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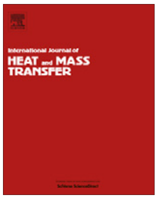

The influence of surface heating on the flow dynamics within a transpired air collector

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ABSTRACT

An experimental study was conducted to examine the air flow behavior in the channel of a transpired air collector under different heating conditions. Velocity fields were measured using Particle Image Velocimetry (PIV). Mean velocities and turbulent properties were computed and evaluated. Results show that at high flow rates, the flow was dominated by forced convection while at the lowest flow rate the flow was primarily buoyancy driven, where buoyancy-induced stabilities and heating effects were strongest. It was observed that the buoyancy-induced instabilities enhanced the magnitude and modified the structure of mean and turbulent properties as compared to the unheated flow. The flow rate influenced the relative magnitudes of the normalized mean and turbulent velocities that were enhanced with a decrease in the flow rate at a given heating condition. Collector efficiencies up to 70% were observed, which could be attributed to the corrugation surface geometry that enhanced turbulence and provided a larger heat transfer surface area.

1. Introduction

A recent estimate from the International Energy Agency (IEA) indicates that the global energy demand is expected to increase by 35% between the years 2008 and 2035 [1]. Due to the limited reserves of conventional fossil fuels and their harmful effects on the environment, it is crucial to explore renewable energy alternatives to meet this growing energy demand. The IEA has also projected that more than 13% of the increase in energy demand over this period is expected to be provided by renewable energy sources [1]. In cold climates like Canada, heating requires a significant portion of the total energy demand. According to Natural Resources Canada (NRCAN), as of 2008 the average commercial building consumes about 50% of its total heating requirement on space heating, which is primarily supplied through fossil fuels. Therefore, there is a need to develop efficient and cost effective renewable energy systems for building heating applications. One emerging technology is the transpired solar air collector. It has a simple design concept that consists of a perforated, flat, or corrugated sheet metal installed in front of a building façade to create an approximately two-dimensional channel for ambient air to flow. Incident sunlight on the collector wall causes it to heat up; this heat is transferred to ambient air in the channel that is then drawn into the building Heating Ventilation and Air Conditioning (HVAC) system to reduce the total load required to heat the supply air.

Solar air collectors of different geometries have been studied experimentally and numerically. Most of these studies were focused on the investigation of the thermal performance of flat plate solar air collectors with different configurations at various flow rates and solar irradiance to estimate the overall system efficiency [2–10]. These studies concluded that the overall performance was strongly dependent on many system variables including collector material [11], perforation size and spacing [2,3], flow rate [12], wind speed [4], channel depth [13], and irradiation [5]. An asymmetry in the mean velocity profile across the channel has been reported [6–8], which was argued to enhance heat transfer [6]. There is also an agreement that the overall heat removal efficiency improves at higher flow rates [4,8,9]. These studies are all focused on evaluating the thermal performance of flat plate solar air collectors based on bulk parameters, which do not provide sufficient details on the underlying physical processes, which are essential for understanding the energy transfer efficiency of the system. The only experiment for corrugated plates was conducted by Gawlik [14] and this research was focused on the flow separation phenomena with sinusoidal shaped geometry.

Although there have been several studies describing the flow over a heated flat wall from the fundamental perspective, the flow dynamics and hence the associated heat transfer in the transpired air collector with a corrugated waveform is more complex than that over a flat surface. There are some studies describing the flow

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behavior over a wavy wall however, they were conducted in the absence of wall heating. To the best of authors' knowledge there is no reported investigation of the flow behavior in a channel with heating from a wavy wall. As the present study is focused on investigating the flow behavior over a heated corrugation waveform, the literature review is split into two components: turbulent flows over wavy surfaces and channel flows over a heated surface.

Several studies investigated the turbulent flow over smooth wavy surfaces in a 2D channel [15–20]. A common observation in all these studies was that the mean velocity profile was asymmetric with the peak velocity shifted away from the center towards the opposite flat wall. Another common observation was the enhancement of turbulent properties in the trough region due to the flow separation off the crest. The flow reattachment point was observed to vary non-monotonically with Reynolds number on the windward side of each wave [15]. The peak production of turbulent kinetic energy occurred above the trough at a distance equal to the wave height [16,17].

In a 2D channel over a square waveform, a similar velocity profile was observed as flows over a sinusoidal surface. The momentum exchange between the local and bulk flows was seen to increase with both wavelength and Reynolds number. Maximum turbulent kinetic energies were observed above the reattachment point on the windward corner of the square wave [21,22].

