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THERMAL MODELING AND DESIGN OPTIMISATION OF COMPACT BUIILDING INTEGRATED PHOTOVOLTAIC (BIPV) FAÇADES FOR APPLICAQTION AT THE UNIVERSITY OF TECHNOLOGY SYDNEY (UTS)

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KEYWORDS

Building Integrated Photovoltaic (BIPV), Multitask Sustainable University Building & Energy Efficiency

ABSTRACT

Thermal models and correlations for the convection heat transfer coefficients are mainly for isothermal or constant heat flux surfaces and can result in discrepancies of up to 50% in the prediction of surface temperatures or heat fluxes on Photovoltaic (PV) panels. An experimental investigation was conducted to develop the thermal models and correlations for natural convection on a vertical PV module with non-isothermal surfaces. The paper also reports on the PV-configuration with the maximum electric efficiency and natural convection cooling.

A proximity mobile probe with two K-type thermocouples was developed to measure simultaneously local surface and air temperatures on the PV surface at a fixed distance. Thermocouples, anemometers, voltmeter, ampere-meter and Lux-meter were interfaced to a computer and sampled at a rate of 6 samples per minute (one every 10 second). The electric energy conversion efficiency and the natural convection cooling were quantified for the dimensionless channel spacing of s/h=0.015, 0.0.3, 0.045, 0.06 and 0.075 on a PV with a single glazing. An optimum configuration for a PV with single-glazing and the channel spacing of s/h=0.06 was selected for its maximum efficiency and natural convection cooling and proposed to be retrofitted on the existing UTS buildings.

INTRODUCTION

The application of multitasked renewable energy technologies has resulted in the economical operation of buildings as an intelligent electro-thermal system with reduced carbon footprint. Photovoltaic modules are integrated into the façade of high rise buildings to combine energy generation in the PV modules with the functional features required of a building envelope [1].

BIPV modules are designed to aesthetically improve the look of the building, sunshade cladding, and control noise, by replacing non-load-bearing external walls. Material and space requirements of BIPV facades are optimized to further improve their economic, environmental and social benefits. However, there still exist a number of challenges for a complete integration of a PV in buildings including PV poor design and reduced efficiency at higher surface temperatures. To address those challenges, refined thermal models and correlations need to be used in the PV design and the channel spacing can be varied to achieve optimum electric conversion efficiency.

Studies conducted by Menezo et al [2], Chow et al [3], Liao et al [4], Prasad and Snow [5], Wong et al [6] and Bloem[7] have focused on optimization of PV-length, facade glazing and spacing within façade skins and free and forced convection cooling. Fung, and Yang [8] studied performance of semi-transparent BIPV modules using a one-dimensional transient heat transfer model. Masseck [9] reported on the applications of a multifunctional transparent double-glazed façade which operated as intelligent natural ventilation between the inner air-conditioned office space and the exterior environment. He used thermodynamic simulation tools to define the right combination of design factors including materials, natural ventilation and architectonical quality. University of Technology Sydney (UTS) as a member of Australian Technical Network (ATN) Universities has committed to the policies and practices which reduce carbon footprint. The present work is developed in collaboration between UTS academics, students, technical and support staff in the Heat transfer, Energy Conversion, and Design subjects to proactively research on energy efficiency technologies in the UTS buildings in accordance to the UTS Ecologically Sustainable Development (ESD) Masterplan [10]. The desire for a sustainable new millennium in the context of rapid global change has also prompted rethinking by the university community about how the University can act as a catalyst for sustainable engineering. The author has developed a project-based energy engineering subject, entitled "Energy Conversion" where students demonstrate the quality of their learning on the application of techniques to further improve energy efficiency in the university buildings and equipment [11]. The idea of using the University's energy-efficient building or their innovative elements in engineering education are also reported by Stephen et al [12] who used the building's structure and equipment to provide a project-based learning environment for their students.

