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Design of a Mobile Probe to Predict Convection Heat Transfer on BIPV (Building Integrated Photovoltaic) at UTS (University of Technology Sydney)

Jafar Madadnia

Faculty of Engineering and IT, UTS (University of Technology Sydney), Broadway, NSW 2007, Australia

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Abstract: In the absence of a simple technique to predict convection heat transfer on BIPV (building integrated photovoltaic) surfaces, a mobile probe with two thermocouples was designed. Thermal boundary layers on vertical flat surfaces of a PV (photovoltaic) and a metallic plate were traversed. The plate consisted of twelve heaters where heat flux and surface temperature were controlled and measured. Uniform heat flux condition was developed on the heaters to closely simulate non-uniform temperature distribution on vertical PV modules. The two thermocouples on the probe measured local air temperature and contact temperature with the wall surface. Experimental results were presented in the forms of local Nusselt numbers versus Rayleigh numbers "$Nu = a{\cdot}(Ra)^b$", and surface temperature versus dimensionless height ($T_s - T_\infty = c{\cdot}(z/h)^d$). The constant values for "a", "b", "c" and "d" were determined from the best curve-fitting to the power-law relation. The convection heat transfer predictions from the empirical correlations were found to be in consistent with those predictions made by a number of correlations published in the open literature. A simple technique is then proposed to employ two experimental data from the probe to refine empirical correlations as the operational conditions change. A flexible technique to update correlations is of prime significance requirement in thermal design and operation of BIPV modules. The work is in progress to further extend the correlation to predict the combined radiation and convection on inclined PVs and channels.

Key words: Natural convection heat transfer, PV, BIPV, experimental method, empirical correlations.

Nomenclature

z	Vertical distance from the base of the metallic plate and PV (m)
h	Overall vertical height of the metallic plate and the PV
T	Temperature (°C)
h	Convection heat transfer coefficient (W/(m^2·K))

1. Introduction

Building services and air conditioning consume up to 50% of total energy in buildings and produce a significant proportion of CO_2 in the atmosphere. In response, renewable energy technologies and PV (photovoltaic) modules was integrated in buildings [1-3]. Photovoltaic modules offer a promising solution, cogenerating clean local electricity and enhancing cooling and/or heating through natural or forced convection in buildings.

A conventional mono-crystalline silicon PV reflects back around 10% of the incoming solar (photonic), and converts into electricity up to 16%, and into low temperature thermal energy 74%. Application of low temperature heat in air-conditioning systems minimises entropy-rise and irreversibility in the heat transfer processes as outlined in Bejan [4].

Hirata and Tani [5] reported that, in the traditional first generation mono and poly-crystalline silicon PV modules, electricity-conversion efficiency of the PV drops with increase of surface temperature. It may suggest that, when a PV is exposed to solar radiation, its surface temperature, heat flux and conversion efficiency are not uniform.

Corresponding author: Jafar Madadnia, Ph.D., research fields: jet cutting, EHD, engineering education, thermal design and modeling. E-mail: Jafar.Madadnia@uts.edu.au.

Prediction of convection heat transfer from a PV is an important requirement in design and operation of BIPV (building integrated photovoltaic). This is especially urgent at the University of Technology Sydney, where PV modules are being integrated on the facade of new buildings. This paper serves to introduce a simple technique for engineers and researcher to estimate convection heat transfer from the PV system on their buildings.

The natural convection heat transfer and passive cooling have been researched experimentally, numerically and analytically during past few decades. The natural convection from a flat surface with UHF (uniform heat flux) or temperature distribution is investigated considerably and refined over the years. A number of empirical correlations are proposed for in air, water and mercury.

Saunders [6] was the first to study experimentally and theoretically natural convection in laminar and turbulent flows on an isothermal vertical plate in water and mercury. He expressed his results in a power-law form. McAdams [7] studied natural convection heat transfer for a vertical laminar flow in an isothermal surface. He covered Rayleigh number (Ra) for laminar flow in the range of $10^4 < Ra < 10^9$ and developed a correlation in the power law form for air, $Nu = 0.59Ra^{0.25}$.

