced convection is the main cause of heat loss for roof-mounted solar collectors. In this study the importance of using the actual wind velocity distributions over the whole roof area, instead of a commonly assumed single velocity of a reference location, is addressed through experimental measurements and numerical assessment of the performance of solar collectors placed on different locations over the roof of a typical rectangular building. The measurements were carried out at the Boundary Layer Wind Tunnel of Concordia University, for nine different locations on the roof, three different wind directions and cases concerning both an isolated building and a building with surroundings of various configurations. For the isolated building case, it was found that local velocities on different roof locations may vary more than 60% and the effect of these differences on the performance of solar collectors placed on these locations was assessed. In an attempt to generalize the results, 17 different surrounding configurations were considered. For a typical day in Montreal (with 4–7 m/s average wind speed), it was found that the thermal gains between solar collectors at different locations over the same roof could vary up to 21%.

1. Introduction

Solar thermal systems are an efficient means of fulfilling the building's heat demand, or a considerable part of it, reducing CO_2 emissions, while being a durable sustainable technology with an expected life span of 20–30 years (Buker and Riffat, 2015). The various types of flat plate solar collectors, as well as design techniques used to enhance their thermal performance, in terms of reducing thermal losses to the environment, have been extensively reviewed (Suman et al., 2015; Michael et al., 2015). Apart from design enhancement (fins, double glazing, etc.), thermal losses to the environment can be further reduced by strategic placement of the collectors, according to the local wind velocity distributions of the installation area, in the case of this study, the building roof.

The main objective of this study is to investigate the effects of wind on the performance of solar collectors placed on roofs, by measuring the velocity distributions over different locations of the same roof and translating the effect of these local velocity distributions numerically into convective heat losses. The common practice is to assume a uniform wind velocity, as measured at a reference location, over the whole roof area. However, the building configuration, the wind direction and the building surroundings highly affect the velocity distributions over the roof. This is expected to result in different convective heat losses, depending on the location of the collector, and therefore varying thermal performance.

Flat-plate solar collectors (Fig. 1) are mainly used for domestic hot water and space heating. They consist of an absorber plate that absorbs solar irradiation and turns it into heat, which is in turn passed to a circulating fluid inside the collector. Apart from the absorber, the rest of the collector is well insulated to prevent heat losses as much as possible. Since the absorber, which may or may not be glazed, is in direct contact with the environment, it constitutes the main factor of heat loss due to natural or wind-induced convection. More specifics on the solar collectors' features are given by Kalogirou (2004).

In the present study, the importance of using the actual velocity distributions corresponding to different locations on a roof, as opposed to a single reference velocity, is investigated experimentally and numerically. The effect of surrounding buildings has also been taken into account.

2. Aerodynamics of wind around buildings'

2.1. Wind around buildings

Fig. 2 shows a typical vortex formation for the basic case of perpendicular wind approaching an isolated rectangular "bluff body",

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http://dx.doi.org/10.1016/j.jweia.2016.12.008
Received 28 November 2016; Received in revised form 31 December 2016; Accepted 31 December 2016
0167-6105/

Fig. 1. Roof-mounted, flat-plate solar collector.

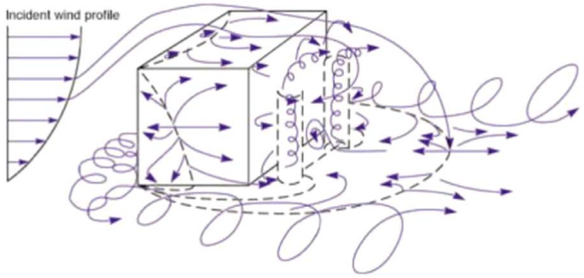

Fig. 2. Three dimensional wind flow around a rectangular body (Woo et al., 1977); modified.

in this case a building, as described in Woo et al. (1977). This is the most common case of air flow around a building, with air coming to a halt at the stagnation point and then being redirected to the edges of the building, where it separates. At the points of separation, the wind accelerates and flow recirculation areas of high turbulence/vorticity are formed. This basic case is described in detail in the wind engineering literature (Kim et al., 2003; Yakhot et al., 2006; Lim and Castro, 2009) and provides the fundamental case for experimental measurements.

However, this is rarely the case in real conditions, since the presence of nearby structures highly influences the flow distributions around the building of interest. Two common effects that nearby structures may cause are the down-washing effect and the channeling effect. In urban settings the flow fields around neighboring buildings interact, forming a very complex flow field.