A closely relevant to the current work is the experimental work conducted by Menezo et al [2], who studied the effect of the channel spacing on the thermal performance of a series 20 vertical rectangular film heaters cooled by natural convection of air. The heater consisted of a thin metal foil (8µm thick) of CuNi44 alloy. The heating configuration can be varied and heat flux ranged from 75 to 200 W/m^2. Their results in terms of surface temperatures show no significant change when the spacing increased from 30mm to 50 mm, and the heat flux from 75 to 200 W/m^2. However, surface temperatures decreased significantly by natural convection cooling when the spacing was increased from 50mm to 160 mm. They also noticed that the convection heat transfer coefficient was higher for non-colliding boundary layers at the first 40 mm of the entry region. The current work extended the work done by Menezo et al [2] for a narrower spacing up to 30mm on a real PV. They increased module thickness from 6mm to 24mm and noticed that heat gain dropped from 210 kWh/m^2 to 150 kWh/m^2 at a constant energy conversion efficiency of 16% for the solar cell. They also reported the efficiency decreased from 18% to 6% with 4.56% increase in heat gain from 204.8 kWh/m^2 to 24.6 kWh/m^2. However, they attributed this effect to the structure of the BIPV module and concluded that some parameters of the solar cell such as its efficiency do not affect the heat gain significantly. Hirata and Tani [13] reported that the gradient for the electrical efficiency of the first generation PV modules with poly-crystalline silicon against the surface temperature was -0.5 %/°C.

PROBLEM DESCRIPTION

At present thermal models of BIPV are based on correlations developed on isothermal or isoflux surfaces. While operational conditions on a BIPV surfaces are not normally isothermal or isoflux. This paper reports on the experimental studies conducted on thermal modeling and optimization of a BIPV with a narrow channel spacing between the PV and a single glass layer (Figure 1). The mail goal is to find the optimum channel spacing in a BIPV to achieve the maximum electric conversion efficiency and to recover as much thermal energy as possible. Radiation, natural convection in the front-side will be determined in parallel with radiation and conduction or natural convection or mixed convection in the channel side.

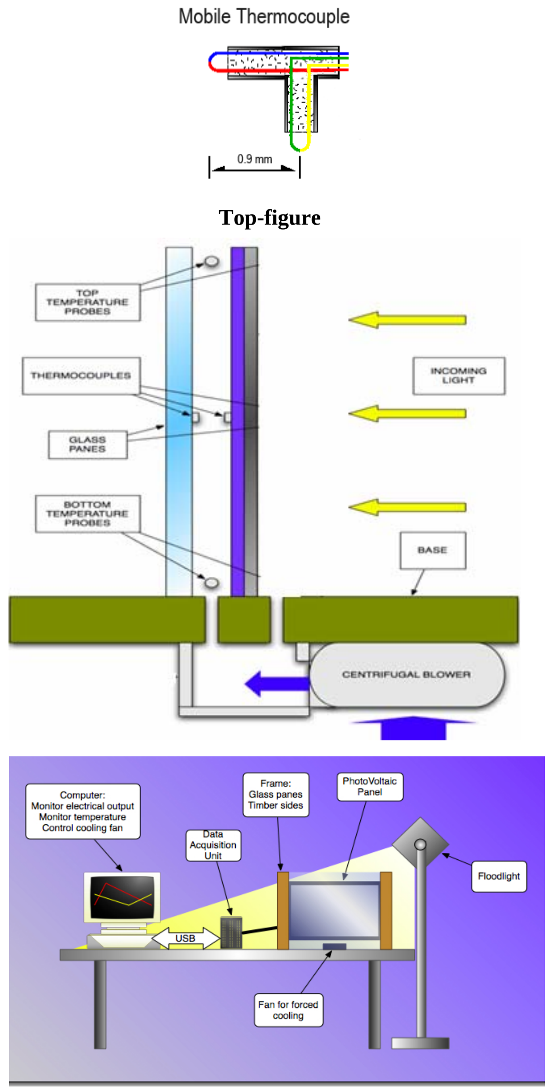

Figure 1: The schematic layouts of a) a mobile proximity probe with two thermocouples (Top), b) a BIPV with a single glazed photovoltaic (Middle), and c) the experimental set up (bottom).