Sparrow and Gregg [8] studied natural convection on a vertical surface with UHF and derived an exact solution for Prandtl numbers in the range of 0.1 to 100 and presented an expression for Nusselt number as a function of Prandtl number and Rayleigh number. Sparrow and Gregg [9] also studied natural convection in the laminar boundary layer over a vertical flat plate with two families of surface temperature variations, namely the power law and exponential. The power law distribution of $T_s - T_\infty = N \cdot Z^n$. The exponential distribution of $T_s - T_\infty = M \cdot e^{mz}$. They developed a correlation with 0.25 as the exponent for Gr or Pr. Their correlation in laminar convection air flows on non-isothermal surfaces can be fitted into a second order parabola form for air. $Nu/(Gr/4)^{0.25} = -0.09n^2 + 0.43n + 0.4$ for air $Pr = 0.7$, $R^2 = 0.965$. Their correlation is in power-law format $Nu = a \cdot (Ra)^{0.25}$, with $a = 0.462$ and 0.53 for an isothermal surface and an UHF surface, respectively with $Ra < 10^9$. Sparrow and Gregg [9] also studied effects of fluid-property in laminar free convection on an isothermal vertical flat plate. For a number of specific cases, they solved conservation equations for the boundary layers with variable-property situations. They used "reference temperatures" to extend the results derived for constant-property fluids to variable-property situations. For gases, the constant-property heat transfer results are generalized to the variable property situation by replacing β (expansion coefficient) by $1/T_\infty$ and evaluating the other properties at the reference temperature of $T_r = T_w - 0.38(T_w - T_\infty)$. They observed that, the film temperature can adequately serve as reference temperature for most engineering applications.

Vliet and Liu [10] experimentally studied natural convection in water on an UHF vertical surface and developed the local and the average correlations for laminar flow in the form of For local values: $Nu = 0.6(Ra)^{0.2}$ for $10^5 < Ra < 10^{13}$.

Natural convection in laminar flows over vertical plates or channels has been reviewed by Rohsenow, et al. [11] and Olsson [12]. Ménézo et al. [13] have recently developed a correlation for prediction of heat transfer on an electrically heated vertical flat surface in the form of the local Nusselt and Rayleigh numbers: $Nu_z = 0.16(Ra)^{0.256}$. The heater consisted of a thin metal foil (8 µm thick) of CuNi44 alloy.

Their results showed that, surface temperature increases up to 0.6 m and then remains almost constant for the rest of the 1.6 m height of the heater, with a small temperature-drop at the trailing edge. This may suggest that, correlations developed for isothermal surfaces can be used in iso-flux surfaces in certain conditions.

Shateyi [14] has recently studied radiation effects on natural convection over an isothermal, vertical, flat plate and concluded that the natural convection flow is appreciably influenced by thermal radiation [14]. He observed that, increasing the thermal radiation produced significant increases in the fluid temperature which consequently induced more fluid in the boundary layer through buoyancy effect, causing the velocity in the fluid there to increase.

The hydrodynamic boundary layer and thermal boundary layer thicknesses were observed to increase as a result of increasing radiation.

Shateyi [14] research may suggest that, convection heat transfer coefficient is higher in the boundary layer flows exposed to thermal radiation and consequently a new correlation need to be developed for a surface where convection and radiation heat transfer are coupled.

Mamun, et al. [15] investigated effects of heat generation on natural convection flow along and conduction inside a vertical flat plate. The interaction between the conduction inside and the buoyancy forced flow of fluid along a solid surface is termed as CHT (conjugate heat transfer) process. They argued that, the convection in the surrounding fluid significantly influences the conduction inside a wall. Accordingly, the conduction in the solid body and the convection in the fluid should be considered simultaneously when a correlation is developed.

Natural convection is widely used in the thermal control of many systems because of its cheapness, easy maintenance and reliability. The characteristics of natural convection in open enclosures similar to actual building façades have been studied. For this reason, several configurations with different boundary conditions are investigated [16-28].

Madadnia and Park [1] tested a PV in the UTS-laboratory and observed non-uniform distributions both for surface temperature and electricity-conversion efficiency.