2.2. *Wind-induced convective heat transfer coefficients (CHTC)*

The main cooling effect of wind on the collector is convective heat transfer occurring on the top side of the collector, which may be exposed or glazed. This convection can be either natural, for still or low velocity wind, or forced, for medium to high velocity wind.

The distribution of wind velocities over the roof area of a building is affected by various parameters such as the building shape, the direction of wind, wind speed, turbulence intensity and the presence of surrounding obstacles (Karava et al., 2011, 2012), and is in most cases non-uniform. In order to assess accurately the convective losses from a collector, the actual velocity distributions need to be known and, thus, the most appropriate location for a collector may be chosen.

Numerous studies have been performed in the past to establish a relationship for the wind induced heat transfer coefficient, h_w, and a reference wind velocity, V_{loc}, for flat plate solar collectors, including wind tunnel studies (Jürges,1924; Watmuff et al., 1977; Sparrow et al., 1979; Kind et al., 1983; Shakerin, 1987), full scale studies (Sturrock, 1971; Test et al., 1981; Kumar et al., 1997; Sharples and Charlesworth, 1998; Hagishima and Tanimoto, 2003; Kumar and Mullick, 2010), analytical studies (Sartori, 2006) and CFD (Emmel et al., 2007; Blocken et al., 2009; Montazeri et al., 2015; Defraeye et al., 2010; Liu et al., 2013). Palyvos (2008) and Mirsadeghi et al. (2013) have provided an extensive review of the wind-induced convective heat transfer coefficients. Fig. 3 presents several of these relationships for the wind induced heat transfer coefficient for 0° wind. The linearity between the local wind velocity and the wind-induced CHTC is apparent in almost all cases. However, there are considerable differences between the results of each study, posing a great difficulty in the choice of the appropriate correlation for each case and this is because wind induced CHTC are normally determined through experimentation due to their dependence on the factors stated above.

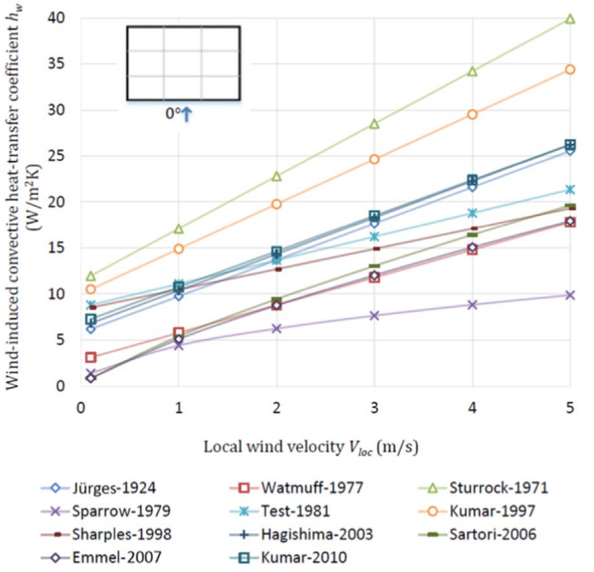

Fig. 3. Comparison of h_w correlations of cited studies for 0° wind.

In this study, h_w was calculated numerically, by applying the velocity distributions measured to one of the established analytical modes. The model chosen for the development of Eqs. (1)–(8) (Table 1), for a solar collector with a 45° tilt on top of a building and assuming south orientation, was that of Sharples and Charlesworth (1998), who provided correlations for various angles of incidence at intervals of 45°. Although these correlations were developed for a building with a pitched roof (35°), the results for 0° wind direction lie within the range of values of wind-driven CHTC for the same direction given by studies performed on flat roofs (Test et al., 1981; Kumar and Mullick, 2010; Hagishima and Tanimoto, 2003) and it is assumed that the behavior for the rest of the studied angles will be similar. Moreover, the study takes into consideration the natural convection phenomena that are dominant during low wind velocities. These regression equations are considered the most practical to adopt for the current

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

Wind incidence angle (deg)	Regression equations for h_w (W/m^{2}K)	
0	$2.2V_{loc}$+8.3	(1)
45	$2.6V_{loc}$+7.9	(2)
90	$3.3V_{loc}$+6.5	(3)
135	$2.2V_{loc}$+7.9	(4)
180	$1.3V_{loc}$+8.3	(5)
−135	$2.3V_{loc}$+7.8	(6)
−90	$2.2V_{loc}$+11.9	(7)
−45	$3.9V_{loc}$+6.0	(8)