EXPERIMENTAL APPARATUS

A schematic layout of the experimental rig built at the University of Technology Sydney (UTS) is shown in Figure 1 (middle). The rig consists of a vertical PV panel separated by a channel spacing of "s" from a single glass layer. The panel is the first generation PV module with mono and poly-crystalline materials and known as the BP solar SX 20 which has the maximum nominal power output of 20W and dimensions of w=0.5m wide and h=0.4m height with a total surface area of 0.20 m^2. The figure 1 also shows the associated data acquisition (UE-9) manufactured by Labjack Corp (bottom).

Figure 1(top) shows the schematic layout of a mobile probe built with two k-type thermocouples of 0.13 mm wire diameter to measure surface temperature and air temperature at a very close proximity of the PV-surface, enabling to quantify the convection heat transfer coefficient and to develop correlations for natural, mixed or forced convection on the vertical BIPV. Standard k-type thermocouples both on the mobile probe and fixed on the surface were employed for measuring surface and air temperatures on the PV panel. A series of k-type thermocouples were fixed on the front of the panel at x/h= 0, 0.5, 1.0 and also at x/h=0.5 on the back of the panel. The fixed thermocouples were also used to measure air temperatures at x/h=0 and 1.0 close to the PV front surface. All measurements were performed at the center line of the PV surfaces. The thermocouples were individually shielded and calibrated against GMBH-17090 with accuracy of ±0.4°C [12]. An IC amplifier (AD595) was used for reference junction compensation and signal amplification from the thermocouples. EI-1022 temperature probes, manufactured by Electronic Innovation Corp were used to measure air temperatures in the range of -40°C to 100°C. The voltage rating of 3.5V to 4.5V was developed for the data acquisition system, using a voltage divider with a combination of wire-wound resistors.

An Halogen lamp (500W) was used as a light source with a single wavelength. The corresponding input irradiation energy to the PV panel was measured using a SK2650-Pyranometer and Lutron LM-8000 with a conversion factor of 0.015 W/Lux*m^2. The device calibration was performed by SKYE Instrument. In the current work, an average irradiation of 14,643 Lux was obtained on the PV with a standard deviation of 7.7%. This radiation is lower than the average daily solar irradiation at Sydney which varies from 32,000 Lux in the winter to 100,000 Lux in the summer. The area-averaged irradiance was therefore 220 W/m^2. The input power is then determined to be 44 W for the panel area of 0.2 m^2. The coefficient was also determined experimentally from measuring heat rates on the PV.

The channel spacing of s=6mm, 12mm, 18mm, 24mm and 30 mm were tested and dimensionless heat transfer rate by radiation, convection and electric energy (η) were optimized against the dimensionless spacing (s/h). The local convection heat transfer coefficient (h), the Nusselt number (Nu), the Rayleigh (Ra), and heat transfer rates by convection and radiation on the PV were all determined.

EXPERIMENTAL PROCEDURES AND RESULTS

The following standard test conditions as described in IEC 61215 [15], were used to evaluate the performance of the PV panel. Laboratory temperature: 25°C, Irradiance: ≤ 1000 W/m^2, Vertical Tilt angle (90 degrees): Irradiation normal to the PV panel.

A number of experiments were carried out to confirm the repeatability of the test results. For the channel spacing of s/h=0.015, 0.0.3, 0.045 , 0.06 and 0.075 each experiment was conducted for approximately 6000 seconds with the sampling rate of 6 per minute per channel for the data acquisition system and repeated at least three times. The transient condition was continued until the steady state condition was achieved with a negligibly snall rate of temperature change ($\Delta T/\Delta t$ < 0.1 K/sec). At the steady state conditions, the radiation energy is converted into both the electrical energy and the natural convection from the PV. The project is aimed to maximise at the PV the absorbed radiation energy, the electric energy and the natural convection cooling. The surface temperatures decreased when the light was switched-off and the stored thermal energy was released to surrounding by the natural convection cooling. Figure 2 shows that the maximum surface temperature occurred at the back of the PV where its electronic-board is situated.

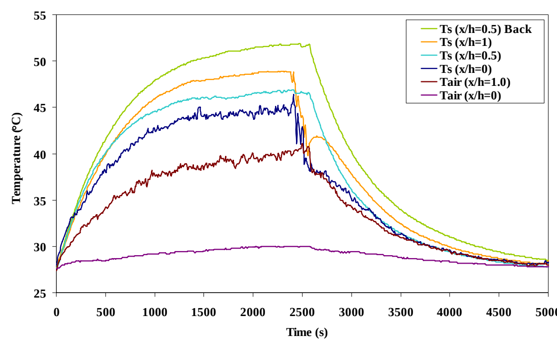

Figure 2: Typical temperature distributions on a PV (SGNF) for the channel spacing of (s/h=0.06) as a function of time.