The fore-mentioned empirical correlations experience discrepancies of up to 50% in the prediction of convection heat transfer coefficient as reviewed by Rohsenow, et al. [11] and Olsson [12]. The reviews showed that, the large number of correlations which are developed to predict convection heat transfer on different conditions, did not include BIPV. A simple technique based on local measurements is investigated here.

2. Description of the Problem

Prediction of convection heat transfer from a PV is important in design and operation of BIPV modules especially at UTS where PV modules are integrated into new buildings. Empirical correlations to predict convection heat transfer on a photovoltaic panel are very scarce, suggesting that, not much work has been done in this field. This paper serves to investigate viability of application of a mobile probe to predict surface temperature and heat transfer on photovoltaic modules.

3. Apparatus and Experimental Procedures

The PV apparatus is described in details in Madadnia and Park [1]. In brief, the vertical PV panel in Fig. 1b is the first generation PV module with polycrystalline silicon materials and known as the BP solar SX 20[1] which has thermal capacity of 903 kJ/(kg·K), emissivity of 0.8, absorptivity of 0.8, maximum nominal power output of 20 W, W = 0.5 m wide and h = 0.4 m height with a total surface area of 0.20 m^2. The dimensions of the PV module are 690 mm height and 294 mm wide, providing a total surface area of 0.203 m^2. Two top photos in Fig. 1a show the schematic layout (left) and a photographic view of the mobile probe (right) with two thermocouples at a fixed distance apart.

Fig. 1c shows the schematic layout of the associated experimental set up.

Fig. 2 shows a photographic view of 12 vertical stainless steel heaters with 12 embedded thermocouples with controllable heat flux and surface

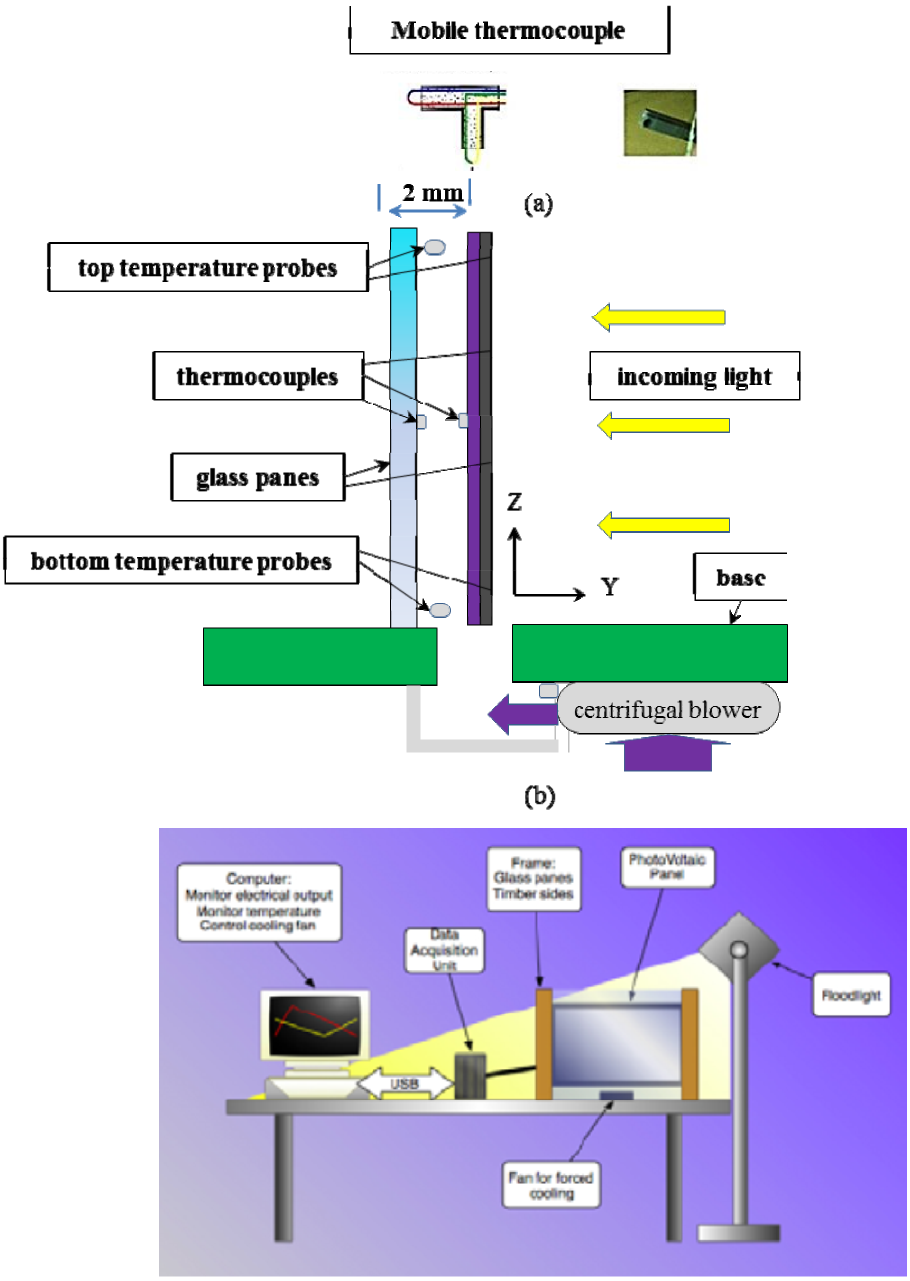
[1] http://www.solarpanelsaustralia.com.au/downloads/bpsolar_sx20-30.pdf.