Significant work has been done on forced and natural convection in differentially heated channels. It has been observed that the peak mean velocity shifted towards the heated wall [23–25], which is consistent with that observed in flat plate solar air collectors [7,8]. The wall heating induces buoyancy driven secondary flow which increases mixing and thereby enhances the heat transfer to the fluid near the heated wall. For channel flow with one side wall heated and the opposite wall cooled, there is agreement that heat transfer is increased for large Grashof numbers [23,26] where natural convection is the dominant mode of heat transfer. Radiation generated from the surface of the heated wall creates thermal instability between the fluid and the top and bottom channel walls and enhances heat transfer [26]. After the flow reaches its maximum kinetic energy ratio, it gradually decreases as the temperature of the flow grows and buoyancy forces decrease. The heat generated from the side walls rises and accumulates in the top of the channel creating a stratification that dampens the buoyancy [23]. A numerical study was conducted of a 2D vertical cavity with one heated side wall with buoyancy driven flow. Emitted radiation from the heated wall increases the temperature of the opposite insulated surface for laminar and turbulent buoyancy driven flows, but this only visibly affects the flow at laminar Reynolds numbers with the existence of two peak streamwise velocities near the boundaries [27]. Yilmaz and Fraser [28] conducted a numerical and experimental investigation of mean velocities and turbulent kinetic energies in a vertical channel with one wall at constant temperature. Numerical and experimental results showed that the maximum mean velocity shifted towards the heated wall as the flow developed downstream. The turbulent kinetic energy profile was very erratic towards the inlet of the channel. The maximum magnitude decreased rapidly from the inlet and then steadily increased to the end of the channel. The location of the maximum turbulent kinetic energy however shifted from the unheated wall at the inlet to the heated wall halfway down the channel, and then gradually moved to the core of the flow. Gajusingh and Siddiqui [25] studied the impact of wall heating on the initially turbulent and laminar channel flows. They reported that the addition of heat transitions a laminar flow into turbulent due to the buoyancy-induced turbulence. Conversely, in an initially turbulent flow, the addition of heat reduces the magnitude of turbulent properties due to the dampening of shear-produced turbulence as it interacts with the buoyancy forces.

As the literature review shows, there is a scarcity of studies investigating the influence of a heated waveform and the associated flow structure on convection. For the corrugated geometry of the transpired air collector considered in the present study, there are some studies that investigated its bulk thermal performance in practical applications [14,29]. Belusko et al. [29] predicted the thermal efficiency increase of jet impingement on the channel flow moving parallel to the corrugations in a perforated corrugated air collector. The study showed that the additional pressure loss required to produce an air jet through the perforations into the channel, is a small factor for an increase in thermal performance. They also commented that it was necessary to determine the flow distribution in the air channel for local convection coefficients. Gogakis [30] conducted experiments on the commercial corrugated transpired air collector in the field with the collector corrugations mounted parallel with the air flow. The collector and air temperatures were measured to calculate heat exchanger efficiency between the panel and the bulk air, and total energy savings. General results showed an increase in efficiency with air flow rate and incident irradiance with a maximum heat exchanger efficiency of 21%.

These studies have shown the promising potential of corrugated transpired air collectors, however there is no detailed study on the fundamental thermo-fluid interaction between the heated corrugation wall and airflow in the channel. Such understanding of these interactions and the flow characterization is vital to optimize the collector performance. We have recently conducted a detailed investigation of the flow structure in the corrugated transpired air collector to characterize the mean and turbulent flow behavior in the absence of wall heating [31]. The results have shown that the corrugation waveform significantly alters both the mean and turbulent flow fields in the collector channel. The flow was observed to be oscillatory with respect to the waveform throughout most of the channel length. Turbulent property profiles show the enhancement of turbulence around the height of one waveform, in particular over the trough sections [31]. Presented study is the continuation of this work with the focus on the influence of corrugation wall heating on the mean and turbulent flow fields in the collector channel. The presented results not only been applied to the implementation of transpired air collectors to optimize their performance, but also contribute to the understanding of the fundamental physical processes involved.

2. Experimental setup

A full scale transpired air collector system was built for experiments to be conducted in a laboratory environment. A residential construction wall was built with dimensions 1.83 m long, 1.22 m wide and 0.1 m deep, which was well insulated with R20 insulation and a vapor barrier. A 1.3 cm thick plywood board was fixed to the external face of the construction wall, and a 1 cm drywall was attached to the opposite face. A commercial corrugated and perforated solar collector made of 18 gauge sheet metal of size 1.83×1.22 m was used. The material and geometry of the collector was the same as that used in real transpired air collector applications [30]. The corrugation amplitude (h) and wavelength (λ) were 3.5 and 15 cm, respectively. The surface of the sheet metal has triangular shaped (1.4 mm amplitude) perforations spaced 2.2 cm apart from their center (approximately 1.5% porosity). This transpired collector was mounted across the construction wall to create a channel with the corrugation waveform normal to the flow direction. The height of the channel (H) was defined as the distance from the mean corrugation height to the construction wall, which was 10.95 cm. The length of the channel (L) was 1.83 m (see Fig. 1). The channel sides were sealed with Plexiglas sheets to allow