The surface temperatures air temperatures from the fixed thermocouples are shown as a function of time (s) in Figure 2. All six fixed thermocouples recorded higher temperatures when the light was switched-on and the corresponding radiation energy was stored in the PV-panel. This transient condition was continued until the steady state condition.

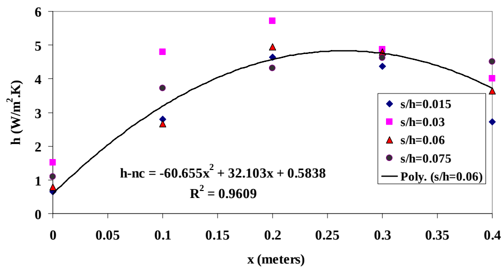

Figure 3: The natural convection heat transfer coefficient on the PV surface as a function of vertical distance (x) for the channel spacing of (s/h=0.015, 0.03, 0.06, and 0.075).

Figure 3 shows the local heat transfer coefficient as a function of the vertical distance from the base. Local surface temperature (Ts) and local air temperature (Tair) were measured by the mobile probe using the two thermocouples at a fixed gap of Δy=0.9mm. The local convection heat transfer was quantified at the measuring location on the PV using the following relation;

$$h_{-nc}\ (W/m^2.K) = ((T_s - T_{air}) * K_{air}) / (\Delta y * (T_s - T_{lab})) \quad (1)$$

The natural local convection heat transfer coefficient as a function of the vertical distance (x) in meter is presented as;

$$h_{-nc}\ (W/m^2.K) = -60.66 * x^2 + 32.1 * x + 0.58 \qquad R^2 = 0.96 \quad (2)$$

The maximum convection occurred at x = 0.25m. The corresponding correlation for natural convection on a vertical PV with laminar flow was determined as

$$Nu_{-nc} = 0.52\ Ra^{0.449},\ \text{with } R^2 = 0.92 \quad (3)$$

This correlation results up to 30% higher values for the natural convection heat transfer coefficient than the correlation suggested by McAdams [16] for the natural convection on an isothermal surface for laminar flows and Rayleigh numbers of $10^4 < Ra < 10^9$.

Figure 4 shows the electric energy conversion efficiency (η) of the PV with s/h=0.06 decreased as the surface temperature increased. Figure 4 also shows the curve fit to the experimental data for efficiency as a function of the temperature and the degree of discrepancy in the experiment.

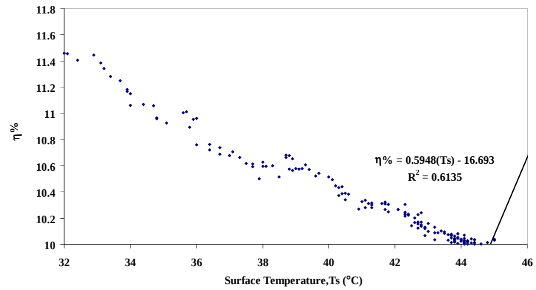

Figure 4: Electric energy conversion efficiency (η) of a PV with s/h=0.06 as a function of the surface temperature at the back of the PV.

Figure 5 shows the dimensionless natural convection heat rate from both surfaces of the PV as a function of spacing (s/h). Thermal boundary layer thickness (δ) at x=h was determined to be thicker than the largest channel spacing (s).

$$\left[\delta = 6 * x * \left(\frac{Gr}{4}\right)^{-0.025}\right] = 0.0366\ m > s = 0.03\ m \quad (4)$$

Therefore, the back surface of the PV was cooled by the internal natural convection cooling in the channel, while the front surface was cooled by the external natural convection. Heat transfer rate by natural convection between an isoflux vertical PV (the back surface) and a parallel adiabatic glass plate was determined using the Nusselt number correlations obtained by Bar-Cohen and Rohsenow [17] and added to the heat transfer by the natural convection on the front surface of the PV and shown in Figure 5 as a dimensionless ratio ($q°_{-conv}/q°_{-tot}$) as a function of dimensionless spacing (s/h). Figure 5 shows that natural convection is constant (0.036) in the front surface of the PV, and increases to (0.6) as (s/h) increased from 0.015 to 0.075. It indicated that the natural convection was promoted with increase of the channel spacing in consistent with the results of Menezo et al [2] for higher values of s/h, and the theory natural convection in the vertical channels [16]. It is clear that natural convection cooling is affected by the channel spacing on the back surface of the PV in the channel.