temperature for each heater.

The apparatus is described in details by Zoubir, et al. [16]. In brief, each stainless steel plate is electrically heated by a constant current resistor and used in UHF conditions in air to evaluate the mobile probe.

The heated wall is roughly 600 mm high and 200 mm wide and located at the centre. The boundary condition in the plate is UHF on the heated walls (stainless steel plates) and adiabatic condition on the lateral walls.

Temperature and electrical heat flux for each heater are controlled and measured individually, so data from 12 thermocouples, 12 heat-flux meters from the 12 heaters, cold junction (to be added to thermocouple readings) and a platinum thermometer for room temperature were sampled one every 3 s.



(c)

Fig. 1 The schematic layouts of (a) a moile proximity probe with two thermocouples, (b) a BIPV with a single glazed photovoltaic and (c) the ecperimental set up with a PV-panel and a data acquisition unit interfaced to computer.

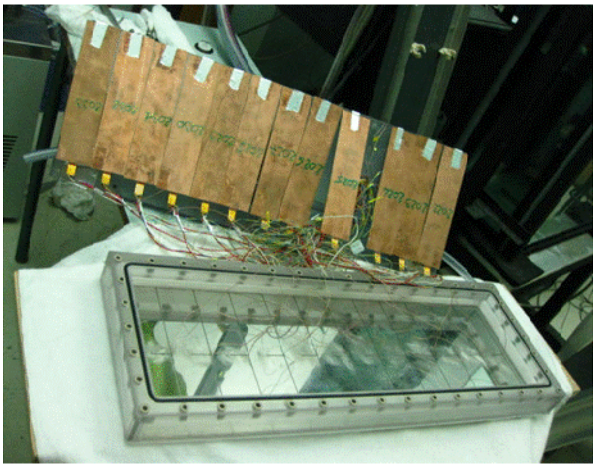


Fig. 2 A photographic view of the vertical plate with 12 electrical-heater.

The experimental apparatus in this project are considered as a simplified and scaled representation of a BIPV. In such cases, the vertical wall and the PV modules act as thermal sources, thus thermal boundary layer is formed by free convection, and surface temperature varies as boundary layer thickness increases.

A purpose-built mobile probe was designed as shown in Fig. 1a. It is a rectangular-shape probe with dimensions of 100 mm × 8.42 mm × 72 mm. There is a cylindrical convection hole of 3 mm in diameter tangent to the tip-surface of the probe. Two k-type thermocouples are positioned on the tip and in the hole, 2 mm apart, and connected to a LabView data-acquisition board via a long wire of 1 mm in diameter (model 818-0.015). Distance between thermocouples on the mobile probe remains fixed at 2 mm.