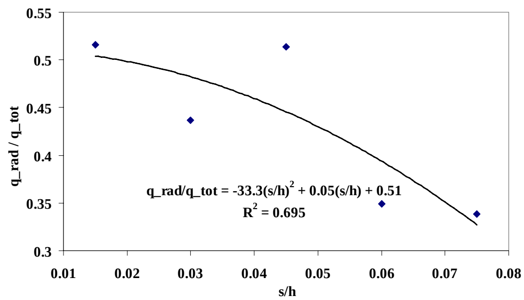

Figure 5: Dimensionless convection heat transfer ratio for a PV at the steady state conditions as a function of the spacing s/h.

Figure 6 shows the dimensionless radiation transfer ratio from both surfaces of the PV as a function of the spacing (s/h). The radiation heat loss ratio ($q°_{-rad}/q°_{-tot}$) decreased from 0.53 at s/h=0.015 to 0.33 at s/h=0.075 mainly due to increase of the natural convection cooling with s/h. Spacing only affect the radiation rate in the back surface.

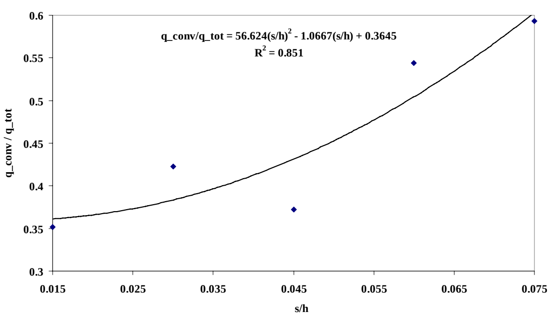

Figure 6: Dimensionless radiation heat loss from a PV for s/h=0.015, 0.03, 0.045, 0.060, 0.075.

Figure 7 shows the electric conversion efficiency (η) of the PV panels as a function of the dimensionless channel spacing (s/h). The effects of spacing on efficiency is seen to be non linear the following relation can be fitted to the results with a resolution of $R^2 = 0.96$.

$$\eta\ \% = -37.65(s/h)^2 + 3.1(s/h) + 0.05 \qquad (5)$$

Figure 7 also shows that a higher value of η = 10.65% is obtained between s/h= 0.03 to 0.06 with variations within ±0.3% and lower values of η = 8.7% and 6.7% were obtained at s/h = 0.015 and 0.075 respectively. It seems that the electric energy conversion efficiency (η) reached to its maximum at s/h=0.03 to 0.06 for an optimum value of cooling by both natural convection and radiation. However, the electric efficiency (η) was lower at the spacing of s/h=0.015 due to higher both surface temperatures and radiation. The electric efficiency (η) was also lower at the spacing of s/h=0.075 due to a higher natural cooling and lower radiation rate.

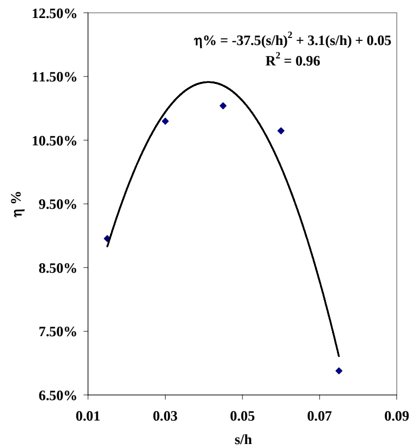

Figure 7: Electric energy conversion efficiency (η) of a PV at the steady state conditions for s/h=0.015, 0.03, 0.045, 0.060, 0.075

ANALYSIS AND DISCUSSION

A series of tests were performed out by changing the channel spacing s/h=0.015, 0.0.3, 0.045, 0.06 and 0.075 at a fixed radiation input and repeated three times for repeatability check-ups. It was noticed that the PV panel experience a combination of conduction, natural convection, and radiation heat losses. The rate and the mode of heat transfer from a PV panel depend on many factors including the Rayleigh (Ra), Reynolds (Re), the Prandtl number (Pr), flow conditions (laminar, transition or turbulent), PV-geometry, channel configuration and spacing, and operating conditions. Conduction heat losses were considered for channel flows with Rayleigh number (Ra) less than 2000. Natural convection heat losses were considered for the laminar flows with Ra less than 10^9. Forced convection heat losses were considered negligible at $Gr/Re^2 << 0.1$.

Natural convection heat losses ($q°_{nc}/q°_{tot}$) increased directly with s/h and contributed up to 60% of the total cooling. The total heat loss on the PV was calculated from summing-up all the heat losses from the PV by conduction, convection and radiation. The calculated total heat loss was used to determine the dimensionless ratio. This value was found to be in average 67% of the total irradiation (16441 Lux) from a mono-wavelength light source with a conversion factor of (0.015 $W/Lux*m^2$). The difference may correspond to errors in the assumptions made on the mono-wave length radiation from the light source.

Finally, it was decided to recommend a single-glazed BIPV panel with s/h=0.06 to be retrofitted at UTS buildings.

CONCLUSION

An improved correlation was developed for the natural convection heat transfer coefficient on a real PV with a reasonable prediction of the natural convection heat transfer. It is concluded that the single-glazed BIPV systems performed with a higher electric energy conversion efficiency and natural convection cooling at s/h=0.03-0.06 and the spacing of s/h=0.06 was recommended for a higher natural convection cooling to be retrofitted to existing buildings at UTS.

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NOMENCLATURE

x vertical distance from the base of the PV (m)
h vertical height of the PV (0.4m)
w horizontal width of the PV (0.5m)
s horizontal spacing between a PV and its glazing (mm)
T temperature (°C)
k thermal conductivity of air (W/m.K)
h convection heat transfer coefficient (W/m^2K)
q° heat transfer rate (W)
η% electric energy conversion efficiency

SUBSCRIPTS

nc natural convection
conv convection
rad radiation heat transfer
tot total heat transfer

REFERENCE

[1] Madadnia, J, and Park, H.M, 2009 " Design Of Compact BIPV Façades For The Buildings At The University Of Technology Sydney (UTS)", Proceedings of The ASME 2009 Heat Transfer Summer Conference HT2009, July 19-23, 2009, San Francisco, California USA.

[2] Menezo, C. Fossa, M. and Leonardi, E. 2007, 'An experimental investigation of free cooling by natural convection of vertical surfaces for building integrated photovoltaic (BIPV) applications", Experimental Thermal and Fluid Science, Vol. **32**, Issue 4, pp. 980 – 990

[3] Chow, T. T. Fong, K. F. He, W. Lin, Z. and Chan A. L. S. 2006, 'Performance evaluation of a PV ventilated window applying to office building of Hong Kong', Energy and Buildings, Vol. **39**, Issue 6, pp. 643 – 650

[4] Liao, L, Athienitis, A. K. Candanedo, L. Park, K. W. Poissant, Y. and Collins, M. 2007, 'Numerical and experimental study of heat transfer in BIPV-Thermal System', Journal of Solar Energy Engineering, Vol. **129**, Issue 4, pp. 423 – 430

[5] Prasad, D and Snow, M. 2005, 'Designing with solar power: a source book for building integrated photovoltaic', Mulgrave, Vic.: Images Publishing Group

[6] Wong, P.W. Shimoda, Y. Nonaka, M. Inoue, M. and Mizuno, M. 2007, "Semi-transparent PV: Thermal performance, power generation, daylight modeling and energy saving potential in a residential application, Renewable Energy, Vol. **33**, pp. 1024-1036

[7] Bloem, J. J. 2008, 'Evaluation of a PV-integrated building application in a well-controlled outdoor test environment', Building and Environment, Vol. **43**, Issue 2, pp. 205 – 216