The probe inside the convection hole in the probe measures local air temperature (T_{air}) and the second thermocouple measures contact temperature (T_1) when probe is in contact with a wall. Steady state reading is selected from the thermocouple readings. The accuracy obtained after calibration and automatic correction of the cold junction is ±0.5 °C.

A series of experiments is carried out by traversing the probe in the thermal boundary layers formed over both the heater and the photovoltaic. The experiments on the heater was carried at a UHF of 25 W/m^2 and a room temperature of T_∞ = 20 °C.

The thermocouple on the tip of the probe was in complete contact with the wall surface during the span-wise traverse. Temperature and heat flux in each electric heater are measured using an embedded thermocouple and heat flux meter in the heater. Those primary measured quantities were used to quantify the local surface temperatures, convective heat transfer coefficients and dimensional-less parameters the local Nusselt number *Nu* and Rayleigh number *Ra*.

The uncertainty analysis, conducted according to the procedures described by Moffat [27], resulted in less than 0.5 °C for the thermocouples readings in the calibration range of 15-65 °C as compared with the pyrometer reading.

Fig. 3 shows the photographic view of an oscilloscope screen displaying the two thermocouples readings on the probe. Local air temperature and local contact temperature are shown in white and red respectively. Both thermocouples read the same ambient temperature (T_∞) before the contact is made with the wall surface (region "I"). A sharp increase in temperatures is noticed when the probe is inserted inside the thermal boundary layer and a contact is made with the hot surface (region "II"). Region "III" associated with cooling of thermocouples when probe is detached from the wall and moves out of the thermal boundary layer.

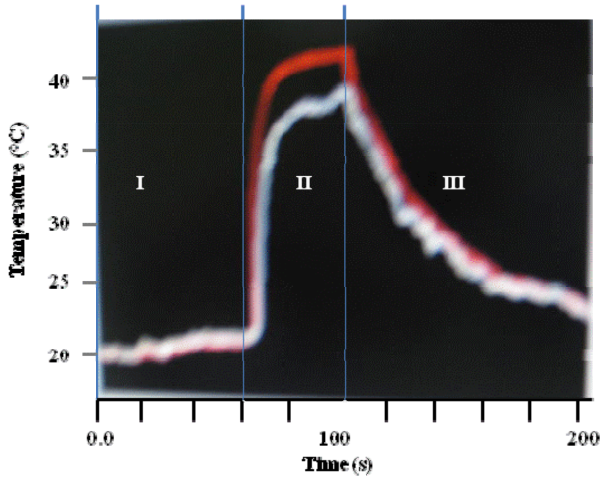


Fig. 3 Shows transient readings of thermocouples in the probe. Local air temperature (T_{air}) is shown in white and local contact temperature (T_1) is shown red.

The steady state condition is assumed when a change of less than 0.1 °C in thermocouple readings is noticed. Each complete cycle of reading starts and ends with steady state conditions. The steady state period is defined with a negligibly small rate of temperature change and transient conditions are the periods in which the probe experienced warming-up or cooling down.

4. Experimental Procedures and Results

Thermal boundary layers was traversed stream-wise by the probe at three span-wise directions (x/h = 0.0, 0.5, 1.0). The average values were used for further data-processing. The uniform heat flux of UHF = 20 W/m^2, and the ambient temperature of T_∞ = 20 °C were maintained during the experiments. Contact temperature (T_1) on the heater or PV and the local air temperature (T_{air}) were measured with the probe, while UHF and heater temperature were controlled and measured by the flux meter and the embedded thermocouples for each heater.

The sampling rate of one signal per 3 s per channel was used for the data acquisition system. Each traverse was repeated at three span-wise locations to confirm repeatability and two-dimensionality at steady state conditions and the average values were used.

Standard relations are used to determine the local convection heat transfer coefficient, the local Nusselt number and the Rayleigh number.