[8] Fung, T.Y.Y., and Yang, H. 2007, "Study On Thermal Performance of Semi-transparent building-integrated photovoltaic glazings", Energy & Building, doi:10.1016/j.enbuild.2007.03.002, [www.elsevier.com/locate/enbuild]

[9] Masseck, T. 2005, "Transparent Amorphous Silicon PV-Facade as Part of an Integrated Concept for the Energetic Rehabilitation of an office building in Barcelona" 20th European Photovoltaic Solar Energy Conference, 6-10 June 2005, Barcelona, Spain

[10] UTS Website On Green Energy http://www.green.uts.edu.au/for/students/student-sustainability-projects.html

[11] Madadnia, J., Koosha, H., and McKenzie, J., 2001 "Development of a Learner-Focused, Sustainable-Engineering Subject" Australasian Journal of Engineering Education, Vol. **9,** No 2, pp. 179-193

[12] Stephen R., Lay D.A, McCowan, J.D, 2008" Using the Technology of University Buidings in Engineering Education", Int. J. Eng Ed. Vol. **24**, No. 3, pp. 521-528

[13] Hirata, Y., Tani, T., 1995, "Output variations of PV modules with environmental factors-I" Sol Energy; Vol. **55**, pp. 463-8

[14] ESIS, 2008, M17090 USB humidity & temperature sensor, http://www.esis.com.au/Sensors-ther/TempSensor-USB.htm

[15] International Electro-Technical commission, 61215, 2005, 'Summary of test levels according to IEC61215', http://www.arsenal.ac.at/downloads/pvst3.pdf

[16] McGraw-Hill, New York, 1954, chap.7

[17] Bar-Cohen, A.' and Rohsenow, W. M. 1984, J. Heat Transfer Vol. **106**, pp. 116

Proceedings of the 7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT2010)

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INTRODUCTION TO PROCEEDINGS

The purpose of most conferences in this field, including this one, is to provide a forum for specialists in heat transfer, fluid mechanics and thermodynamics from all corners of the globe to present the latest progress and developments in the field. This will not only allow the dissemination of the state of the art, but it will serve as a catalyst for discussions on future directions and priorities in the areas of heat transfer, fluid mechanics and thermodynamics. The additional purposes of this conference are to introduce Africa to the rest of the world and to initiate collaboration in research.

In 2002, the 1st International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT2002) was hosted in the Kruger National Park, South Africa. In 2003, the 2nd International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT2003) was hosted at the Victoria Falls, Zambia. The 2004 conference (HEFAT2004) was in Cape Town and the 4th conference (HEFAT2005) took place in Cairo, while the 5th conference (HEFAT2007) was in Sun City. The 6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT2008), was held in Pretoria, South Africa as part of the University of Pretoria's 100-year celebrations “A century in the service of knowledge”.

This year's conference, the 7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT2010), is held in Antalya, Turkey.

For this conference and proceedings, all papers were peer-reviewed by and approximately 360 papers were accepted. The review policy was that only original research papers that were recommended unconditionally by an independent reviewer who is a distinguished subject specialist in the field of the relevant paper were accepted.

A large number of papers were submitted, and I wish to express my sincere thanks to the reviewers whose generous efforts made it possible to select only papers of a high standard for publication in the proceedings.

The papers in these proceedings will be read in 64 parallel lecture sessions over a period of three days from 19 to 21 July 2010 during which ten keynote papers will be presented. The large number of scheduled presentations will no doubt contribute towards creating a meaningful forum for discussing the latest developments as well as for keeping abreast with the state of the art in heat transfer, fluid mechanics and thermodynamics.

Allow me to extend my sincere gratitude to the keynote speakers as well as participants for their invaluable written and oral contributions to HEFAT2010. Thanks are also due to every reviewer, member of the International Advisory Committee, and member of the Organising Committee, named and unnamed, who have contributed to the success of this conference and the quality of these proceedings.

It is my pleasure to welcome you now at HEFAT2010 on behalf of the Organising Committee. I trust that this conference will reach the common objective of bringing together scientists and engineers, and for inspiring us to uncover, share and glean more knowledge in order to tackle humankind's future problems.

JP Meyer
Editor

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