Fig. 4 shows stream-wise temperature distributions for surface and air temperature. The two thermocouples on the probe measured a contact temperature T_1 and local air temperature T_{air} at z = 2 mm. The true surface temperature of the wall is estimated with assuming $T_s = (2T_1 - T_{air})/2$. The estimated surface temperature is compared with the thermocouple reading embedded in the vertical heater highlighted as UHF. The experimental results are presented in terms of the average working temperature differences ($T_s - T_\infty$) along the dimension less vertical coordinate (z/h) where h is the height of the wall.

Temperature distributions from the three traverses were fitted to the power-law equation and the best curve-fits are shown in solid lines. Experimental results showed that at the upper values of (z/h) temperatures decreased mainly due to heat transfer from the tip of the wall. Trailing edge effect, it has also been reported by Ménézo, et al. [13] and Manca, et al. [28]. Fig. 4 also shows that, surface temperatures are converging at higher z/h. A suggestion is made to revisit and to refine the relation between the measured contact temperature (T_1) and the true surface temperature (T_s) in future analysis.

Experimental results from the heater-apparatus are used to plot Fig. 5 which shows variations of local Nusselt numbers (Nu) with Rayleigh (Ra) numbers in logarithmic coordinates. The solid lines represent the power-law fits ($Nu = a\cdot(Ra)^b$) to the experimental results and the empirical correlations:

- From the mobile probe: $Nu = 0.34(Ra)^{0.26}$, $R^2 = 0.98$;
- From the embedded probe: $Nu = 0.46x^{0.22}$, $R^2 = 0.99$;
- Empirical correlations for local values from open literature sources also plotted in solid line and listed here for comparison;
- From McAdams [7]: $Nu = 0.59(Ra)^{0.25}$;
- From Sparrow & Gregg [9]: $Nu = 0.53(Ra)^{0.25}$;
- From Vliet & Liu ([10]: $Nu = 0.6(Ra)^{0.2}$;
- From Fossa et al. [26]: $Nu = 0.16(Ra)^{0.256}$.

It is noted that, both empirical correlations from the probe and the embedded thermocouple on heater are within the range covered with McAdams [7], Sparrow & Gregg [9], Vliet & Liu [10] and Fossa et al. [26]. It means that, for a fixed Ra, Vliet & Liu [10], and Fossa et al. [26] have underestimated Nu and have predicted smaller values. While McAdams [7] and Sparrow & Gregg [9] have overestimated Nu and have predicted bigger values for Nu relative to the predicted Nu from the two correlations proposed in this paper. Considering the vast number of correlations, it is a reasonable validation for the probe and its viability.

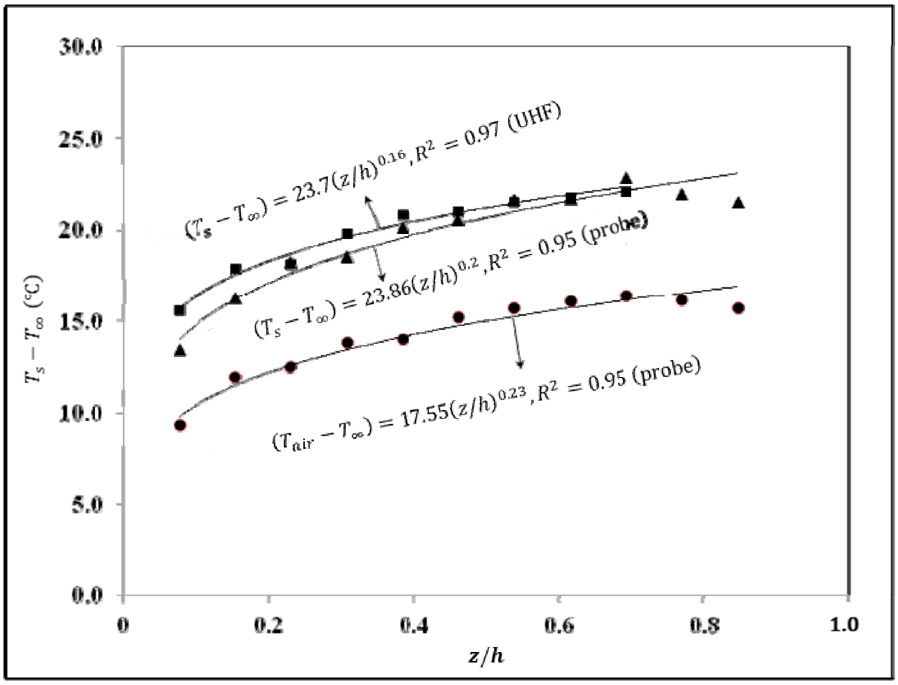


Fig. 4 Stream-wise temperature distributions on heater with UHF measured by mobile probe and the thermocouple embedded in the heater.

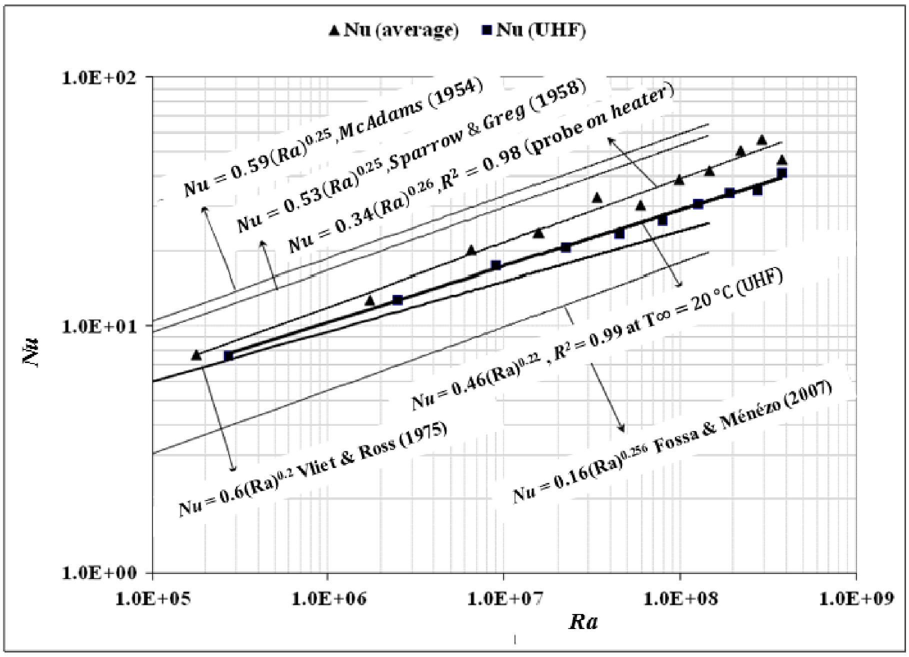


Fig. 5 Variations of local Nusselt number (*Nu*) with Rayleigh number (*Ra*), for measurements made on the heater with the best fits to $Nu = a \cdot (Ra)^b$.

Experiments were also carried out on the PV with its front surface was exposed to solar radiation. The laminar thermal boundary layers on the back surface of the PV was traversed stream-wise at three span-wise positions (0.0, 0.5, 1.0) using the probe test data at steady state conditions were used for further processing. Fig. 6 shows the average values of the local Nusselt number versus Rayleigh number in logarithmic coordinates. The best power-law-fits are shown in solid lines:

$$Nu = 0.385(Ra)^{0.2531}, R^2 = 0.98.$$

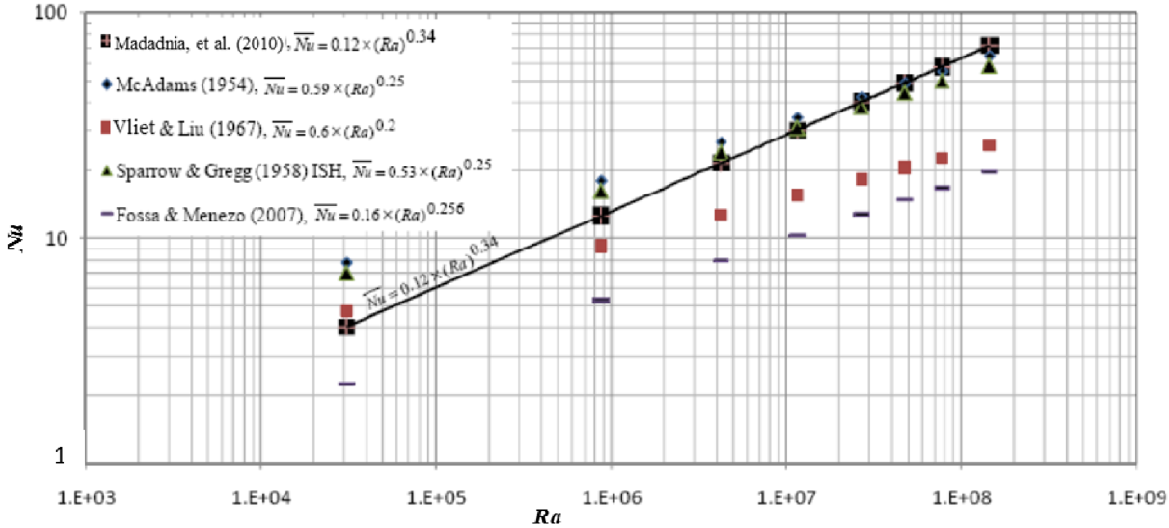


Fig. 6 Comparison of correlations: the average Nusselt number against Rayleigh number on a PV.

It is noticed that, the empirical correlations from the PV has also fallen between the correlations proposed by McAdams [7], Sparrow & Gregg [9], Vliet & Liu [10], and Fossa et al. [26]. The exponent in the power-law correlation is 0.2531 which is very close to 0.25 in the correlations recommended by McAdams [7], Sparrow & Gregg [9] and Fossa et al. [26], which may suggest a universal slop for all natural convections.

5. Concluding Comments

The majority of current renewable research is focused on understanding and modeling of existing systems and development of design codes. However, multitasking and multiple applications of BIPV modules at a ever changing environment require real time evaluation and prediction of performance with accessing to local data. Empirical correlations need to be refined and updated as the environmental conditions change and a agile BIPV need to be designed to reshape itself as thermal parameters change.

The operational condition of a PV is unpredictable due to uncertainty in prediction of surface temperature, heat flux and electric-conversion-efficiency. Convection on PV modules is coupled with radiation and conduction. The steady-state condition in a PV is difficult to achieve as ambient conditions and solar radiation vary all the time. Temperature and heat flux on the PV are rarely predictable in the design or operational stage of BIPV. Published correlations with large discrepancies cannot be used to predict thermal performance of a PV. Published correlations are also found to be sensitive to the coupling of convection, to the test conditions, to the experimental apparatus used, to the ambient conditions, temperature and thermophysical properties. A flexible technique to refine the required correlation using the local test data is a necessity. We envision a design process for BIPV in which operational conditions are integrated continuously in design and performance of the system.

Thermal boundary layers formed on a flat vertical both heater and Photovoltaic were traversed the mobile probe designed at this project. Only thermal boundary layers in the laminar range $Ra < 1.1 \times 10^8$ were investigated. It was noted that, the probe overestimated surface temperature at the leading edge of the heater by less than 10%. The accuracy improved at closer to the trailing edge of the heater. The discrepancy is mainly attributed to the assumption made to evaluate surface temperature from the contact temperature, thus suggesting a refined assumption in future works.

Empirical correlations in the power-law format of $Nu = a \cdot (Ra)^b$ have been curve-fitted to the experimental results satisfactorily. The prediction of convection heat transfer *Nu* from the correlations is in agreement with the corresponding correlations proposed in the open literature.

Only two test data from the probe are needed to determine the constant values of "*a*" and "*b*" and to develop a correlation from a wall. This simple technique is very practical in thermal design of BIPV modules.

Finally, it may be concluded that, this paper has proposed to update the convection heat transfer correlations using two local measurements of the probe. Universal correction in the power-law format is viable. An updated correlation then can predict thermal performance using two local test results. The work is in progress to further extend the correlation to predict the combined radiation and convection on all PV configurations, as required in the efficient design of BIPV systems.

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